Memo

To
Mr. Stephen Lane, Environment Agency

Date	**Number of pages**	
29 March 2016	15	
From	**Direct line**	**E-mail**
Tom Buijse	+31(0)88335 7116	tom.buijse@deltares.nl

Subject
Air curtain feasibility study to reduce the impact of salt intrusion on freshwater fish populations in the Broads

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Introduction
In November 2015 Stephen Lane (Environment Agency, Norwich) contacted Deltares (Rob Uittenbogaard) to explore the feasibility to apply air curtains in the Broads to reduce salt intrusion during storm surge events in order to minimise freshwater fish mortality. This contact resulted in an order (No. 1070008623) from the EA to Deltares for a short mission to the Broads. After deliberation it was decided that Tom Buijse being a fish and river ecologist could best perform this mission with background support by Rob Uittenbogaard. The mission was planned on 16 and 17 February 2016. The scope of the study and final report should focus on the feasibility of air curtains to prevent or reduce the impacts of saline incursions on fish stocks at key locations in the Broads. It should include the following issues and assessment:

1. How frequent and serious are the fish kills compared to their growth rate, in other words is there evidence of fish stock being seriously reduced by salt intrusion driven by storm surges?
2. Where are the locations of fish kills: upstream or inside the salt intrusion, or trapped in refuges (harbours, enclosures) that later on became too saline?
3. The statistics of water levels, longitudinal and vertical distribution of salinity of the relevant river sections (Yare, Bure and Thurne) in and directly following storm surges periods?
4. Indicative assessment of applicability of bubble plumes for reducing salt intrusion compared to salt intrusion by water level (storm surge) set-up.
    a. Should the study and site visits conclude that air curtains may well be a feasible option at one or more sites, the additional work will focus on producing an outline estimation of potential system costs. This would be very helpful to inform a future business case/bid for funding to work up a design and build project, or it may conclude that the costs are likely to be prohibitively expensive
    b. Should the study and site visits conclude that air curtains are unlikely to be suitable, the additional work will focus on examining other possible solutions to the problem at key sites. It would be very useful to draw on your experience of potential design solutions that may be in operation in Holland and elsewhere in Europe
5. Indicative assessment of the consequences in terms of construction, hindrance of ship traffic, hindrance of road traffic, energy consumption, and maintenance? [cost?]

On beforehand Stephen Lane has sent background information to Deltares regarding salinity intrusions and the impact of fish stocks, hydroacoustic surveys of the fish stocks, socio-economic importance of the recreational fisheries in the Broads, fish mortality and the barrier at entrance of the marina Potter Heigham (Appendix 1). In the following each of the above topics

is discussed as well as other relevant aspects. Appendix 2 gives the itinerary of the visit by Tom Buijse on 16-17 February 2016.
This mission report has been prepared by Tom Buijse and reviewed and amended by Rob Uittenbogaard.

1. How frequent and serious are the fish kills compared to their growth rate, in other words is there evidence of fish stock being seriously reduced by salt intrusion driven by storm surges?

Storm surges occur every year predominantly in the winter. Also fish kills are observed in a substantial number of years mostly in the winter half year. Observed numbers of dead fish may be low, but can run into tens of thousands and occasionally even hundreds of thousands (Stephen Lane; pers. comm.). Species impacted generally are roach, bream, pike, perch, ruffe and rudd. It is unclear what percentage of the population it comprises and whether it affects the viability of fish populations in the Broads, but during a harmful storm surge numbers of dead fish definitely are substantial and cause serious concern among the local people and anglers. Hydroacoustic surveys in 2006 before and after a storm surge showed a decline of roughly 40% in the fish stocks in the surveyed river stretch (Environment Agency 2006; Appendix 1). It is not fully clear whether this decline is caused by fish killed or by fish moved to safe river stretches. The long length of the surveyed river stretch makes it probable that there had been a significant mortality.
Another aspect is that even when fish might have successfully avoided the salt intrusion they may have moved suddenly from popular angling locations and cause a poor perception of the area and adversely affect the tourist trade. This is thus also an important aspect when considering investment in potential protection schemes (Stephen Lane, pers. comm.)
<u>Conclusion</u>: Fish kills can be very substantial with tens to hundreds of thousands dead fish and occur in some but not every winter. It is unclear whether this affects the viability of the fish populations, but hydroacoustic surveys indicate significant declines in the rivers following storm surges. Surveys before and after significant storm surveys can yield important evidence on the impact and changes in fish distribution to support future decisions how to combat this phenomenon.

