ASSESSMENT OF IMPACTS OF AN ALTERED TIDAL REGIME IN COPPERHOUSE POOL DURING CONSTRUCTION OF A TEMPORARY CAUSEWAY.

AQUATONICS LTD

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SUMMARY

The proposed change in the tidal regime in Copperhouse Pool for one month during construction of the causeway has the potential to adversely affect the flora and fauna present. We have therefore reviewed the available information to try and assess the likely extent of any adverse impacts.

The change in tidal regime we have assessed is for flood tides to be excluded during daylight on weekdays for a period of approximately a month.

There are several unknown factors that will determine the extent of any adverse impacts. The main factors are the weather (hot and dry conditions will be most damaging) and the biomass of fish and other fauna in the low water pool. We expect that the biomass in the low water pool will change seasonally and perhaps on a daily basis. The worst case scenario for impacts on fish and invertebrates in the low water pool would be a high biomass combined with high water temperatures. On the intertidal, the worst case scenario is a prolonged period of high temperatures combined with low humidity.

A monitoring programme is required that can assess impacts in real time and provide feedback to consultees and Carillion regarding the severity of any impacts. We have therefore suggested a trial exclusion of a daytime high tide well before construction works start. During this trial period we propose monitoring of water quality and fish behaviour in the low water pool.

We have also suggested a cost-effective monitoring programme of fish, invertebrates and algae that would commence one week before the change in tidal regime and continue for approximately one week after the normal tidal regime is reinstated.

As part of the mitigation we propose that the maximum period of emersion (i.e. exclusion of the flood tide) in Copperhouse Pool should not be greater than 12 hours.

If unacceptable adverse impacts occur it will be necessary to amend the working practices, for example by reducing the construction activities from every weekday to alternate weekdays (Monday, Wednesday and Friday). This would extend the overall duration of the works, which could also be damaging, so there is a fine balance to be struck.

Other mitigation measures may also be necessary, for example the ability to require construction work to cease temporarily to allow recovery of water quality and reduce temperatures in the low water pool. We also propose temperature limits of approximately 25°C predicted maximum air temperature and 24°C in the low water pool. The latter could possibly be predicted by correlating baseline measurements of maximum air temperatures with maximum water temperature.

We have made every attempt to ensure that there is no possibility of a fish kill, as trying to rescue already stressed and dying fish would be an additional stress that would cause further mortalities. If a fish rescue is required then we would need assistance from the Environment Agency Fisheries staff or have a team on standby. The latter would be very expensive.

As the temporary causeway was not part of the scheme assessed in the Environmental Impact Assessment there was no budget allocated for the additional monitoring work that is now required. Funding for the additional monitoring is outside the scope of this report.

1. INTRODUCTION

Aquatonics Ltd have been asked by Carillion Ltd to assess the impacts on fish, invertebrates, algal beds and *Salicornia* beds of an altered flow regime in Copperhouse Pool. The proposed altered flow regime is due to the need to have reduced water depths at the construction site for the temporary causeway. A report on the impacts of the changed flow regime on saltmarsh plants (excluding *Salicornia*) will be produced by Spalding Associates.

Carillion Ltd would like to have a period of approximately one month with the Copperhouse gate in the closed position. The plan would be to lower the gate when the water was at or near its lowest level. This will allow more rapid construction of the temporary causeway.

There is also a plan to retain winter opening for the gate throughout the year during bridge construction. The impacts of this on the ecology of Copperhouse Pool is outside the scope of this report.

2. INITIAL MITIGATION

At a meeting with Carillion Ltd, Aquatonics staff made it clear that a total closure of Copperhouse Pool for a period of approximately a month would be very damaging to aquatic life and is therefore unacceptable. We proposed that at a minimum the scheme to be considered would be that the night time high tides should be allowed in on every occasion. We also checked whether weekend working was proposed. Carillion Ltd said that it isn’t so we asked for a normal tidal regime during weekends.

The proposal assessed in this report is after this initial mitigation, i.e.:
Low water level throughout the day (Monday to Friday), but normal tidal flow into Copperhouse Pool at night. This will mean that for each weekday the high tide during daylight hours does not occur. All intertidal species will therefore experience a prolonged period of emersion (i.e. absence of water, the opposite of immersion).

Clearly even this revised scheme has the potential to adversely affect the flora and fauna of Copperhouse Pool. This report assesses the impacts on fish (section written by Prof Anne Smith, a specialist in fish physiology and fish welfare) and invertebrates (section written by Dr Phil Smith, a specialist on the impacts of pollution and engineering schemes on aquatic invertebrates). Comments on algae and *Salicornia* were written after discussions with Professor Nick Smirnoff, (University of Exeter) who is a specialist on the impacts of stress on plants.

3. FISH

Surveys of Copperhouse Pool in October 2001 and September 2010 have shown that it is an important nursery area for fish. When Copperhouse Pool empties, a large low water pool (approximately 25 m radius) is retained near Copperhouse Bridge and many young fish remain in this pool. In our 2010 survey of the low water pool, a partial catch of fish in the pool caught more than 4000 fish. Large numbers of juvenile Golden Grey Mullet, mostly 0+ or 1+ fish, represented the dominant biomass. This survey and an earlier survey of Copperhouse Pool in 2001, suggest that the Hayle Estuary complex may be one of the key nursery areas for Golden Grey Mullet in the South West. Thick-lipped Grey Mullet were also identified in the 2001 survey at Copperhouse. Surveys have also shown that Copperhouse Pool is a nursery area for Sand Smelt and Sea Bass, and juvenile Gilthead Seabream and Sandeel occur in the pool from time to time.

3.1 Principal Species Potentially Affected

Liza aurata	Golden Grey Mullet
Chelon labrosus	Thick-lipped Grey Mullet*
Atherina presbyter	Sand Smelt
Dicentrarchus labrax	Sea Bass
Ammodytes tobianus	Lesser Sandeel*
Pomatoschistus microps	Common Goby
Pomatoschistus minutus	Sand Goby
Sparus auratus	Gilthead Seabream*

**Species found in October 2001 survey of Copperhouse Pool, but not in September 2010 survey*

3.2 Predicted Impacts

The proposed lack of daytime inundation of Copperhouse Pool during weekdays will mean that there are significant periods when large numbers of fish are retained in the low water pool for extended periods. This will lead to a daytime deterioration of water quality, beyond that normally experienced by fish in the low water pool, and potentially result in stress and other physiological impacts on the fish. Secondly, retention for a prolonged period in the low water pool may increase predation by birds or carnivorous species of fish.

3.2.1 Predation by birds

Little egret, kingfisher, cormorants and gulls feed on fish in Copperhouse Pool, especially at and around low tide. If the normal return of water on the flood tide is prevented, these birds can continue to consume fish for an extended period. It also seems likely that more birds will be attracted to the pool, so that predation of fish will be significantly increased.

3.2.2 Predation by Sea Bass

Sea Bass are important for anglers and commercial fishermen, and a series of designated inshore nursery areas have been set up to provide protection while they are in their inshore nursery areas, during their first 3 years of life (Pickett et al., 1995). The Hayle Estuary is not currently a designated (protected) nursery area for Sea Bass although fish surveys indicate the presence of juvenile Sea Bass (0+ through to 3+) in Copperhouse Pool (Aquatic Environmental Consultants, 2001; Aquatonics, 2010).

