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Original citation & hyperlink:
Burgess, H., Nelson, K., Colclough, S. and Dale, J., 2020. The Impact that Geomorphological Development of Managed Realignment Sites has on Fish Habitat. In *Coastal Management 2019: Joining forces to shape our future coasts* (pp. 375-389). ICE Publishing.
https://dx.doi.org/10.1680/cm.65147.375

DOI 10.1680/cm.65147.375
ISBN 978-0-7277-6514-7
eISBN 978-0-7277-6515-4

Publisher: ICE Publishing

THE IMPACT THAT GEOMORPHOLOGICAL DEVELOPMENT OF MANAGED REALIGNMENT SITES HAS ON FISH HABITAT

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Abstract

When coastal sites are breached and introduced to intertidal processes for flood defence and habitat creation purposes, the design primarily focuses on energy dissipation, the flora and the '*air breathing fauna which are fluffy, feathered or rare'.* Little attention is paid to the underwater habitat created which, for fish, can provide rich feeding grounds and refuge from larger predators, as well as acting as a nursery. This positive impact on the aquatic eco-system can, in turn, add to the local economy through improved commercial fishing and increased tourism (e.g. diving, recreational fishing, birdwatching) leading to improvements in human health and wellbeing. This paper presents a holistic overview of a large meso-tidal coastal managed realignment (MR) site, Medmerry MR, as it evolved during the first five years following site breaching. The data gained from bi-annual fish surveys is synthesised with the changes in geomorphology and hydrology to understand how MR design is impacting on fish colonisation in a changing habitat, providing lessons for future MR designs.

Limited design catering for fish was incorporated into the Medmerry site. The borrow pits, where material was excavated to create the flood bunds, were designed as lagoon habitats to attract fish primarily as bird feed. Saloon type tidal flaps were installed to allow for the migratory passage of eels. Following site inundation, the resulting variations in salinity levels and depth across the site attracted a large variety of fish species, both estuarine and marine, with thirty species of fish recorded. During the earlier stages of development, the borrow pits near the breach quickly became used by fish. However, geomorphological changes meant that one of these borrow pits filled rapidly with sediment, morphing into an intertidal sand/mud flat three years after breach. After four years, the others remained flooded at low tide, but blockage of the single feed channel resulted in reduced water exchange and higher low-tide water levels. This impacted on the ingress and egress of fish on the tide and may have impacted temperature and salinity levels which also affect fish colonisation.

This paper proposes features and actions that can be easily incorporated when designing new intertidal wetlands to help optimise fish habitat. Incorporation could potentially open up additional funding streams, given the benefits accruing to society.

Introduction: Incorporating fish habitat into MR design

At the European level, saltmarsh is a featured habitat in the EU Habitats Directive and in the UK as a Priority Biodiversity Action Plan (BAP) habitat type. Every year, 2% of English saltmarshes are lost though sea level rise and erosion due to processes such as coastal squeeze (Dixon *et al.* 1998; Doody, 2004). This pressure became the prime early driver behind the creation of Managed Realignment (MR) sites in the UK, in order to offset habitat losses. Most of the ecological information feeding into the design of the early MR was focussed around replacement bird habitat. The underwater habitat which is created and the fauna which exploit this transitional habitat has been largely ignored in MR design.

In the US, where over 50 years of detailed research has taken place, saltmarshes are recognised as an integral part of marine fish production, acting as vital nursery grounds for a range of commercial coastal species (Boesch and Turner 1984; Bell 1997). Existing habitats are protected and promoted, with new intertidal sites created deliberately with public finances to boost coastal fish production. In contrast, in situ fish production was never considered to be an important output in the early managed realignment (MR) sites constructed in the UK in the 1990's. This was largely a reflection of both the lack of research on fish association with European saltmarshes combined with the difficulty of sampling in such dynamic environments (Colclough *et al.,* 2005).

Research into fish associated with saltmarshes only began in earnest in Europe in the late 1990's in Mont St Michel Bay, France (Laffaille *et al.*, 2000). This was followed in the UK in 2003 with studies at the MR sites of Abbotts Hall, Orplands, Tollesbury and Wallasea Island and in adjacent mature saltmarshes. The outputs from these projects agreed that given the active, close and strong association of the early life stages of species with the saltmarsh habitats, they represent the optimal nursery ground for certain fish, such as bass (Colclough *et al.,* 2005). Historically, landclaim has removed much of this vital habitat. In the UK 85% of British estuaries have been impacted by significant landclaim with over 80% of the intertidal area lost in some cases (Attrill et al.,1999). Given the established link between the intertidal habitats and juvenile fish production, it is estimated that fish production has been severely impacted. An example of this is the loss of habitat in the Forth estuary which is thought to have reduced fish production by 66% over the last 200 years (McLusky et al., 1992).