2. Where are the locations of fish kills: upstream or inside the salt intrusion, or trapped in refuges (harbours, enclosures) that later on became too saline?

Visual observations depend on reporting and mostly concerns fish kills in the side canals (so-called ‘dykes’) and marinas where fish concentrate in winter time using the shelter below the boats and jetties (Figure 1). This is where the fishermen mostly angle and where local people go for a walk. Information from more remote areas is generally lacking. So it is unclear whether the mortality is restricted to the side canals. In the rivers themselves there is less evidence of substantial fish kills. However, dead pike have been observed on the river banks following a storm surge even in the lower reaches of the tidal rivers, which suggests some pike may not successfully move upstream ahead of the salt water (Stephen Lane; John Currie pers comm.). The assumption is that those pike did not try to escape upstream.
The side canals are dead-end streets (Figure 2). Fish that are trapped cannot escape when the salinity in these canals rises to lethal levels. In some canals such as Loddon there is an inflow of freshwater that may reduce the salinity concentrations (Figure 3). Loddon is on the River Chet and the mill is the tidal limit. Upstream of the mill is the freshwater river system. The freshwater flow is the river discharge from the River Chet catchment passing through the mill structure (Stephen Lane pers. comm.).

Figure 1 Acle Bridge an example of side canal with a marina where fish mortality occurs during saltwater intrusion. There are a large number of such marinas in the Broads e.g. Upton Dyke, Loddon where similar fish mortality may occur.

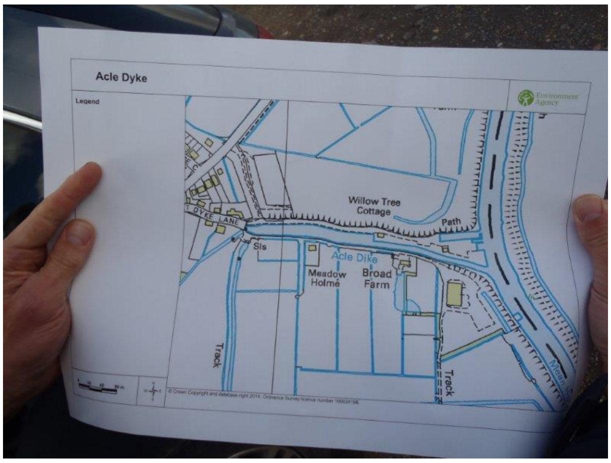

Figure 2 Map of the side canal 'Acle Dyke' showing the dead-end street which is characteristic for these side canals with marinas. The side canal are situated perpendicular to the river.

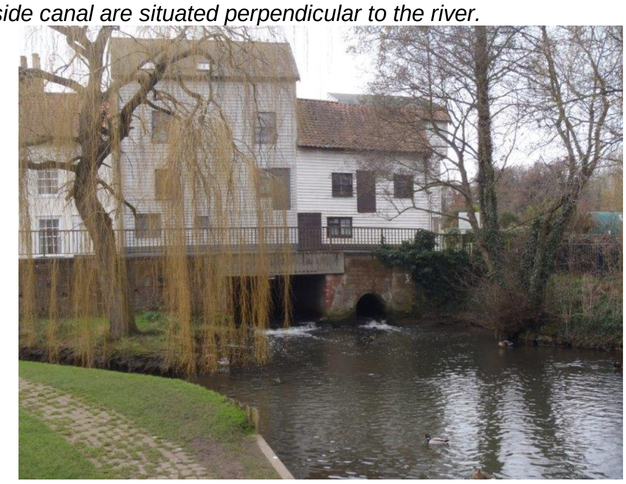

Figure 3 At Loddon the side canal has a freshwater inflow that will help to lower salinity concentrations during storm surges with salt intrusion and may reduce fish mortality.

3. The statistics of water levels, longitudinal and vertical distribution of salinity of the relevant river sections (Yare, Bure and Thurne) in and directly following storm surges periods?