Juvenile sea bass feed on invertebrates but as they age, they increasingly feed on fish and the proposed extended emersion of Copperhouse Pool during daylight hours would significantly increase the period in which Sea Bass in the low water pool can prey on fish retained in the low water pool. Sea Bass are cannibalistic; older, larger Sea Bass (2+) feed on younger Sea Bass (1+) and 1+ fish feed on 0+ fish (Henderson & Corps, 1997; Kelley, 2002). However, the high numbers of other species of juvenile fish in Copperhouse Pool suggest that the more common Sand Smelt and Mullets, and Common and Sand Goby are most likely the dominant prey species, along with the shore crab, *Carcinus* (Henderson & Corps, 1997; Kelley, 2002).

Whilst prevention of tidal influx for several hours could potentially increase predation of fish in the low water pool, it is probable that the juvenile Sea Bass will rapidly reach satiation and may already do this within the normal period available to them between tides. The additional period for feeding may therefore have limited net effect on predation and hence recruitment of fish in the Hayle Estuary complex.

If predation levels are increased they may cause some distress for all fish species/year classes, except for 2+ and 3+ Sea Bass for two reasons: (i) because of the stress of being chased around more frequently, and (ii) because the resulting stress will have an adverse impact on water quality.

3.2.3 Water quality

3.2.3 (i) Temperature

In Copperhouse Pool the relatively shallow low water pool is likely to increase in temperature above that normally seen in the pool, during the period of extended emersion. Shallow water pools in northern temperate regions can show temperature fluctuations of up to 13^{o}C during the alternating periods of immersion and emersion (Bridges, 1993), and during an extended emersion we can expect greater fluctuations, but this will also be influenced by air temperatures. Fish species vary in their temperature preferences and their sensitivity to high temperatures. For example the optimal temperature for Sea Bass is 22^{o}C (Pichavant et al., 2001). However, water temperatures may exceed optimal temperatures, and may potentially reach lethal levels for some species. At sub-lethal levels, a high temperature will have implications for many physiological processes, in particular metabolic rate and the oxygen consumption of fish in the pool.

To allow an assessment of the effects of the extended period without inundation of Copperhouse Pool on temperature in the low water pool and the impacts on fish species in the pool, we propose that temperature is one of the parameters monitored during a trial study of extended emersion prior to construction (see 3.3.1).

3.2.3 (ii) Oxygen

Many of the fish present in Copperhouse Pool remain in the low water pool during the ebb tide (Aquatonics, 2010). The amount of oxygen consumed by these fish will depend on a range of factors (Holeton, 1980) including:

- Species of fish present.
- Number of fish present.
- Life history stage and size of fish. In Copperhouse Pool, the majority of the fish are juveniles of < 10 cm. Small fish generally have a high metabolic rate, and consume more oxygen per unit of body weight than larger fish. Despite this, small fish tend to cope with water that has lower oxygen % saturation. This is because they have a large gill surface area relative to their body weight which allows more oxygen transfer across the gills.
- Recent food intake. Oxygen consumption is increased after feeding. Searching for food, digestion and assimilation can account for the majority of energy expenditure, for example 60% in Sea Bass (Pichavant et al., 2001).
- Activity. Swimming activity increases oxygen consumption in all species (Holeton, 1980). Male gobies (Sand Goby and Common Goby) ventilate their nests of eggs to ensure good development and if oxygen levels are low they significantly increase ventilation which increases their oxygen consumption (Jones & Reynolds, 1999).
- Stress. Fish may be more stressed by being held at a high density for a longer period than usual, particularly if there are higher than normal levels of predation. Early life stages are generally more vulnerable than adult fish.
- Temperature of the water. Oxygen solubility in water is reduced by an increase in temperature, but at the same time oxygen demands of fish increase because their body temperature closely follows that of the water (except in a few species that do not occur in Copperhouse Pool). These effects are more significant when temperature changes occur rapidly, rather than seasonally. About 2-3 fold increase in oxygen consumption occurs for a 10^{o}C rise in water temperature (Jensen, 1993).

Because of the high biomass of fish in the low water pool and their oxygen consumption, it is highly likely that the dissolved oxygen (DO) concentration of the seawater in the low water pool decreases between each tidal exchange. A further influence on the DO of the water is its 'Biological Oxygen Demand' (BOD), due to organic matter and nutrient content which determine oxygen use by bacteria in microbial degradation processes.

Without a tidal inflow of seawater DO is highly likely to decline to lower concentrations than normal. A DO concentration of 4-5 mg/l is often used as the minimum sustained level for healthy fish populations (Alabaster & Lloyd, 1980), but a concentration of 6.7 mg/l has been suggested to be necessary for long term health of marine fish (Davis, 1975). However, short periods of lower DO are not likely to be harmful.

Sensitivity to low DO differs between species and life stages. For example, the Sand Goby, studied in brackish water, showed increased activity when DO was below 60% saturation (~ 5.2 mg/l) and starts to shows 'avoidance responses' when the water DO is less than 4 mg/l (Petersen & Petersen, 1990). Such avoidance responses would not be feasible during the proposed lack of inundation of Copperhouse Pool. In the low water pool DO might decline below 60% saturation to a point where fish mortalities can occur. For Sand Goby there is an increasingly narrow window between no mortality and 100 % mortality as DO declines; at 15 % saturation (~1.3 mg/l) approximately 10% of the Sand Gobies died within about 8 hours (Peterson & Peterson, 1990), which is within the time-frame of the proposed extended emersion.

In contrast to the sensitivity of Sand Gobies to low DO, Sea Bass, which are active fish with a high oxygen demand, are adapted to cope with low DO. Sea Bass have a high oxygen carrying capacity in the blood and a strong ability to unload the oxygen in metabolising tissues (Pichavant et al., 2001; 2003). In experimental studies of long-term exposures to DO of between 3.2 and 7.4 mg/l, a low DO had limited impacts, except for a reduction in feeding at 3.2 mg/l. This reduced the oxygen requirements by about 20 % (Pichavant et al., 2001; 2003). So, in Copperhouse Pool, Sea Bass may cope with the proposed extended emersion reasonably well. However, at this stage we do not know how much of a decline in DO in the low water pool there will be during the proposed extended emersion. The longer the tide is held out, the lower that the DO will get in the low water pool and rates of oxygen consumption will have an important influence. We therefore propose monitoring DO in the low water period in a trial study prior to the start of constructions (see 3.3.1).

The impact are of a low DO on fish is adversely influenced by other factors, such as high ammonia or metal concentrations and high temperature (Davis, 1975; Alabaster & Lloyd, 1980; Davis, 1975).

3.2.3 (iii) Metals

The high water content of metals such as copper, arsenic and zinc in Copperhouse Pool means that the impacts of low DO will be combined with the impacts of metals, and these may change during the extended emersion of Copperhouse Pool. We therefore propose monitoring the metal concentrations in the low water period in a trial study prior to the start of construction work (see 3.3.1). We will then assess the impacts of the metal concentrations in combination with measured ammonia and DO on the fish species present.