These losses have important implications for marine fisheries management. Today there is wider acceptance that sustainable fisheries management is not just about controlling the historic over-fishing but is also very much about building back the nursery capacity lost over the past two centuries. In life strategy terms, fish are r-selected species, so produce vast numbers of young, most of which will die early and very few attain adulthood. If those very early life stages can access the optimal cryptic habitat providing shelter and abundant food in warm shallow water, recruitment is likely to be much higher. There is a demonstrated high site fidelity of bass juveniles for the same piece of saltmarsh over their first summer of life (Green et al., 2012). This evidence strongly suggests that adding new saltmarsh habitat in an MR site is very likely to be adding to overall fish production, rather than simply producing displacement of existing stocks.

To date fish studies have been conducted, or are underway, on at least 15 MR sites in the UK. The consistent finding is that these sites provide very important nursery grounds for a range of estuarine and marine fish species (Colclough, pers.obs.). As our understanding of the behaviour of fish on these sites grows, we can inform site design to optimise fish habitat, without constraining any of the other important ecosystem services provided. In this study we have looked at a coastal MR site as it evolves during the first five years following site breaching, synthesising the observed geomorphology and hydrodynamic development with the demographics of the fish population. Suggestions for the incorporation in future designs to improve fish habitat in MR sites are presented.

The general guidance for fish in the design of UK MR sites

Often, MR sites are designed based on the theory that once a site is flooded and the plants and invertebrates have established, then the fish will naturally come and colonise a site. Although this may be partially true, it does not provide optimum habitat and the associated benefits that occur with a properly functioning intertidal environment. UK guidance into MR design is out of date with regards to fish habitat creation. However, a growing awareness is demonstrated through time; Burd (1995) only mentions flora and no fauna at all, Leggett *et al*. (2004) indicate that MR could provide enhancement for fisheries, but problems for shellfisheries and Nottage and Robertson (2005) acknowledge that the importance of saltmarsh in the fish lifecycle was unknown with more research needed.

More up to date detailed guidance is provided by Dixon *et al.* (2008) based on the work at Wallasea. They explain that deeply incised channels should be avoided because the lack of gradual slopes and reduced plant growth at margins provide fewer refugia and are less favourable for fish populations. Instead, a shallow gradient across the site along with good drainage channels will create conditions for significant vegetation growth across the upper and middle shore (Burgess *et al*., 2015). Also, there must be continuity between the drainage system within the MR site, the breach and any existing intertidal channels on the lower shore beyond the breach. This will allow easy ingress and egress of fish to the site and reduce fish strandings. Dixon et al. (2008) also acknowledge any initially created morphology will change as the mudflats evolve. Scott et al. (2012) also detail site gradients and depth of lagoons.

The Medmerry MR design

Medmerry, on the south coast of the United Kingdom (Fig. 1), was the largest coastal MR site in Europe when it was breached in September 2013. As well as protecting 350 properties and the surrounding infrastructure, the site was designed to create 183 hectares of compensatory intertidal habitat. The design of the internal hydraulics of the Medmerry MR scheme primarily made use of the existing freshwater rifes (streams) and the old field drainage network. To accommodate eel passage the through the freshwater drainage outputs (DO), ‘saloon door’ tidal gates were installed rather than the traditional top opening tidal flaps. The angle of the gates being able to be set to enable prolonged tidal opening.

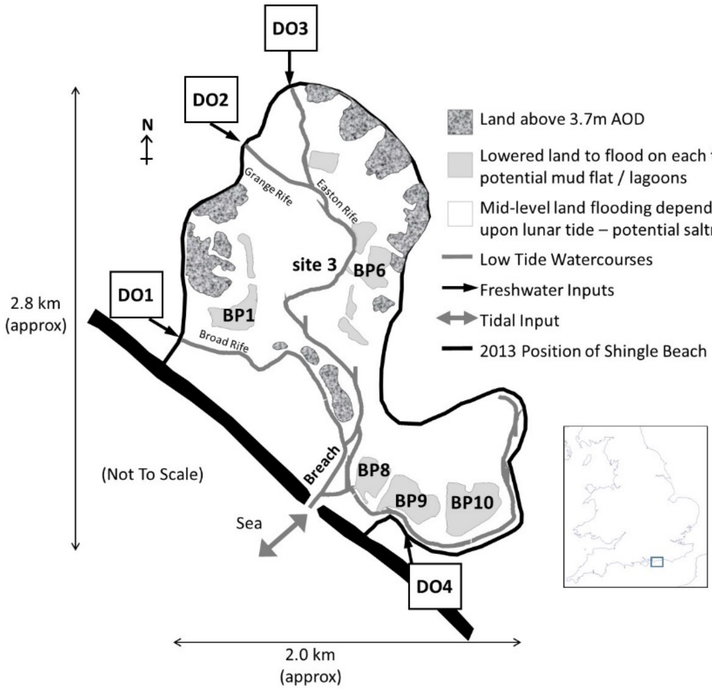

Fig.1: Schematic Map of Medmerry MR site, indicating Drainage Outputs (DO), freshwater channels and Borrow Pits (BP)