Information has been supplied on beforehand on storm surges (tidal amplitude at Great Yarmouth) and salinity recordings at Acle, Cantley and Potter Heigham preceding and the days following a storm surge. High salinity concentrations in the rivers persist at least for several days following a storm surge. Levels drop more rapidly at Cantley (River Yare) than at Acle (River Bure), which is most likely due to the higher discharge of the River Yare and Cantley being more upstream situated. How far the increased salinity front penetrates upstream is not recorded in a standardized manner and depends amongst others on the magnitude of the storm surges. During the field visit on February 17 John Currie indicated these locations for two events on the River Yare. The locations differed considerably (several km). The medieval bridge at Potter Heigham reduces the upstream salt intrusion (Stephen Lane; personal comm.). No data are available on longitudinal measurements how far the salt intrusion penetrates. We consider such data highly relevant to obtain The river and canals are relatively shallow (up to 3-4 m during surges). John Currie indicated that the pattern of salt intrusion differs between storm surges. He observed in the River Yare on one occasion high salinity concentrations in the middle and low concentrations along the shore and vice versa during another surge event. This was at the front of the salt intrusion. No information has been available on the length of the wedge of saline water below the freshwater and thus on the vertical distribution. It is expected that the shallow depth results in a relative short stretch of the saltwater wedge. Air curtains that would make the transition zone more vertical will consequently be effective in the river only over a short distance (Figure 5). It would be relevant to obtain longitudinal profiles of salt intrusion as a source of information how much the upstream penetration of salt intrusion may be reduced when measures are evaluated to reduce the tidal surge.

4. Indicative assessment of applicability of bubble plumes for reducing salt intrusion compared to salt intrusion by water level (storm surge) set-up.
    a. option at one or more sites, the additional work will focus on producing an outline estimation of potential system costs. This would be very helpful to inform a future business case/bid for funding to work up a design and build project, or it may conclude that the costs are likely to be prohibitively expensive.
    b. Should the study and site visits conclude that air curtains are unlikely to be suitable, the additional work will focus on examining other possible solutions to the problem at key sites. It would be very useful to draw on your experience of potential design solutions that may be in operation in Holland and elsewhere in Europe.

Air curtain have been successfully applied in shipping locks to reduce salt intrusion in freshwater lakes and reservoirs (e.g. Volkerak-Zoommeer in the Netherlands). The side canals along the rivers in the Broads do resemble to some extent such locks by being most dead-end water segments perpendicular to the river with little flow velocity (Figure 2). In our opinion there will not be strong currents in these marinas, but that water level is being pushed up because the marina functions as an impoundment. The canals in the marinas are generally 10 -15 m wide and 2 m deep. During storm surges water levels rise depending on the distance inland and the magnitude of the surge. This may result in overbank flow in between the flood defences typically raised flood banks, which may be set back from the dyke channel (e.g. at Upton Dyke). The distance between the flood defence structures is much wider than the canal (Figure 4). Air curtains might thus be effectively applied in marinas, but there is one significant difference with the application in shipping locks. In shipping locks there is only a short time span when the locks are open at the sea side that air curtains are applied to reduce salt intrusion. In side canals, however, there is a situation which persists for a number of days.

There is always leakage of saline water through the air curtains. Due to this time span of several days we foresee that air curtains will lose their effectiveness over time. In our opinion there may be other solutions, which we recommend to explore first.

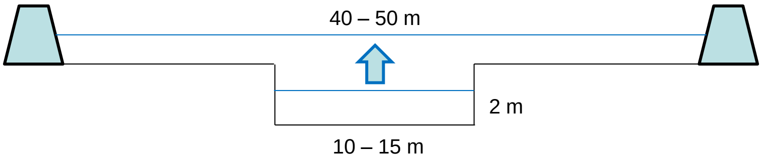

Figure 4 Cross profile of a side canal Upton dyke. The arrow indicates the water level rise during a surge. The trapezoid represents the flood defence structure.