3.2.3 (iv) Ammonia

Fish excrete up to 90% of their nitrogenous waste as ammonia which is normally diluted by the water and therefore non-toxic. The high density of fish in the low water pool means that ammonia concentrations may rise towards toxic levels and with time this becomes more likely so it could occur during the prolonged emersion of Copperhouse Pool.

Ammonia chemistry is complicated by the existence of different forms. Toxicity increases with higher temperatures, salinity and pH, mainly due to the increased proportion of unionized ammonia, (NH_3), which is 300-400 times more toxic than the ionized form (NH_4^+) (Alabaster & Lloyd, 1980; Lemarie et al., 1996).

Susceptibility to ammonia varies between fish species. There have been fewer studies of marine species than freshwater species, but the general picture seem to be that marine fish are more tolerant of ammonia than freshwater species and relatively high acute LC50s (lethal concentrations for 50% of the tested animals) have been reported for several marine species.

LC50s of 0.3 - 1.76 mg/l unionized ammonia have been reported for various studies of juvenile Sea Bass and the ‘lethal threshold concentration’ (LTC) of ammonia in seawater, at which no mortalities occurred was 1.0 to 1.3 mg/l unionized ammonia (Lemarié et al., 1996). Gilthead Seabream juveniles appear to be more tolerant of ammonia: an LC50 of 1.27-2.55 mg/l and an LTC of 2.5 mg/l (unionized ammonia in both cases) have been reported (Lemarié et al., 1996; Wajsbrot et al., 1991).

Mortality during acute exposures to ammonia is a crude measure of toxicity and sub-lethal effects need to be considered. The maximum acceptable toxic concentrations (MATC) for marine fish species, at which there are no sub-lethal effects such as effects on growth and swimming behaviour, lie between 0.04 to 0.5 mg/l unionized ammonia, with Gilthead Seabream at the upper end of this range (Wajsbrot et al., 1993). These values are based on chronic impacts and can only give a guide for assessing likely the impacts of extended emersion at Copperhouse Pool. The proposed short term (12 hour maximum) exposures to rising ammonia concentrations should be less damaging. However, the repeated exposures during the week may mean that there is some similarity to the effects of chronic exposures.

The toxic effects of ammonia are increased in the presence of high concentrations of copper, lead or zinc (Davis, 1975), which may occur in the low water pool as a result of the extended period of emersion and increased disturbance of the contaminated sediments on the bed of the pool. Furthermore, a low DO increases ammonia toxicity (Alabaster et al., 1979; Wajsbrot et al., 1991). In Gilthead Seabream, at below 40% DO saturation, the response to ammonia is increased non-linearly and mortalities occur rapidly as a consequence of additive effects (Wajsbrot et al., 1991).

3.3 Proposed Monitoring and Mitigation

During construction, Carillion plan closure of the gate when water levels in Copperhouse Pool are near their minimum, which is about 3 hours after low tide, and the return of inflow by opening the gates at an appropriate time, to allow tidal inflow overnight. Exact timings will be complex. As mitigation we propose that the maximum period of emersion (i.e. exclusion of the flood tide) in Copperhouse Pool should not be greater than 12 hours.

3.3.1 Pre-Construction Monitoring

To assess the likely risks to the fish in the pool when the proposed lack of daytime inundation occurs, we propose that prior to the start of the causeway construction we undertake a pre-construction trial, in which water in Copperhouse Pool is held at low water levels for 12 h. This is the maximum period per day which we suggest should be the limit for the construction phase. The proposed trial study would need approval from relevant authorities such as Hayle Harbour Authority Ltd, Natural England, Environment Agency, and RSPB.

During the proposed trial we would investigate the changes in water quality (water temperature, DO, conductivity, ammonia and metal concentrations), and assess fish behaviour using the approaches outlined below.

3.3.1 (i) Water quality

The results will provide information on the normal variability in water parameters that are experienced by fish in the pool during a natural tidal cycle and the further changes that occur over the subsequent 6 hours.

Salinity can be readily recorded with our hand held accurate meter (YSI) that Aquatonics Ltd have found to give reliable data in field studies.

Frequent monitoring of DO can be easily achieved using a robust luminescent probe (Hach LSO) which is regularly used by Aquatonics Ltd in field studies.

For measurement of ammonia and metal concentrations we would collect water samples and dispatch these for chemical analysis by the National Laboratory (Environment Agency).

Young fish are more generally vulnerable to adverse water quality, particularly when pollutants are present and this is pertinent as Copperhouse Pool is a nursery area for several species of fish (Aquatonics, 2010). More specific focus on the individual species requirements will be made using the data for DO, ammonia and metal concentrations obtained during the trial study.

3.3.1 (ii) Fish behaviour linked to physiological events

Alongside the assessment of water quality we will monitor fish behaviour in the low water pool during the trial study.

We have observed fish jumping at the surface in the low water pool at Copperhouse Pool. During the pre-construction study we will assess the extent of such behaviour, as it may increase in frequency during longer periods of low water.

When normal gill ventilation does not provide sufficient oxygen for metabolism, digestion and physical activities, most fish show behavioural changes in an attempt to compensate (Davis, 1975). Increased swimming and avoidance responses occur in some species (Petersen & Peterson, 1990). Fish species differ in their sensitivity to low DO but generally at some point (known as the incipient oxygen response threshold) they will increase their gill ventilation by breathing more frequently and/or more deeply and they may also rise to the surface where oxygen concentrations may be higher, or they may gulp air (Holeton, 1980; Peterson & Peterson, 1990; Fritsche & Nilsson, 1993). If oxygen uptake cannot be increased by the additional ventilation of the gills or by air gulping, or if water quality is sufficiently adverse, then swimming is likely to be adversely affected (favouring predation) and they may become disoriented and some may die.

We will employ visual observations and recording, and/or still and surface video photography. Further information could be acquired by use of drop-down video recording. We have experience in use of these techniques for assessing fish behaviour in the field (http://www.sarf.org.uk/Project%20Final%20Reports/SARF021%20-%20Final%20Report.pdf) for single species; the mixture of species present will add to the complexity of assessing behaviour in Copperhouse Pool.

If for any reason a trial 12 hour period of low water in Copperhouse pool is not feasible, then as a fall back we could make measurements during a normal tidal cycle and use the results to predict the changes in water quality and their impacts on fish during a longer period of low water. These estimations could include allowance for the likely increase in oxygen consumption when fish are stressed, for example by a more sustained period at high density or by increased predation, but our predictions could not be as reliable as monitoring the events during a trial 12 hour period of low water.

3.3.2 During causeway construction

The results from the pre-construction trial will determine the intensity of monitoring and parameters to be monitored during the construction phase and may lead to modifications of our plans.

If metal concentrations and/or ammonia concentrations and/or DO change significantly during the trial (section 3.3.1) and suggest possible toxicity for fish held in the pool, something closer to real-time monitoring will be needed to provide rapid feedback on events and enable appropriate reaction, which could include a requirement to allow return of water inflow at the next available opportunity.

Meters can provide frequent measurements of DO, temperature and salinity. Field measurement of ammonia and metal concentrations are less straightforward. For metal concentrations, an electrochemical method could be employed in a mobile 'laboratory', provided equipment was hired. For ammonia, relatively inexpensive semi-portable colometric devices are available.