Shallow warmer standing tidal lagoons, which retain water during low tide, were also incorporated in the design to provide a habitat for fish and invertebrates, a food source for birds. The lagoons were to be made primarily from the borrow pits (BP) (Fig. 1). The original design of the borrow pit locations and shapes was determined primarily by hydrodynamic modelling results (Higuchi et al. 2014). However, the design had to be altered after the winter of 2012, when it was found that the onsite core clay, which was to be used to construct the outer bund, was not as abundant as the initial site investigations had suggested. This resulted in deeper, steep sided, less topographically varied borrow pits than in the original design. With a small amount of funds procured for habitat landscaping, the EA and RSPB were able to soften the edges of some of the borrow pits and construction vehicle haul routes were broken up, linking some of borrow pits together. The relatively flat fields surrounding the channels and borrow pits, which had mainly been used for arable farming, were largely left unaltered to develop into mudflat and saltmarsh naturally. Trees or hedgerows were generally not removed.

Results

The fish species using the site

Sampling targeting the juvenile fish population and took place in June/July and September/October for the five years following the breach (2014-18). Various sites and methods were trialled, with the most appropriate sampling solution found to be to use a 22m seine net in the borrow pits and in the channels, a 0.5m high fyke net at high tide and a 1m wide push net at low tide. Overall, thirty species were found and nearly 10,000 fish sampled. There was a mix of small fish which spend their entire life cycles in sheltered coastal waters and the juveniles of larger fish which spend their adult life in open coastal waters and are often commercially important species. The most abundant species was juvenile goby (*Pomatoschistus* spp.) (28% relative abundance), followed by sand goby (*Pomatoschistus minutus*) (20%) and bass (*Dicentrarchus labrax*) (16%) (Fig. 2).

Fish habitat within the Medmerry MR site

Unlike the majority of other MR sites, Medmerry is located on the open coast rather than in an estuary. Its size and freshwater input means that across site there is variation in both depth and salinity, providing a range of different habitats and conditions for fish; from the freshwater input at the drainage outfalls, to the deeper fast flowing channels and the large shallow borrow pits. This has resulted in a greater diversity of fish species using the site from those who are freshwater tolerant to those species which have typically only been associated with open coast environments (Fig. 2).

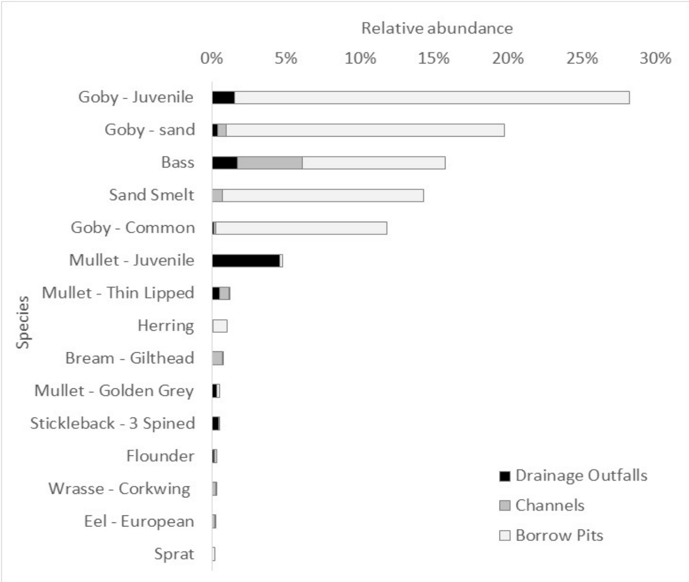

Fig. 2: The 15 most abundance of fish species sampled within the different areas of Medmerry MR site 2014 to 2018

The gobies preferred the borrow pits; this is where 94% of the juvenile gobies, 95% of the sand gobies and 98% of the common gobies (*Pomatoschistus microps*) were caught. Other species which showed a strong preference for the borrow pits were sand smelt (95%), herring (*Clupea harengus*) (95%), sprat (*Sprattus sprattus*) (100%), black seabream (*Spondyliosoma cantharus*) (100%) and greater and lesser pipefish (*Syngnathus acus* & *S. rostellatus*) (both 100%). Other species preferred the channels; gilthead bream (*Sparus aurata*) (88%), corkwing wrasse (*Symphodus melops*) (92%) and European eel (*Anguilla anguilla*) (89%). Whilst juvenile mullet (*Liza* spp.) (95%) and 3 spine stickleback (*Gasterosteus aculeatus*) (98%) preferred the drainage outfalls.