The applicability of air curtains in tidal rivers themselves, such as the rivers in the Broads, is considered less or even ineffective for several reasons:

i) Air curtains cannot block the water displacement caused by a storm surge. They are meant to shorten the wedge of saltwater below freshwater (Figure 5).

ii) Air curtains are only effective at the locations where both saltwater and freshwater are present (Figure 5). Because the saltwater front will migrate upstream during a surge and the extent of this upstream migration will depend on the magnitude of the surge fixed locations for air curtains in the rivers will not work. The only option would be a mobile application combined with real-time monitoring of salinity (Figure 6).

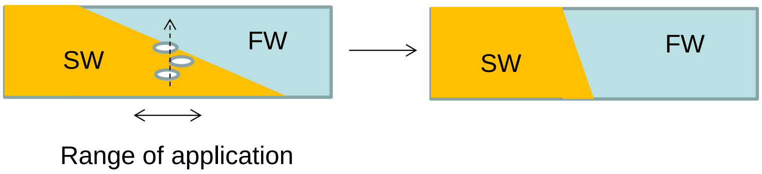

Figure 5 Air curtain can be applied in zones where both saltwater and freshwater occur (left: rang of application) and result in a more vertical separation (right). Please note that air curtains reduce the salt intrusion, but cannot completely stop it.

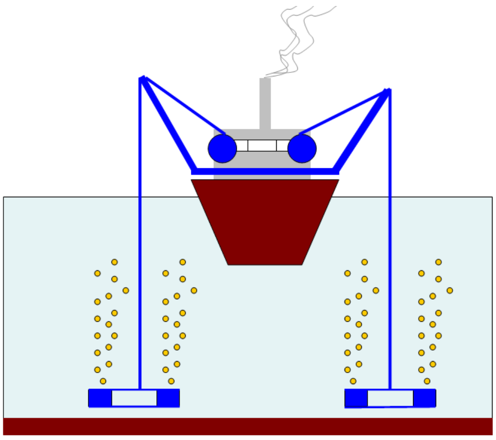

Figure 6 Proposal for a mobile application of air curtains for circumstances where the transition zone is not always at the same locations such as in tidal rivers. The air curtain is mounted on a ship.

<u>Alternative solutions</u>

We would like to suggest several alternative solutions to explore. Hereby we distinguish between solutions to reduce salt intrusion for the entire catchment and for blocking salt intrusion at specific locations in dead-end side canals where fish concentrate in winters and kills are recorded in the past. It is clear any solution for the catchment level will be substantially more expensive, but at the same time may serve multiple functions i.e. flood defence for urban settlements and agriculture and multiple locations.

<u>Catchment level</u>
Certain catchment level options to reduce impacts on fish stocks may align with wider benefits for flood defence and water level management. It is therefore important that these are considered alongside any future cost-benefit assessment of future flood defence options for the Broads area.
At present there is already a brackish transition zone in the Broads. This zone now functions as warning zone for freshwater fish under normal conditions. We advise that a measure should not result in translocating this transition zone downstream as it will result in freshwater fish to migrate further downstream and becoming more susceptible to salt intrusion.

- Water retention in washlands surrounding the brackish zone. Depending on the land use and the possibility to inundate washlands with saltwater without undesired side-effects it can be explored how much water could be retained to shorten the upstream boundary of the saltwater front (Figure 7). A hydrological model study could estimate the required water storage to reduce the upstream boundary of the saltwater front to a desired location and support drawing conclusions whether this may be an effective measure.