We anticipate that frequent monitoring of water quality and fish behaviour will be necessary during the first week of construction. We propose that fish behaviour is closely monitored for evidence of increased numbers of fish close to the surface or apparent changes in behaviour patterns and activity. Water quality monitoring will be determined by the results of the trial study.

On subsequent weeks, provided that there are no signs of significant behavioural changes, less frequent monitoring may be sufficient and might be undertaken by Catriona Neil of Spalding Associates (the Ecological Clerk of Works for the scheme), provided suitable monitoring equipment is available and that she is familiarised with the behavioural monitoring. However, if there are signs of behavioural disturbance, coupled to significant deterioration in water quality, then monitoring would need to be stepped up.

3.4 Mitigation measures if monitoring shows unacceptable adverse impacts

Part of the mitigation would be the restriction of the period of construction each day, and we propose that the maximum period of low water is set at 12 hours.

Adverse impacts should be discussed with the appropriate regulatory bodies (EA & NE) and landowner (RSPB). If it is agreed that they indicate unacceptable adverse impacts then the working practices will need to be amended, for example by allowing work only on alternate days (Monday, Wednesday and Friday). However, this would slow the construction, which may then take an extra couple of weeks, and could in itself have a greater overall impact on fish in Copperhouse Pool.

A possible engineering solution that may partially offset the effects of a lack of inundation is to increase the height of the overflow into the deep channel, so that the volume of the low water pool is increased during the construction of the causeway. The pool would need to be returned to its previous state after the period of engineering. Once pre-construction monitoring of water quality in the low water pool has been undertaken, we could calculate how much of a change in volume would be needed and whether this is a feasible option.

If the pre-construction monitoring of a trial 12 hour period of low tide conditions indicates that oxygen levels may reach unacceptably low levels, then a compressor could be used to provide continuous aeration.

If there are significant adverse effects on water quality, such as water temperature exceeding a particular temperature, perhaps 24^{o}C, it will be necessary to resume normal tidal flows at the earliest opportunity. This could possibly be predicted by correlating baseline measurements of maximum air temperatures with maximum water temperature.

A fish rescue plan needs to considered as the final option if severe adverse impacts become evident during construction. However, as the rescue in itself is likely to be very stressful to already stressed fish, the value of a rescue at that point is questionable. If a fish rescue is required then we would need assistance from the Environment Agency Fisheries staff or have a team on standby. The latter would be very expensive.

4. INVERTEBRATES

4.1 Principal Species Affected

Enchytraeids	A family of oligochaete worms
Nereis diversicolor	Harbour ragworm
Pygospio elegans	A spionid polychaete worm
Arenicola marina	Lugworm
Corophium volutator	A gammarid amphipod crustacean
Orchestia species	A gammarid sand hopper
Crangon crangon	Brown shrimp
Mysid shrimps	Ghost or opossum shrimps
Carcinus maenas	Shore crab
Littorina saxatilis	Rough periwinkle

4.2 Predicted Impacts

Prolonged emersion (i.e. when the tide is out and the flora and fauna are not covered by water) is not a naturally occurring phenomenon. However, there are some occasions when closure of man-made tidal barriers (such as the Oosterschelde storm-surge barrier in the Netherlands) causes prolonged emersion. In laboratory experiments to study impacts of such a closure, Hummel et al. (1988) found that the average mortality of the intertidal community reached 50% within 3 days of emersion when the temperature was over 19°C.

The most directly relevant paper is a field study of densities of intertidal species in the Zwin nature reserve in Belgium and the Netherlands before and during a 27 day emersion event (Van Colen et al, 2006). The main difference from the proposed change in tidal regime at Copperhouse Pool is that the emersion was during the winter months. This difference may explain why no species disappeared from the study area in the Zwin nature reserve and there were only modest declines in the population densities of most species. The study by Van Colen (2006) did not examine whether the populations that survived were healthy and whether subsequent reproduction was affected. Nevertheless, it is surprising that the impacts of a 27 day emersion event were not very severe.

Each intertidal species has a different response to prolonged emersion and desiccation. The best way to assess likely impacts is therefore to consider the daily activity rhythms of each species (where known) and whether activities such as reproductive behaviour, feeding and predation are influenced by tidal state. Recovery of populations from any mortalities will depend on a number of factors, such as the extent of the mortality and reproductive processes (e.g. whether the species has a pelagic larval stage). To do a complete assessment of all relevant papers on these species would take several weeks, so in this report we have concentrated on those species that are of greatest importance as bird and fish prey.

Enchytraeids **A family of oligochaete worms**

Enchytraeid oligochaetes (Figure 1) cannot be identified to species level on routine surveys and it is likely that there are several species present in the Hayle estuary complex. Enchytraeid worms have their highest densities in the uppermost parts of the sedimentary habitats in Copperhouse Pool. They seem to prefer relatively dry sediments. They may have some importance as wader prey in the algal and *Salicornia* beds. We think this group is the least likely to be affected by the change in tidal regime.

Nereis diversicolor **Harbour ragworm**

Ragworm (*Nereis diversicolor*, synonym *Hediste diversicolor*) (Figure 2) is one of the two main wader prey species in Copperhouse Pool and it is therefore very important that the population is protected. Ragworm have a wide variety of feeding mechanisms, the main ones are:

- Suspension feeding by forming a mucous net around the opening to their burrow. The mucous net and attached particles are then consumed.
- Actively preying on smaller benthic invertebrates, using their powerful jaws.
- Deposit feeding on sediment with its associated detritus, microalgae and bacteria etc

The first of these feeding methods presumably can only be effective when the burrow is covered by a layer of water and would therefore be affected by the proposed change in tidal regime. However, the other two feeding methods would be unaffected by the changes and it is unlikely that ragworm will suffer significant reductions in food intake.

Reproduction of ragworm in SW England in mild winters can start as early as January or February (pers. obs. Phil Smith), but the peak period is in the spring and early summer. Core from Copperhouse Pool, collected in July 2010 contained large numbers of very small (0+) individuals. The expected timing of the causeway construction in June could therefore have an adverse impact on reproduction. Females outnumber males by a ratio of 4 – 5 :1 (Olive and Garwood, 1981) and the males actively seek out burrows of sexually mature females and release their sperm near the entrance. This release of sperm presumably requires a layer of water over the burrow to be effective, so would be adversely affected by the proposed tidal regime.

Vismann (1990) showed that the harbour ragworm, *Nereis diversicolor* is much more tolerant of high sulphide and low oxygen concentrations (hypoxia) in the sediment than the closely related king ragworm (*Nereis virens*). The latter species is not present in Copperhouse Pool. In both species, when they are exposed to high sulphide and low oxygen concentrations feeding declines and some of the population come to the surface (head first for *Nereis diversicolor*, tail-first for *N. virens*) and crawl on the surface but are not as active as normal. Although *Nereis diversicolor* is very tolerant of high sulphide concentrations and hypoxia, it is possible that the change in tidal regime will affect behaviour and feeding. The presence of an unusual number of specimens on the surface will be a good indicator that this species is being affected.