Bass: There are concerns about the stocks of bass (European Commission, 2015) and sheltered coastal areas are very important for the juveniles (Fig. 3). Bass was one of the most abundant species across Medmerry and particularly in borrow pit 9, where the average length was smaller than elsewhere on site (56mm compared to 67mm in the channels and drainage outfalls). Having been spawned offshore in February/March and drifted inshore to settle in the sheltered coastal environment of Medmerry, the summer samples of bass were 16-65mm long (Fig. 4). The adult bass have multiple spawning events, producing 'waves' of larvae which drift inshore to protected areas such as estuaries and harbours during the late spring/early summer, resulting in some overlap between the summer and autumn measurements. By the autumn, these group 0 bass had grown to be 28-85mm, indicating that Medmerry was a good nursery ground, providing shelter and food. The bass 90-165mm long were considered to be one year old bass. Bass mature at 5-8 years old and will spend these juvenile years in shallow coastal waters. No bass larger than 165mm were caught as the sampling methods and locations targeted the early life stages.

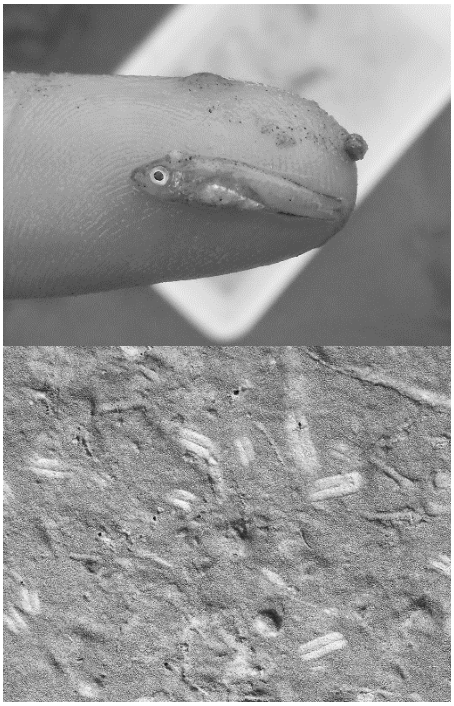

Fig. 3: Bass fry (top); Mullet grazing marks (bottom)

Gobies: Whilst bass use the sheltered waters of Medmerry mainly in their juvenile stage, sand and common gobies use the site for their entire one to two year life cycle. Rock (*Gobius paganellus*), black (*Gobius niger*) and transparent (*Aphia minuta*) gobies were also caught but sand and common were by far the most abundant. When the goby was too small to have developed its distinguishing features (generally less than 40mm), it was recorded as 'juvenile'. Sand and common gobies are common estuarine and coastal species and were found at all locations in

Medmerry, observed in even small tide pools. It is considered that gobies do not move large distances at egg, larval, juvenile or adult stage, yet they were present in Medmerry the first summer after the breach. Therefore, it is likely that the gobies were already present in the brackish rifes pre-breach.

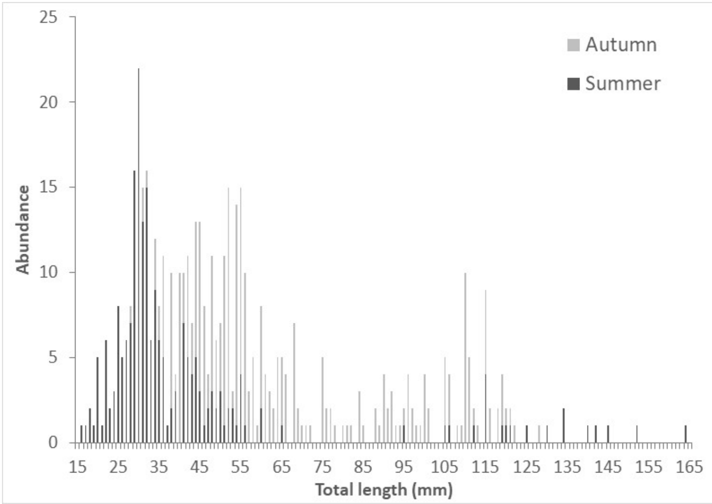

Fig. 4: Samples of Bass, caught in Borrow pit 9, comparison of variation of length and abundance between Summer (Jun./Jul.) and Autumn (Sept./Oct.).

The male forms a nest and will look after the eggs after the female has laid them. The common goby can lay up to 3400 eggs in a breeding season. Common gobies are more tolerant of low salinity than sand gobies (Henderson, 2014). The largest common goby was 70mm and the largest sand goby was 86mm. These are adult sizes. Both sand and common gobies were found in large numbers in borrow pit 9. They were present in almost all samples, although sand were more abundant than common (1173 and 481 respectively), as the salinity was fully saline seawater and the substrate was sandy, preferred by the sand goby.