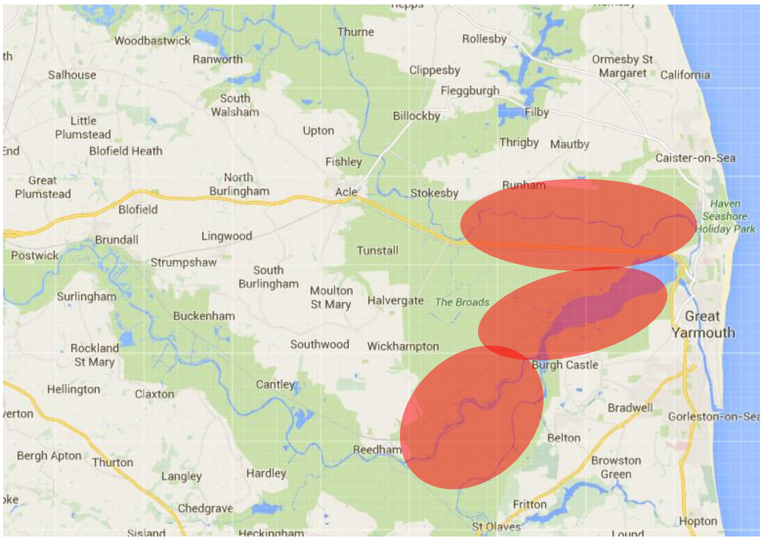

Figure 7 Suggested search areas for washlands (in red) surrounding the present brackish transition zones in the tidal rivers that could be inundated with saltwater without undesired side effects for reducing salt intrusion in the river.

- The Broads fulfil an important recreational role for navigation. Measures should thus not hamper navigation and when they do then at the most only at times when needed. An option would be a complete and at the same time temporal barrier. In the Netherlands an inflatable rubber dam has been installed in the mouth of the River Ijssel for flood protection (https://nl.wikipedia.org/wiki/Balgstuw_bij_Ramspol) allowing complete free navigation when not used (Figure 8). This rubber dam can be closed in 1 hr.

Figure 8 Inflatable rubber dam Ramspol open (left; source: nl.wikipedia.org) and closed during storm (right; source: www.rtvoost.nl)

- Temporal partial barriers to increase channel roughness. The medieval bridge at Potter Heigham reduces the upstream salt intrusion (Figure 9). As the same time it restricts the size of vessel that can pass further upstream and as such considered an obstacle for navigation. From the discussions held it was not clear whether channel dimensions (width, depth, removing obstacles) have been enlarged in the past to improve navigability on the rivers. In case this has been done then one of the undesired side effects is that saltwater may intrude nowadays further upstream due to less flow resistance. By any means increasing the flow resistance in the channels through more roughness will shorten the upstream intrusion. Such roughness should be temporal to avoid hindrance for navigation under normal conditions. Flexible constructions which partially block the river could fulfil this function. Given that these constructions do not block the river totally the required strength will be much less, because water levels are nearly equal on both sides. Flow velocities and tidal amplitude determine the forces on such constructions. A hydrodynamic model could estimate how much channel roughness is required to reduce the upstream boundary of the saltwater front to a desired location. We do not have concrete examples where this has been applied and possible designs need to be further explored.

Figure 9 The medieval bridge at Potter Heigham forms an obstacle for navigation but it also considered to diminish salt intrusion in the River Thurne. Previously there has been a similar medieval bridge further downstream in the River Bure(?) at Acle. Its removal may have amplified the salt intrusion inland[1].

<u>Local level in dead-end side dykes/canals</u>

The most likely approach to reduce fish kills in dead-end side canals is to create and retain a sufficiently large freshwater refuge during and in the day following storm surges. With such a freshwater refuge is meant keeping salinity concentrations below lethal levels.

At present it is unknown but likely that in the more landward parts of the river(s) first the water level rises and then salt intrusion follows. The tidal storage in the river's side canals is then supplied by more freshwater (Figure 10). Subsequently, in the river, salt intrusion follows and by a so-called lock-exchange mechanism the heavier/salty river water penetrates under the freshwater volume of the side canal and pushes the side canal's top layer of freshwater volume out of the side canal into the river. The speed of the salt intrusion is 0,3 m/s. The latter action removes the freshwater refuge. By deploying a so-called skimmer wall across the top layer at the entrance of the side canals the outflow of the freshwater is blocked and the freshwater volume is lifted by salt water penetrating from the river under the skimmer wall. The depth of the freshwater is roughly 10 – 20 cm less than the underside of the skimmer wall. The water level in the river decreases when the storm surge decays. Then the lower volume of salty water in the side canals flows into the river under the skimmer wall while the freshwater top layer still remains as a refuge in the side canals. The separation of fresh and saline water is very stable. Of course freshwater fish will only have a refuge in the top layer and cannot move to the bottom. We are unsure whether that would be problem.

[1] The late Tom Cable, who was a River Authortity Water Bailiff and Fisheries officer for the Broads, wrote in his book 'Broadland Tom' that he was convinced that the removal of the old bridge at Acle had resulted in increased levels of salt water pushing upstream during storm surges.