Pygospio elegans **A spionid polychaete worm**

This small spionid polychaete worm lives in the surface of the sediment, inside an almost vertical tube constructed of sand grains (Figure 3). The tube often extends slightly above the surface of the sediment, so dense populations can be spotted during surveys. *Pygospio elegans* reproduces both sexually and asexually (Gibson & Harvey, 2000). In our opinion this reduces the possibility that changes in behaviour of adult worms will significantly affect recruitment. In Copperhouse Pool, it is restricted to sites which are lowest on the intertidal. This may mean that it is susceptible to drier conditions, but it is likely that moist conditions are retained in the tube.

Although *Pygospio elegans* is widely regarded as a surface deposit-feeder (when the tube is covered by water), it is also a suspension feeder and a carnivore on oligochaete worms (Piesik and Obolewski, 2007). It is likely that it mainly feeds when the tube is covered by water, regardless of whether this is in daytime or nightime. It is therefore likely that this species will obtain only half the normal amount of food during the weekdays for the month of construction. Taking weekends into account it may obtain about 70% of its normal dietary intake during the month. We do not know whether it could partially compensate by feeding more at night. We also do not know whether 70% of normal intake is sufficient for survival, but suspect that it is.

It is likely that *Pygospio elegans* is more important as a prey item for fish and brown shrimps than for birds. Predation *of Pygospio* by brown shrimps and fish would be reduced during the day, due to the smaller area of *Pygospio* habitat covered by water.

The overall impacts on *Pygospio elegans* are difficult to predict. If the population density is affected it is likely to recover within 1-2 years, due to the short life cycle and ability to reproduce asexually. The next benthic survey in Copperhouse Pool is scheduled for July 2012. This will show whether the population is present at the expected densities.

It is probably not cost-effective to monitor behaviour or condition index of *Pygospio elegans* during the works, but this could be done if consultees require it.

Arenicola marina **Lugworm**

Lugworms are one of the most intensively studied intertidal species in Europe. The Marlin web site provides a very useful summary of the ecology of this species (see http://www.marlin.ac.uk/biotic/browse.php?sp=4238). The relevant text on the Marlin web site is too long to repeat here and we recommend consulting it for further details.

Arenicola marina burrows into sediment with its anterior end, forming a J-shaped burrow with a vertical shaft and a horizontal limb where it lies head first. *Arenicola marina* ingests sediment and this produces a characteristic funnel or 'blow hole' on the surface. The ingested material contains food in the form of bacteria, meiofauna and benthic diatoms. The processed sediment is retained in the long posterior part of the lugworm body and at intervals of about 42 minutes in large worms and 15 minutes in smaller worms this is discharged at the surface, forming the characteristic cast. After defaecation (when the worm is mainly in the vertical part of the tube) there is a period of rapid irrigation of the burrow, followed by a longer period of feeding. Irrigation of the burrow with clean water is very important as this provides oxygen. Lugworms can extract 32 - 40% of the oxygen in the burrow water, mainly through the gills but partly through the body surface (information from the Marlin web page). The blood has a high oxygen carrying capacity due to the presence of high concentrations of extracellular haemoglobin. At low tide, when a supply of oxygenated water is not available, movement is reduced to a minimum.

The timing of reproduction in lugworm varies between different locations. The following text is an edited version of the section on reproduction on the Marlin web site. We have added comments in italics on the implications for the Copperhouse Pool population.

- Spawning usually occurs in late autumn or early winter but may occur in early spring. The exact timing of spawning varies between locations and some populations demonstrate protracted spawnings. For example, on sandy shores near St Andrews and Dublin spawning occurred between mid October to mid November, peaking in early November, whereas at Millport spawning occurred between April and May and again in autumn. *The proposed change in tidal cycle will be outside these dates.*
- Spawning is inhibited by temperatures above 13 or 15 °C (depending on study). *It is likely that water temperatures in the low water pool will be high enough naturally to inhibit spawning, but if the weather is cool the longer period of shallow water during daylight hours could increase the chance that spawning will be inhibited. However, as the proposed works are scheduled for June no spawning is anticipated.*
- Warm summer temperatures (May to July) may facilitate gametogenesis, due to increase metabolic rate and food availability, allowing the population to mature earlier and hence spawn earlier. *The changed tidal regime may affect feeding, condition and hence the ability of the lugworm to produce the normal number of gametes. This would reduce the reproductive potential of the lugworm stock for the autumn spawning.*

Lugworms have a life span of 6-10 years but are sexually mature from an age of 1-2 years (Marlin web site). If there are adverse impacts on the adult population at Copperhouse Pool it will take a few years for the age structure of the population to return to normal.

The survival of lugworm during prolonged emersion was studied in the laboratory by Hummel et al (1986). In the summer experimental period (14 – 27 °C) 10% of the population died each day on average. No mortalities were observed in the autumn experiments, and in spring there was an intermediate level of mortality.

The proposed change in tidal regime is likely to affect feeding, predation and reproduction of lugworm. Different factors will be important for the submerged population in the pool (where increased duration of predation and possible changes in water quality will be the most important factors) and in the intertidal population (where we expect reduced aeration of the burrow, reduced feeding and reduced reproduction). Both populations are expected to decline as a result of these changes, but there is a great deal of uncertainty about the extent of the decline. We therefore propose monitoring of lugworm casts in the intertidal population as a method of assessing feeding and as an indicator of the density of active lugworm. Monitoring the subtidal population effectively would be very difficult and add another disturbance factor for the fish and invertebrates in the low water pool and is therefore not recommended.

Corophium volutator **A gammarid amphipod crustacean**

Corophium volutator (Figure 4) is the most numerous benthic macrofaunal species in Copperhouse Pool and was present at high densities (maximum 32,000 per sq metre) at 12 of the 15 locations surveyed in July 2010. Although it is smaller than ragworm, the high densities and higher availability of *Corophium* near the surface are likely to mean it is the most important wader prey in the autumn months. In the winter, densities of *Corophium volutator* will be much lower due to natural mortality in the population.

A study by Jensen and Kristensen (1990) in the Danish Wadden Sea showed that burrow depths were normally in the range 3.0 – 5.5 cm (max 6.5 cm). We have not measured the depth of *Corophium* burrows in Copperhouse Pool, but we have seen the depths of burrows when obtaining *Corophium* samples for metal analysis and they were similar to those recorded in the Wadden Sea. The sediment in areas favoured by *Corophium* in Copperhouse Pool retains water for a long time after the tide has receded. It seems likely that moisture levels will be sufficiently high to prevent mortality due to desiccation during the altered tidal regime, provided that unusually hot and dry conditions do not occur.

The reproductive biology and swimming activity of *Corophium volutator* are well known from various laboratory and field studies. Fish and Mills (1979) studied a population in the Dovey estuary (Wales). They found that there were two generations per year; a relatively small overwintering generation that breeds from March and peaks in May and decreased sharply in June. The offspring from this recruitment grew rapidly and bred in summer through to October. The survivors of the second generation overwintered to repeat the cycle. This reproductive cycle means that if the works are carried out in June 2011 they could adversely affect the success of recruitment of the cohort that will become the overwintering population. However, provided there is a good stock of *Corophium* left at the end of the works the fact that reproduction may extend to October could prevent a large scale failure in recruitment.