Mullet: All three species of grey mullet – golden (*Liza aurata*), thin lipped (*Liza ramada*) and thick lipped (*Chelon labrosus*) – were caught in Medmerry, as well as 'juvenile' mullet which were too small to confidently identify to species level. The juveniles were mostly (95%) caught at the drainage outfalls, (Fig. 2) whereas some thin lipped (51%) and thick lipped (50%) mullet were caught in the borrow pits. Even when the mullet were large enough to identify, they were still considered juveniles as the maximum size caught was 245 mm and they do not mature until 250-300 mm. Whilst it was clear that the juveniles preferred the shallow, low salinity drainage outfalls, there was evidence that adults were present in the borrow pits. Although none were caught using the seine net in the borrow pit at low tide, there were marks on the mud, showing where the adults had been grazing, scraping off the layer of algae (Fig. 3). Adult mullet were observed in one of the channels, moving upstream as the tide flooded in, reaching the feeding grounds as soon as it was deep enough for them.

Smoothhounds and non-fish species: Whilst conducting the fish surveys, non-fish taxa were also recorded and included sea squirts, cockles, algae, shrimps, jelly fish, cuttlefish, squid, marine snails and crabs. There was a large abundance of shore crabs *(Carcinus maenas)*, a species which excretes ecydysones throughout the moulting process (Seifert, 1982). Shore crabs and smoothhound sharks are known to move inshore in the spring months. In July 2015, a group of approximately 50 smoothhound sharks (*Mustelus mustelus*) were observed in borrow pit 8. They were present in the channel at low tide, then as soon as the tide flooded into the borrow pit, approximately 50 smoothhounds entered the borrow pit (K. Nelson, pers. Obs.).

These observations, made on two consecutive days, and not been observed since, stand as a unique UK record to date. Sea angling magazines report that the best bait for the smoothhound is the pre-moult "peeler" crab (Sea Angler, June 2010). Therefore, it is probable that the smoothhounds were attracted by the pheromones released by masses of moulting crabs, presumably to feed on the shore crabs, which had quickly and very successfully colonised the new MR site. Whilst smoothhounds are known to hunt in packs, it was unusual behaviour to see so many in a shallow pool.

The majority of fish species found in Medmerry were targeting benthic invertebrates (10) as their main prey, particularly species such as the gobies, flat fish (sole, plaice, flounder) and wrasse. Other species were feeding on zooplankton; sand smelt, herring, sprat and the pipefish. Only a few species are piscivorous; bass and eel, whilst the mullet are detritivores. Their presence in Medmerry demonstrate that this MR site is diverse by providing valuable habitat to a range of species.

Why MR sites are so attractive to fish and how they use them?

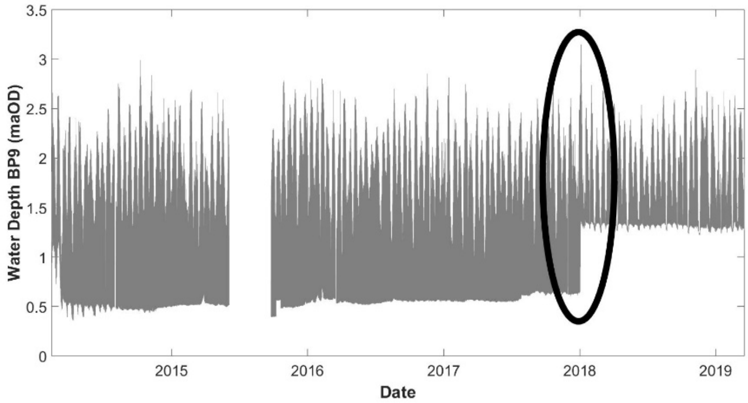

Fig. 5: Time-series of water level data in BP9 from March 2014 to March 2019. Note the effect of storm Eleanor in January 2018, the height in the surge followed by the rising of low-tide water levels in the lagoon.

Saltmarshes are normally characterised by a mosaic of habitat types set out across a shallow gradient with a complex pattern of connected sinuous drainage channels. There may or may not be salt pannes (shallow lagoons) across the site, which might be inundated occasionally depending upon their position. Flows across the site are gentle both on the flood and ebb. Studies on a number of MR sites and saltmarshes have indicated that, where possible, incorporating all of the elements of a mature saltmarsh would optimise site design for fish life (e.g. Dixon *et al.*, 2008).