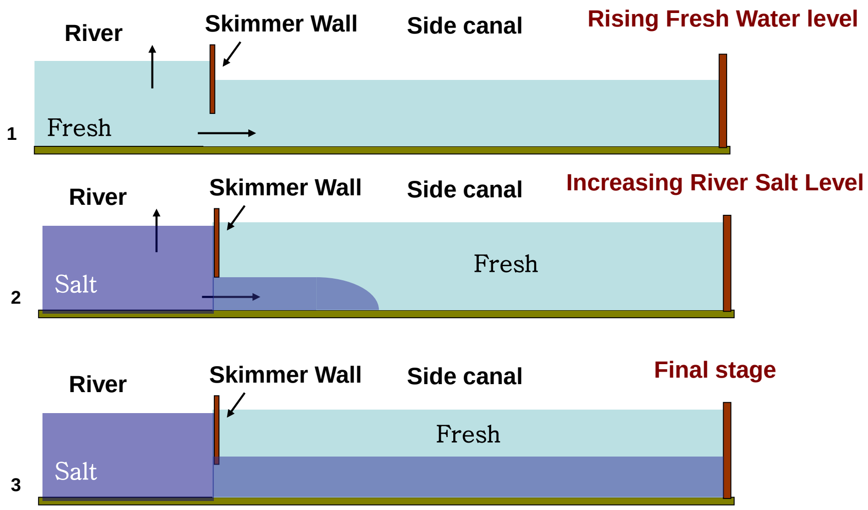

Figure 10 Skimmer wall creating fish refuge against salt intrusion due to storm surge

Detailed monitoring of salt intrusion in side canals during and in the days after a storm surge will yield a better insight into the rise of salinity concentrations in the side canals. We suggest combining this monitoring will surveys to monitor fish movement between the river and the side canal as well as flow velocities in the side canal. ARIS sonar camera techniques would be well suited to such a study, potentially combined with hydroacoustic survey runs of the main river channel to map the spatial distribution of fish before, during and after the surge.
Because such skimmer walls do only partially block the side canal and supposing flow velocities are modest it would require less strength for the construction also since water levels being nearly equal on both sides. At the same time such construction would allow fish to migrate underneath the skimmer wall. The best place for a skimmer wall could be estimated by the freshwater volume available in the canal before the surge and the shortened stretch it will fill once the water level has risen i.e. in between the flood defences structures.
An aspect of which we are not sure how it affects the effectiveness of skimmer walls is the fact that the adjacent land in between flood defences also overflows (Figure 4). It will be more complicate to block this (Figure.11). We suggest blocking this partially, but do not know whether and how this interferes with the effectiveness of the skimmer wall. The majority of water movement will take place in the canal, but once a skimmer wall would be placed it is uncertain to which extent the freshwater is pushed out over the adjacent land and thereby reducing the efficiency of the skimmer wall.

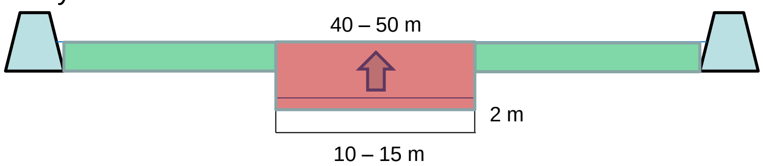

Figure.11 Skimmer wall (brown) in the canal will induce selective withdrawal of saltwater at the bottom. On the adjacent land between the flood defences structures obstacles (green) may reduce with freshwater withdrawal and mixing. Preferably these obstacles should simply increase the roughness and not complete block the water movement.

Skimmer walls might be tested first whether they are effective by their own. A demo scale model in the form of a long Perspex tank with or without a skimmer wall and on one side saline coloured and on the other side blank freshwater can illustrate the phenomena and as such help to convince stakeholders (Appendix 3).

We are less convinced that air curtains offer an effective solution to combat salt intrusion in side canals. Our main consideration is the persistence of the salt intrusion for a number of days. Air curtains leak and can thus not fully block salt intrusion. Application in shipping locks is effective because of the short time span (< 1hr), but becomes less effective when the salt intrusion persists a longer period i.e. a number of days, which is the case in the Broads. We therefore recommend to explore the use of skimmer walls.