Although adult *Corophium volutator* can be seen crawling on the mud surface, close inspection shows that these are almost entirely males (Fish and Mills, 1979). As the tide recedes the males emerge from the burrows and crawl over the surface to find a burrow with a female in. Mating is thought to occur in the burrows rather than in the water column. The highest levels of crawling activity on the sediment surface were recorded when the amplitude of the spring tides was increasing. Some activity was recorded during the highest spring tides, but this fell to negligible levels on neap tides (Fish and Mills, 1979). As the proposed works are over a one month period this will probably disrupt this rhythm, which is probably so ingrained that the males will continue the activity even without the cue of receding water. Two periods of rising spring tides will occur during a month, but the number of suitable days when the males can seek out females will be reduced by the change in tidal regime. In June 2011 the period of increasing spring tides unfortunately occurs during the week rather than at weekends (when no work is proposed and tidal regimes will be normal).

The MarLin site at www.marlin.ac.uk/speciesbenchmarks.php?speciesID=3052 summarises information on sensitivity of *Corophium volutator* to various stressors. An edited version of the text on desiccation and increased emergence time is below:

> "Despite the large amount of interest in the biology of *Corophium volutator*, no information was found detailing its resistance to desiccation. However, it occupies

> estuarine mud that has a high interstitial water content that rarely dries out. Therefore it probably avoids the effects of desiccation in its burrow. Males crawl on the mud surface shortly after emersion but this behaviour only lasts a short time and probably does not make them vulnerable to desiccation. Tolerant has been recorded because of the burrowing habit of *Corophium volutator*.
>
> An increase in emergence caused by a decrease in tidal amplitude would dry out mud at the top of the shore and exclude *Corophium volutator*. As a consequence the amount of suitable habitat for *Corophium volutator* would probably decrease (squeezed between the dry upper shore and tidal/river channels at the bottom of the shore) and lead to a population decline. Increased emergence is unlikely to kill *Corophium volutator* in the mid shore but may cause some mortality at the population fringes. Intermediate intolerance has been recorded to account for the worst case scenario, and potential loss of population extent."

The lack of information on desiccation is an important gap in our knowledge, in particular how this affects feeding and reproduction, which are likely to be the most important impacts of the change in tidal regime.

Young are brooded in a pouch beneath the female. This may protect them from the worst effects of desiccation and elevated temperatures. Juvenile *Corophium volutator* are more resistant to high temperatures than adults (Mills and Fish, 1980). However, even adult *Corophium volutator* are relatively tolerant of high temperatures. In laboratory experiments no mortality was observed at temperatures below 32°C (Mills and Fish, 1980).

***Orchestia* species**　　**A gammarid sand hopper**

Orchestia mediterranea and *Orchestia gammarellus* are found under stones on the upper parts of the sedimentary habitat in Copperhouse Pool. Results from a 27 day emersion event in Belgium and the Netherlands showed that *Orchestia* species were found further down the shore than would be normally expected (Van Colen et al., 2006). This was thought to be due to their migration down the shore to take advantage of the prolonged dry period. We therefore expect *Orchestia* species that are normally restricted to the uppermost parts of the shore at Copperhouse to move slightly further down the shore during daylight hours. Overall, we do not expect any adverse impacts on *Orchestia* species as they are semi-terrestrial and can tolerate long periods of desiccation.

Crangon crangon　　**Brown shrimp**

Brown shrimp occur in the low water channels and in the low water pool at Copperhouse. They are important in the food web as both predators on smaller species and prey for fish and birds. The main impacts will probably be related to water quality in the low water pool and reduced water depths in the low water channels. They can be found naturally in channels with only 5-10 cms of water present, so unless the low water channels drain down completely water depth should not cause mortalities.

Water quality is expected to decline in the low water pool during the extended emersion (see section 3.2.3). We expect the monitoring measures we will put in place to protect fish will also protect brown shrimp.

We think there is a low probability that reproduction of brown shrimp will be affected by the altered tidal regime.

Mysid shrimps **Ghost or opossum shrimps**

Mysid shrimps are very mobile, moving actively with the flood tide to reach the shallows then descending again with the ebb tide. It is likely that the low water pool at Copperhouse is the main location for the majority of the population that stays in Copperhouse (some will leave with each tide). The extended period when the mysid shrimps will need to remain in the low water pool during construction work is expected to increase their mortality due to predation by brown shrimps and various fish present in the pool. They will also experience any decline in water quality caused by the large biomass of fish held in a relatively small pool for an extended period (see section 3.2.3).

The water quality in the pool will be monitored as part of the proposed fish monitoring. We do not propose any specific monitoring of mysids in the pool, but this could be added if necessary.

Carcinus maenas **Shore crab**

Shore crabs kept in laboratory conditions exhibit two distinct cycles, one of about 12.4 hours which is related to tidal state, and the other approximately 24 hours (Naylor, 1958). These laboratory studies suggested that activity was highest around high tide and for a few hours afterwards, with the highest activity recorded at high tide during the hours of darkness. However, field studies have shown no difference in the activity of migrating crabs between day and night (Hunter and Naylor, 1993).

The partitioning of the intertidal resource between juvenile and adult crabs and between males and females is complex. On the lowest parts of the shore most of the crabs are adult males. Some of these larger males migrate up from subtidal locations to the lower shore when it is exposed. The crabs that were on the lower part of the shore move further up the shore during the ebb tide. Searching for food is mainly concentrated around the flood tide and is minimal on the ebb tide (Hunter and Naylor, 1993).

It is likely that these tidal migratory rhythms will be maintained when Copperhouse Pool is kept emersed during the daylight hours, as they occur for several days in the laboratory when *Carcinus* are kept in moist but tide-free conditions. This may have some minor effects on the *Carcinus* population in Copperhouse Pool, but these are expected to be relatively minor, such as reduced food intake during daylight and perhaps increased predation by birds and decreased predation of juvenile crabs by fish.

The following text on reproduction in *Carcinus maenas* is edited from the MarLin web site (www.marlin.ac.uk/biotic/browse.php?sp=4286):

> Egg-bearing females can be found throughout the year in the south of England. Males preferentially select females with a carapace width 10 mm smaller than their own but are not size selective below this threshold and do not select females on the basis of imminence of moult. After moulting the 'soft' female is turned over by the male and copulation ensues through modified pleopods on the much reduced abdomen. The female bears the fertilized eggs in a mass held between the abdomen and underside of

> the carapace. Females are berried (i.e. are carrying fertilised eggs) for up to 4 months, depending on temperature, before the eggs hatch in spring/summer. Females in estuaries migrate to the mouth of the estuary to release larvae at night on ebb tides into fully saline water. At the southern limit of its range, larvae are released in winter when water temperatures are cooler. *Carcinus maenas* has been reported to breed only at temperatures below 18°C.

It is therefore likely that the amended tidal regime for a month in summer 2011 will only have a minor impact on the reproductive cycle of *Carcinus maenas*, provided that desiccation does not affect the fertilised eggs being carried by female crabs. If there is an impact on summer recruitment it seems likely that reproduction later in the year will be able to compensate to some extent.

Littorina saxatilis **Rough periwinkle**

Some gastropod snails, including *Littorina saxatilis*, have an operculum, which can be shut to reduce desiccation. In addition, the shell has a low permeability and periwinkles can find moist sites to hide in during emersion. These factors make periwinkles resistant to emersion. Hummel et al (1988) found that *Littorina saxatilis* was one of the most resistant intertidal animals to desiccation.