Round fish species such as bass have swim bladders and can maintain a neutral buoyancy and simply float in the current if they so desire. Very small early larvae (sometimes as small as 10mm), as yet unable to swim strongly, can use the tidal flow to manoeuvre themselves deep into the marsh, riding out the faster flows just under the surface in the middle of the stream. The flood will take them into the area of soft vegetation where they stay and feed actively as long as they can. As the tide ebbs, these fish will follow the drainage channels back out to the subtidal shallows near the marsh, hugging the bottom as they go to avoid predators. This is known as Selective Tidal Stream Transport and is not well reported in estuaries (Colclough *et al.*, 2002). By this means, very young fish can access the optimal areas for feeding and shelter twice a day while expending minimal energy. For some species, this can be a structured sophisticated process (Fonseca *et al.,* 2011). Very young bass fry enter the marsh penetrating as far as possible on the spring tides to feed on specific small invertebrates present there. As they grow, they penetrate less far, feeding on a broader range of items available a little further down the marsh. As much as 45% of overall feeding benefits for early bass fry in their first few months of life might be achieved in the few days a month when they can access the high marsh on the spring tides (Laffaille *et al.,* 2001).

How spatial and temporal changes in geomorphological and hydrology have impacted on fish habitat across the site

To aid future design of MR sites it is important to understand how the spatial and temporal development of the geomorphology and hydrology has impacted upon the fish habitat across the site. With the understanding of the types of fish using the site, the post-breach monitoring data collected can now be used to provide detail of how specific habitats have developed over the six-year period post-breach and how this may continue into the future.

Lagoon Development: It was always planned that borrow pit 8 (Fig. 1) would gradually infill with sediment, but because of the rapid movement of the sand layer which backed the shingle spit, this occurred at a more rapid rate than expected resulting in the loss of a lagoon habitat. With the hindsight that some fish spend most of their life (particularly in early life stages) in a limited area of marsh, the question needs to be addressed as to whether these individual temporary ponds have any benefits in the longer-term for fish populations. For example, does this new sandflat provide a productive feeding ground during high tide for larger fish feeding off of the invertebrates and algae? Continued monitoring will be required.

The hydrodynamics of borrow pit 9 changed considerably potentially impacting the types of fish which can access and exit this lagoon. Originally there was a wide tidal channel running along the back of the shingle barrier which fed and drained this lagoon. Strong ebb and flood currents in this channel meant that fish could easily access and exit the lagoon with the tide. However, the channel to this lagoon was blocked by the roll back of the shingle beach during storm Eleanor in early January 2018

(Fig. 5). This has raised the low-water levels within the lagoon, which could help protect against avian predation, but may also affect salinity levels and temperature. At the lower/mid stages of the tide, water now flows via the adjacent filled-in borrow pit 8 which is developing a mudflat creek system.

Borrow pit 9 did benefit from some pre-breach landscaping and wind blowing over the surface of the lagoon at low tide produces small depth and fetch limited wind waves which were gently sculpting the banks of the lagoon, resulting in a lower gradient. However, since storm Eleanor and the loss of the protective shingle beach in January 2018, at high tide larger sea waves are now rolling over this area. In early 2019 a second breach formed feeding directly into borrow pit 8 which will influence the water exchange in all lagoon systems towards the front of the MR site.

Changing channel geomorphology: The main intertidal creek system was formed dominantly from remnants of the field drainage systems and of Easton, Grange and Broad rifes (Fig. 1). Despite being reasonably sinuous, the creek systems were overly deep with extremely steep sides. In some areas there has been a mild lowering in bank steepness, through bank collapse and the action of wind waves. With salt marsh now developing along the banks this could be being used as a new habitat by the fish, but as much of this was flat farmland the fish may not be venturing too far into these areas as they may get stranded on the falling tide. As the creek systems continue to develop across these areas (Dale et al., 2018) then there is a possibility that these intertidal areas may become accessible to fish.

Salinity variations along the site and seasonal variations: Although tidal gates were installed to allow for the passage of eels, the effects of the amount of fresh water passing through the system was not considered in the original design. However, with the installation of Conductivity, Temperature and Depth (CTD) probes capturing data at a high frequency (10 minute) at a number of strategic sites, variations in salinity have been recorded from tidal extremity to breach (Fig. 6). Results show that after periods of high rainfall, at the end of the ebb tide, saline levels have been found to be extremely low even at the breach. This will influence the movement and behaviour of most of the fish species which access the interior of the MR site.