5. Indicative assessment of the consequences in terms of construction, hindrance of ship traffic, hindrance of road traffic, energy consumption, and maintenance? [cost?]

There is intense recreational navigation in the Broads. The measures suggested above take this all into account by being only operational during storm surges and the days thereafter until salinity levels have dropped to non-lethal concentrations (conductivity < 10,000 µS). The hindrance of traffic is thus restricted to a minimum. Since most recreational use in the winter period concerns angling we anticipate there will be public support and understanding for the measures when proven effective.
Broads tourism data suggests that angling may have influenced expenditure worth between £91 million and £153 million in 2014. This may thus well be worth several investments to reduce fish kills at the local level. The local solutions encompass barriers, skimmer walls and air curtains. The barrier at Potter Heigham has proven to be effective. Skimmer walls are considered easier to operate and require less maintenance and exploitation costs than air curtains.
The cost of the measures proposed to reduce salt intrusion at the catchment level may be considered too high when they would solely protect freshwater fish e.g. the cost for the 80 m wide inflatable rubber dam at Ramspol (the Netherlands) amounted 100 million EUR, but this value is probably not realistic for the situation in the Broads, because the dimensions are smaller. Such solutions should thus have other significant benefits e.g. flood protection. Therefore we recommend that the potential fisheries protection benefits are an important consideration when considering flood defence options for the Broads. The cost of measures to increase channel roughness during storm surges have not been further investigated. A modelling exercise should first demonstrate to potential effectiveness.
Air curtains require maintenance and have exploitation costs. It would be best when the construction is stored outside the water when not used, because it only will be used incidentally. Being permanently in the water will reduce its efficiency due to fouling.
<u>Conclusions and Recommendations</u>

- Explore the possibility for catchment level measures to shorten the upstream front of salt intrusion inland. Possible options embrace water retention in brackish washlands, temporal barriers to block storm surges or increase channel roughness. Hydrological models that can calculate with either water retention or channel roughness to estimate the reduction in upstream movement of the salinity front can support drawing conclusions on the effectiveness of these measures.
- Collect longitudinal profiles of the upstream penetration of salt water intrusion as a source of information to assess the effectiveness of measures reducing the magnitude of storm surges.
- Investigate the salt intrusion in side canals in detail to explore whether freshwater could be retained and function as a refuge during and in the days following storm surges. Simultaneously investigate the flow velocities in and the inundated areas around the side canal.

- Survey the migration and movement of fish between the river and a side canal and within the side canal (e.g. Acle dyke or Loddon) during and after a storm surge to obtain a better insight how fish try to avoid lethal salinity concentrations.
- Air curtains might be a potential solution for the side canals, but unlikely to be effective in the rivers. They may also increase the effectiveness of physical barriers such as the one at Potter Heigham by improvement reduction of salt intrusion in marinas. However the fact that salt intrusion persists for a number of days will reduce the effectiveness of air curtains over time.
- What we consider a more favourable option for side canals is a skimmer wall to induce selective filling and withdrawal of saltwater at the bottom and retain a freshwater top layer as refuge in the side canals. It is assumed that flow velocities in the side canals are modest where water is pushed up because the dead-end side canal behaves like an impoundment. This would reduce the requirements for the design of such skimmer wall.

Solution	Location of application	Cost	Effectiveness
Air curtain	Local in side canals; multiple locations	Investment per side canal 23,000 GBP. Equipment storage: 750 GBP / yr. Operational costs per intrusion installation 3,500 GBP and 750 GBP / day compressor rental.	Local. Doubtful, particular because the salt intrusion persists for several days and only applicable at the transition point
Skimmer wall	Local in side canals; multiple locations	Several (ten of) thousands GBP. Little maintenance. Storage of skimmer wall: p.m.. Operational costs for closing and opening during intrusions: p.m.	Local. Considered the best local option
Retention in brackish washlands	In the main channel in the brackish transition zone	Cost for purchasing land (GBP/ha) and placing flood control structures. Prefeasibility study required for a reliable cost estimate.	Entire upstream catchment. Prefeasibility model study to estimate required retention capacity. Potential creation of estuarine wetlands (SPA; SAC)
Temporal barrier i.e. inflatable rubber dam	In the main channel at the upstream boundary of the brackish transition zone or further downstream	(tens of) millions GBP depending on dimensions.	Entire upstream catchment. Potential other significant benefits such as flood protection.
Increased channel roughness through partially blocking and movable constructions	In the main channels anywhere downstream of potentially impacted stretches	Prefeasibility study required for a reliable cost estimate.	Entire upstream catchment. Prefeasibility model study required to demonstrate potential effectiveness