We think it is unlikely that *Littorina saxatilis* will show increased mortality during the changed tidal regime, but condition could decline due to reduced feeding and this could affect reproduction.

4.3 Proposed Monitoring and Mitigation

We recommend that monitoring commences a week before the tidal regime is altered and continues for at least one week after the normal tidal regime is reinstated. This would be extended for any studies that continued to show abnormal results.

No monitoring is proposed for enchytraeid oligochaetes, *Pygospio elegans*, *Orchestia* spp., mysid shrimps, brown shrimps and shore crabs. If consultees require any of these species to be added to the monitoring plan we will propose some suitable methods.

Nereis diversicolor

We will count the number of ragworm visible on the surface in 1 square metre quadrats (5 replicates per site) at 2 locations. This should be standardised to a particular time of day.

Arenicola marina

We propose to monitor lugworm by counting casts in 1 square metre quadrats (5 replicates per site) at two locations in Copperhouse Pool. This should be standardised to a particular time of day.

Corophium volutator

Aquatonics Ltd will produce a map showing two sites with high densities of *Corophium volutator* that are readily accessible and suitable for routine monitoring. In advance of any work starting Catriona Neil (Ecological Clerk of Works for Carillion) will check normal behaviour of *Corophium* on the surface of the mudflat. During the first week of construction works Catriona will do a daily examination of the two sites with high *Corophium* densities. This should be standardised to a particular time of day. If no differences in behaviour are observed then the frequency could be reduced to Tuesdays and Thursdays in subsequent weeks.

Aquatonics Ltd will assess the condition index (i.e. weight in relation to body length) of larger specimens of *Corophium volutator* by taking samples of at least 50 specimens from each of the two locations. The condition index of males and females would be assessed separately. If time permits we may also be able to count the number of eggs or developing juveniles carried by each gravid female. This work should start immediately prior to the amended flow regime and continue at weekly intervals throughout the causeway construction. The final sample would be taken 1 week after the flow regime has returned to normal.

Littorina saxatilis

To monitor the health of *Littorina saxatilis* we propose to temporarily remove 20 individuals from the upper shore and place them in saline water (salinity to be determined, probably about 80% seawater). We will then note the time required for 50% of the individuals to become active. In the baseline survey this test needs to be standardised to a set time after high water (say 6-8 hours). During the construction work we propose to monitor them at 6-8 hours and also at the maximum emersion period (12 hours).

During the first week of construction work the tests would be done each weekday. If there are no reduction in activity during prolonged emersion it would be sensible to reduce the frequency of monitoring during the remainder of the construction period, unless there is a period of hot dry weather.

Mitigation measures if monitoring shows unacceptable adverse impacts

Any adverse impacts on the chosen species would be discussed with the appropriate regulatory body and landowner (RSPB). If it is agreed that they indicate unacceptable adverse impacts then the working practices would need to be amended, for example only allowing working on alternate days (Monday, Wednesday and Friday). However, this would slow progress on the construction, which may then take an additional couple of weeks.

The other main mitigation measure would be to have a ban on extended emersion when the air temperature was predicted to be above a set temperature, perhaps 22°C.

The only other mitigation measures that would allow construction to proceed would require saltwater irrigation of selected intertidal areas. This would only be considered if the reduction in the number of working days per month did not produce an improvement.

5. ALGAL & SALICORNIA BEDS

Information on the algae and saltmarsh species present in Copperhouse Pool was obtained in various surveys by Aquatonics Ltd, mainly in 2010 as part of the baseline monitoring. These reports are available from Aquatonics Ltd to any of the consultees.

5.1 Principal Species Affected

5.1.1 Filamentous green algae

The main algal species on the intertidal areas of Copperhouse Pool in mid August 2010 were various filamentous green algae:

Ulva prolifera (the most common algal species at Copperhouse Pool)
Ulva torta (co-dominant with *U. prolifera* at some locations)
Ulva intestinalis
Ulva compressa
Ulva linza
Rhizoclonium riparium (sometimes co-dominant with *Salicornia, U. prolifera & U. torta* in upper reaches of Copperhouse Pool
Blidingia minima
Blidingia marginata

Note that all species of *Ulva* were until recently placed in the genus *Enteromorpha*.

5.1.2 Brown seaweeds

The brown seaweed *Fucus vesiculosus* (bladder wrack) is found in the upper parts of Copperhouse Pool, usually near the margins and normally attached to cobbles and boulders. Some invertebrates, for example gammarid amphipods, shore crabs and the rough periwinkle *Littorina saxatilis* are associated with these seaweeds, which provide cover and a moist environment when the tide is out. Any desiccation of the *Fucus vesiculosus* may adversely affect these invertebrates.

5.1.3 Glasswort (*Salicornia europaea*)

There are extensive beds of glasswort (*Salicornia europaea*) in Copperhouse Pool. Perhaps due to the high metal content of the sediments the associated invertebrate fauna is restricted, and comprises mainly enchytraeid oligochaete worms, various dipteran larvae and pupae and occasionally rough periwinkles (*Littorina saxatilis*).

5.2 Predicted Impacts

5.2.1 Filamentous green algae

Filamentous green algae in the genus *Ulva* have maximum biomass in the late summer and are mainly found on the highest parts of the shore and are therefore likely to be relatively physically resistant to desiccation. However, studies on *Ulva* (*U. linza*, *U. prolifera* and *U. clathrata*) in Oregon, USA have shown that 95% of the photosynthetic activity occurs when they are covered with water, and that desiccation and compression of the algal mat at low tide severely reduces photosynthesis (Pregnall & Rudy, 1985). This finding has important implications for the algal beds at Copperhouse Pool, as the only time they will be covered by water during daylight hours will be during a short period around high tides on weekends (when no working is proposed).

Changes in the inundation cycle are also expected to affect reproduction in *Ulva* spp. The following text is an edited version of the text on reproduction in *Ulva intestinalis* on the Marlin web site (www.marlin.ac.uk/biotic/browse.php?sp=4271&show=reproduction):

> "Species of the genus *Ulva* are rapidly growing opportunists, favoured by the frequency and speed of their reproduction. The short lived plants reach maturity at a certain stage of development rather than relying on an environmental trigger. *Ulva intestinalis* can be found in reproductive condition at all times of the year but maximum development and reproduction occur during the summer months especially towards the northern end of the distribution of the species. The life history consists of an alternation between haploid gametophytic and diploid sporophytic generations but can be modified by environmental conditions. The haploid gametophytes of *Ulva* produce enormous numbers of biflagellate motile gametes which cluster and fuse to produce a sporophyte (diploid zygote). The sporophyte matures and produces by meiosis large numbers of quadriflagellate zoospores that mature as gametophytes, and the cycle is repeated. Together spores and gametes are termed 'swarmers'. Swarmers are often released in relation to tidal cycles, with the release being triggered by the incoming tide as it wets the thallus. However, the degree of release is usually related to the stage of the spring/neap tidal cycle, so allowing regular periodicity and synchronization of reproduction. Swarmer release of *Ulva intestinalis* from the Menai Straits, Wales, peaked just before the highest tides of each neap-spring cycle."