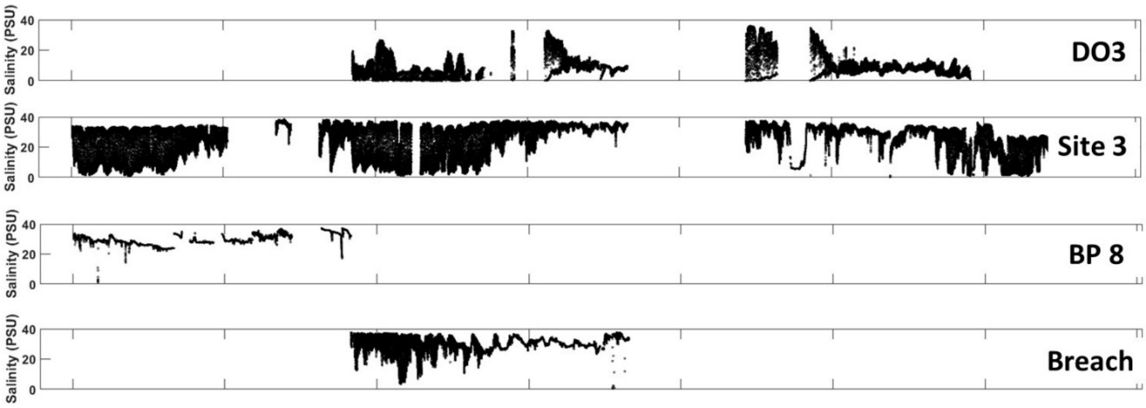

Fig. 6: Range of salinity from 2014 to 2018. With the exception of BP8, all sites from breach to landward extremity, have full range of salinity over the time period.

Discussion: Lessons learnt –guidance for incorporating fish habitat into MR design and the benefits to the wider society

Medmerry functions well for fish, supporting large numbers of various estuarine and marine fish species, although the habitat could be improved upon. The community of species present is similar to that reported in other MR sites (Colclough pers. obs.) and in other inshore areas on the Sussex coast (Sussex IFCA). Although permanent filled lagoons and leaky tidal flaps were incorporated, fish were not a prime focus in the Medmerry site design. However, some of the post construction / pre-breach landscaping undertaken to improve habitat conditions may have improved fish utilisation, i.e. the lowering of the gradient of the banks of channels and lagoons (borrow pits) will have allowed for an easier pathway for fish, but also for the colonisation by flora (Burgess, 2015) providing refuge and feeding grounds for the fish.

Two of the most common fish sampled arrived into the Medmerry site in different ways. The common goby and 3 spined stickleback are not open sea fish, therefore it is likely that the populations reported in the sampling may have originated from the brackish pre-existing tidal drainage systems. The proximity to spawning grounds combined with the presence of permanently flooded lagoons (i.e. borrow pit) means that the site supports sufficient juvenile bass for UK government Centre for Environment, Fisheries and Aquaculture Science (Cefas) to recognise the site as a potential future formal bass nursery.

The developing marsh on the surrounding relic arable fields may, if the gradient is sufficient, improve and extend this habitat, however on the inverse, siltation and tidal waves may destroy the lagoonal habitat. In the short term these lagoon features, as long as they are deep enough, provide refuge and contain large numbers of invertebrates which provide a food source to a range of fish species (e.g. smoothhounds). Geomorphological and hydrological evolution at Medmerry during the first five years after breach was significant, and with the shingle frontage still adjusting and the transition of the agricultural fields into intertidal marsh, the transition is set to continue for many more years to come.

The presence of gobies and bass highlights the need for pre-design fish surveys both within and outside of a potential MR site including the identification of the location of spawning grounds. This will enable adjustments in design to be incorporated in order to maximise fish habitat before breach. In many previous MR projects, formal fish monitoring was not considered before breach, taking place some years later after the sites had evolved considerably. Each site is unique and provides significant opportunities to enhance our understanding and improve future design. The inclusion of funding for fish monitoring in the Medmerry MR project is helping to inform the design of future MR sites.

Additional drivers for incorporating fish habitat into design

Further elaboration of how fish utilise these sites is important for other reasons as well. In the USA, extensive long-term studies have been able to produce robust fish production estimates for a unit of saltmarsh. New marine developments which might impact on fish populations, such as cooling water intakes for new build power stations, are required to develop:

a) The best screening practice to minimise the impact, then
b) Monitor the actual impacts and
c) If that impact is significant, develop sufficient new intertidal habitat which would generate an equivalent fish production to that lost in a protocol named Habitat Production Foregone (Turnpenny *et al.,* 2010).

Elaboration of such data in the UK would permit a similar offsetting protocol to emerge. In itself this would assist in the establishment of a further strategy, now common in the USA. Those beneficiaries that stand to gain from the ecosystem services generated from a new intertidal site should contribute to MR construction costs. That argument was made by one of the authors in 2005 and accepted in principle by the European Commission in relation to MR construction and the then structural funds of the Common Fisheries Policy, the European Fisheries Fund. Little progress has been made with that argument in the EU or UK since, but the considerable data gathered in the UK since 2005 together with the new DEFRA focus on Natural Capital would suggest that the time is now right to pursue this.