Appendix 1 Background information

\004 EA Broads salt intrusion and fish kills\Background information*.*

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Turner et al 2004 Broads Ecological Economics	pdf	513.187	16-08-2015 08:49	-a–

Appendix 2 Itinerary visit Tom Buijse

Date	Time	Place	Topic	Persons
15/2	21:15	Arrival in Norwich		
16/2	09:30 - 12:00	EA office, Dragonfly House, Gilders Way, Norwich	Presentation by Tom Buijse and discussion	Stephen Lane, Claire Humphries, Tom Howard, Adam Clarke
16/2	12:00 – 18:00	River Bure (Acle Dyke, Upton Dyke, Acle Bridge), River Thurne (Potter Heigham Marina, Ludham) River Bure (Horning)	Field visit	Stephen Lane
	18:00 – 20:00	Norwich	Summarising field observations	Stephen Lane
17/2	09:30 – 16:30	River Yare (a.o. Rockland St Mary, Loddon)	Field visit	Stephen Lane, John Currie
18/2	09:45	Departure from Norwich		

Appendix 3

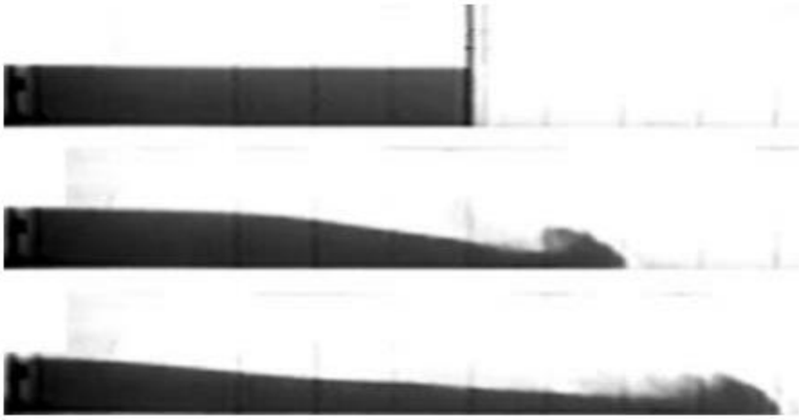

FIGURE 3. Time sequence of the flow from a partial-depth lock release. The initial depth $D = 0.5H$, and $\gamma = 0.989$.

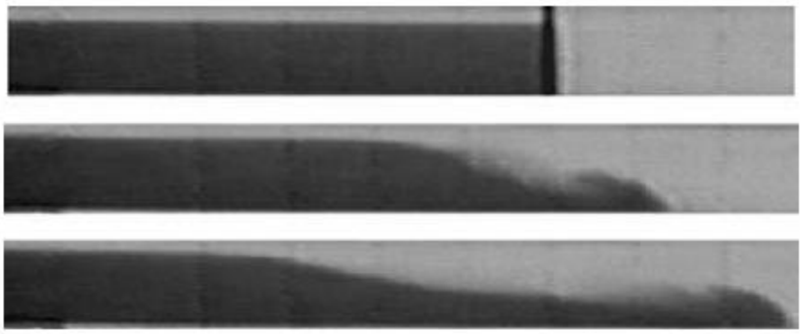

FIGURE 4. Time sequence of the flow from a partial-depth lock release. The initial depth $D = 0.83H$, and $\gamma = 0.990$.

Figure 12 Time sequence of the flow from a partial-depth lock release. Source: Shin et al. 2004

References:

Shin, J.O., S.B. Dalziel and P.F. Linden (2004) Gravity currents produced by lock exchange. J. Fluid Mech. 521: 1–34.

Date
29 March 2016

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