The impact of the altered tidal regime on reproduction by *Ulva* spp. at Copperhouse Pool is expected to be relatively severe during the causeway construction, but no long-lasting impacts are expected as populations should recover within a few months.

Ulva species also reproduce vegetatively. Although vegetative reproduction will not be directly affected by the lack of water over the beds during daylight, it is likely that the amount of vegetative reproduction will be diminished due to lower photosynthetic activity.

The areas of filamentous algae in Copperhouse Pool do not support a very diverse invertebrate fauna. The main groups present are enchytraeid oligochaetes and dipteran larvae and pupae. In some locations there are relatively high populations of rough periwinkle (*Littorina saxatilis*). It is likely that desiccation or partial die-off of the beds of filamentous green algae will have only a minor adverse effect on enchytraeid oligochaetes, but perhaps a larger effect on the dipteran larvae and pupae present.

5.2.2 Brown seaweeds

The Marlin web site (www.marlin.ac.uk/speciesbenchmarks.php?speciesID=3348) contains useful information on the likely effects of desiccation and increased emersion (exposure to air) on *Fucus vesiculosus* (bladder wrack). The following text is from Marlin:

> *"Fucus vesiculosus* can tolerate desiccation until the water content is reduced to 30%. If desiccation occurs beyond this level, irreversible damage occurs. The plants at the top of the range probably live at the upper limit of their physiological tolerance and therefore are likely to be unable to tolerate increased desiccation and would be displaced by more physiologically tolerant species. However, individuals at the lower limit of the species distributional range would probably survive so intolerance is reported to be intermediate. Decreased levels of desiccation may result in the species

colonizing further up the shore. Recovery would be rapid due to the high fecundity of the species, its widespread distribution and capacity for dispersal. *Fucus vesiculosus* recruits readily to cleared areas of the shore although full recovery may take 1-3 years.

The primary effect of emersion upon algae would be desiccation. Emersion for just 4 hours on a sunny day can reduce the water content of *Fucus vesiculosus* to just 30 percent. This is the critical water content for the alga and water loss beyond this would cause irreversible damage. The species cannot tolerate increased emersion. Increases in the period of emersion would cause plants to die at the upper limit of the species. *Fucus vesiculosus* survives readily in fully submerged conditions where lowered salinity reduces the range of competing organisms. However, a reduction in the period of emersion under fully saline conditions may result in the plants at the bottom of the species distribution on the shore being out-competed by algae that normally grow further down the shore and the upper limit of the species distribution may extend up the shore. Recovery would be high due to the high fecundity of the species, its widespread distribution and capacity for dispersal. *Fucus vesiculosus* recruits readily to cleared areas of the shore although full recovery may take 1-3 years."

Kawamitsu et al. (2000) examined the ability of *Fucus vesiculosus* to recover photosynthetic ability after severe desiccation (up to 32 hours). The results show that *Fucus* recovers well from prolonged desiccation events, especially if the relative humidity of the air is in the normal range. For example, after 12 hours of desiccation followed by 2 hours of re-immersion in seawater *Fucus vesiculosus* photosynthesised at approximately 45% of the normal rate. The results in the paper by Kawamitsu et al. (2000) directly contradict the information on the MarLin web site.

Gylle et al (2009) examined the effects of desiccation and salinity on marine and brackish populations of *Fucus vesiculosus*. However, the maximum desiccation they studied was 5 hours, so the findings cannot be directly used to predict what will happen in Copperhouse Pool. However, the paper does lend support to the idea that *Fucus vesiculosus* populations in higher salinity environments (such as Copperhouse Pool) are more able to tolerate desiccation than those found in low salinity areas such as the Baltic Sea. This study cites earlier research showing that marine populations of *F. vesiculosus* have a higher proportion of intracellular water and that they find it easier to regain water after desiccation. Marine populations also have a thicker thallus and a larger amount of the internal osmolyte mannitol and both these factors increase their ability to withstand desiccation.

Schonbeck and Norton (1980) studied the effects of temperature on desiccation in the fucoid algae *Pelvetia canaliculata* and *Fucus spiralis.* Normally on hard surfaces on UK shores *Pelvetia canaliculata* forms a narrow band above a band of *Fucus spiralis*. *Fucus vesiculosus* forms a band further down the shore. This distribution is directly related to their ability to withstand desiccation. Towards the end of a normal tidal cycle most fucoid algae in warm dry weather are likely to be almost air-dry. The paper cites earlier research that gives the following survival times for fucoid algae in an air-dry state:

Fucus vesiculosus	A few hours
Fucus spiralis	1-2 days
Pelvetia canaliculata	4-6 days

These figures do not agree with the findings of Kawamitsu et al. (2000) discussed above, which showed good recovery of *Fucus vesiculosus* after severe desiccation. The severity of the impacts on algae such as *Fucus vesiculosus* in Copperhouse Pool will be dependent on unpredictable factors such as whether there is a period of unusually hot and dry conditions.

5.3 Proposed Monitoring and Mitigation

The condition of the main areas of filamentous green algae and *Salicornia* could be visually assessed by Aquatonics Ltd each week. Any obvious changes in condition (eg changes in colour or wilting of *Salicornia* plants) would be visible to Catriona Neil of Spalding Associates, who would be looking at Copperhouse Pool on a daily basis in the first week. This daily examination will be particularly important if conditions become hot and dry.

5.3.1 Filamentous green algae

We propose to use a Hansatech portable Chlorophyll Fluorometer (see web page at www.hansatech-instruments.com/forum/uploads/infosheets/download/Pocket%20PEA.pdf) to assess whether the photosynthetic capability of the filamentous green algae is being affected by the changed tidal regime. This technique has been chosen following discussion with Prof. Nick Smirnoff of Exeter University.

5.3.2 Brown seaweeds

We expect a full summer day of emersion to start to cause damage to *Fucus vesiculosus*, due to desiccation and reduction in photosynthesis caused by high light levels. However, it is it is difficult to make any firm predictions, particularly in the light of disagreements in the literature (see 5.2.2). The most sensible course of action is therefore to monitor *Fucus vesiculosus* intensively in the first week and if necessary amend the work programme to reduce the effects of desiccation. The simplest assessment would be visual, checking for any abnormal desiccation or bleaching of the algal thallus. However, this may only tell us when things have progressed too far and we recommend a method that could detect damage at an earlier stage. A fluorometric technique has been used to assess the effects of desiccation on young *Fucus* specimens (Lamote et al, 2007). We therefore propose to use the Hansatech portable Chlorophyll Fluorometer to assess adult *Fucus vesiculosus* plants at Copperhouse Pool. We are also examining the possibility of a portable water content meter, so that we get real-time data on water content rather than waiting for accurate water content data from our laboratory analyses.

5.3.3 *Salicornia* beds

The same methods would be used as suggested for *Fucus vesiculosus*. Larger areas would be walked over on transects or examined through binoculars to assess any discolouration or wilting. The portable fluorometer and portable water meter will also be used by Aquatonics staff to assess sub-lethal impacts that will give us an early warning of any adverse effects.

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Figure 1. Enchytraeid oligochaetes worms.

Figure 2. Harbour ragworm, *Nereis diversicolor*.

Figure 3. *Pygospio elegans* - a spionid polychaete worm.

Figure 4. *Corophium volutator* – a gammarid amphipod crustacean.