The Marine Strategy Framework Directive requires the presence of “good local marine fish stocks” as part of Good Environmental Status. Virtually all MR sites constructed to date exist within WFD transitional water bodies and in such waters, fish are a quality element for WFD classification. There is now sufficient evidence from the close association of juvenile fish with vegetated intertidal marginal habitats to suggest strongly that such habitats must be part of Good Ecological Status in these water bodies. MR (and saltmarsh restoration) should then become a major driver under WFD Programmes of Measures simply in terms of associated fish benefits, even before considering the other positive ecosystem services provided.

Conclusions: Optimal MR Site Design Features for Fish Life

The first brief initial review of design features beneficial to fish life in MR sites was included in Dixon *et al.*, 2008. Combining the Dixon review cited above with publicly available reports (Gray, 2007; Scott et al. 2012 TEP, 2018; ZSL, 2016) drawing observations from many other sites with the current Medmerry findings a number of recommendations for potentially advantageous design features for fish life are listed below. No doubt future studies will inform design yet further and performance monitoring of such features should be a key part of future site development and management.

i. ***Develop a gradient across the site if at all possible.*** At Abbotts Hall and the Wallasea MR sites, the natural gradient assisted in the process of creek evolution. Fish studies at these sites has seen significant penetration of young fish deep into the treatment with open access to the vegetated upper marsh areas.
ii. ***Endeavour to create a mosaic of habitat types.*** True saltmarshes are complex environments providing a range of habitats types which can support a broad range of fish species. During high tide fish are closely associated with stands of vegetation. Vegetation provides shelter, food and a migration pathway, particularly for very early life stages of fish. In this manner the extent of vegetation will dictate the carrying capacity of the inner marsh for fish life.
iii. ***Avoid design features where throttles create very fast tidal flows.*** Very small fish are weak swimmers and may be denied access to areas of the site or may even be damaged or destroyed by the fast flows.
iv. ***Lagoons of significant depth (>50cm) will attract fish which might remain at low water***. Lagoon banks need to be low in gradient to allow for transition and access (Burgess, 2016). If the pond is very shallow (30cm), these fish may be picked off by avian predators. Depending upon sediment delivery to the site these lagoons may be temporary features.
v. ***The drainage system should be in continuity with the sub-tidal foreshore on the seaward side of the breach***. Fish exit the site in these drainage channels, all the way down to the low water mark. In some early MR sites, before any obvious drainage channel on the seaward side of the breach had developed, stranded fish have been observed on high mudflats “downstream” of the MR site, unable to find a safe exit route. Many are subject to bird predation (S.Colclough pers.obs.).
vi. ***Where creek systems are constructed, endeavour to develop a naturalistic sinuosity.*** As in freshwater systems, fish utilisation of sinuous channel forms is much greater than in straight smooth ones. Variations in flow associated with sinuosity, including eddy features, are utilised effectively by fish species for migration, refuge and feeding purposes.
vii. ***Where creek systems are constructed, keep the edges as shallow as possible.*** This encourages fish egress onto the marsh as the channel floods out on the rising tide. In severe cases, large concentrations of juvenile fish have been observed remaining in the deep incised artificial channel as the channel floods out because the high mud flat adjacent provides very little shelter for the fish to move across out to the upper vegetated marsh. They enter, remain and leave in the channels without using most of the site. They are very aware of predation!
viii. ***Freshwater drainage outputs need to allow for the effective passage for migratory species such as eel***. This might take the form of adjustable tidal flap valves which permit limited tidal interchange. These will also provide some continuity for other species such as 3 spined stickleback, gobies and grey mullets.
ix. ***Endeavour to encourage colonisation of the site by*** **vegetation as fast as possible**. Consider breaching in early autumn when more seeds will be carried in on the tide.

Other actions to consider

- Since each MR treatment is unique, studies of fish utilisation should be conducted in all future projects as part of an integrated post-project monitoring approach to inform future site design.
- Long term data is vitally important. We need to know how fish utilisation changes as the site evolves. We also need to be able to develop robust production fish per unit area of saltmarsh. This data will stimulate robust offsetting arrangements and aid the development of contributory funding streams operating via the Natural Capital Approach.
- Existing work to identify Essential Fish Habitats, including spawning locations, can be used to influence the location and design of future MR projects in order to optimise local fish production.
- The incorporation of fish habitat into design may enable a project to be eligible for additional sources of funding e.g. European Maritime and Fisheries Fund support.

The findings of this research build upon the knowledge base reinforcing earlier observations that MR sites provide important additional habitats for juvenile fish including commercially important species such as bass and mullet. Intertidal marsh areas provide the optimal habitats for the vulnerable early juvenile life stages. Support at these critical life stages can enhance survival and recruitment to the adult fish stock. This work highlights the positive impact that coastal management can have on fish populations and how a successfully designed intertidal fish habitat is important for coastal food webs underpinning the broader eco-systems including the wider fish communities and the bird populations. However, more research is needed into fish behaviour in intertidal environments, including post breach monitoring.

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