Environment Agency

Evidence

Implications on water quality and sedimentation from the provision of fish access at water-level management structures

Report – SC110017

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This report is the result of research commissioned and funded by the Environment Agency's Evidence Directorate.

Published by:
Environment Agency, Horizon House, Deanery Road, Bristol, BS1 9AH
www.environment-agency.gov.uk

ISBN: 978-1-84911-293-2

Further copies of this report are available from our publications catalogue: http://publications.environment-agency.gov.uk or our National Customer Contact Centre: T: 08708 506506
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Dissemination Status:
Publicly available

Keywords:
Fish access tidal flaps water quality Trent

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Project Number:
SC110017

Product Code:
LIT 7767

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Miranda Kavanagh

Director of Evidence

Executive summary

A field-based study was carried out to investigate the potential impacts on water quality and sedimentation from the installation of fish access structures at several tidal flapped watercourses along the estuarine River Trent (referred to as drains in this report). A monitoring study included measurement of salinity and turbidity over individual tidal cycles at selected drains during spring and neap tidal periods as well as investigating the upstream influence of a single tidal flushing event on a single drain.

Monitoring of salinity and turbidity was undertaken at four drains, three of which had fish access structures installed to their flap valves, namely Burton-on-Stather Drain, the River Eau and Laughton Highland Drain. Burringham Reservoir Drain was also monitored as a control site as it has no fish access structure. Four surveys were undertaken at each site under spring and neap tides with the fish access structures open and closed. Each survey lasted for a single tidal cycle of 12 hours 25 minutes. Measurements were taken in the River Trent and up to 250m upstream in each drain. In addition, flow velocity was measured at each drain to inform fish passage assessments.

The single tidal flushing survey was undertaken at Adlingfleet Drain during the initial inflow portion of a tidal flushing event – a management event used to clear sediment from a creek on the estuary side of the drain tidal structure. Salinity and turbidity were measured to 1,800m upstream before, during and after the flushing event.

The survey results showed that salinity was very low with limited variability, measuring between 0.4 and 0.9 parts per thousand (ppt) in all the surveys regardless of tidal cycle. Salinity values in the River Trent were generally similar and very rarely exceeded 1ppt. These results indicated that the water within the drains was either freshwater or brackish. The most significant trend noted for salinity within a drain was its frequent reduction during tidal inflow on the flood tide due to dilution of water in the drain by the incoming estuarine waters.

Turbidity was found to vary significantly throughout the surveys. The greatest variation in turbidity was found during the spring and neap tides when the fish access structures were open and active. Most changes in turbidity were confined to the commencement of the flood tide when water flowed into drains and the ebb tide when drains flowed out into the River Trent. When fish access structures were closed and inactive, turbidity levels at all drains declined significantly and were within the same range of variation in turbidity measured at the control site. A reduction in the upstream distance impacted by increased turbidity was also found when fish access structures were inactive and closed. Analysis of the data highlighted that the source of the increased turbidity was a combination of sediment supply from the River Trent on the incoming flood tide and bed scour within a drain.

Results of the tidal flushing event survey at Adlingfleet Drain showed that salinity was initially reduced by dilution from the inflow of estuarine waters, with slight increases after flushing ceased due to changes in the salinity of the estuary during the flood tide. However, salinity was noted to decline upstream towards pre-flushing event levels. Turbidity was found to increase dramatically during tidal flushing but to decrease rapidly after flushing ceased due to the cessation of turbid estuarine water and scour within the drain and settling of entrained sediment. Like salinity, turbidity declined upstream.

It was concluded that the presence of fish access structures on tidal flapped drains has a limited impact on salinity within a drain but does have a significant impact on sediment movement into and within a drain. Data show that the fish access structures

do allow enhanced passage of fish between the River Trent and a drain. On drains with fish access structures it is very likely that additional altered management regimes such as sediment management would be required, but more detailed studies are necessary to quantify the extent of this additional management.

Recommendations for future work include:

- considering a wider range of fish access structures
- repeating the study under ‘normal’ flow conditions (low flow and lack of rainfall in this study may have affected the results)
- investigating the upstream impact of different tidal and operational conditions on turbidity
- monitoring a full tidal flushing event (that is, the inflow and outflow stages)
- quantifying the periods of operation of fish access structures
- carrying out repeat bed topographical surveys over several tidal cycles.

Acknowledgements

In addition to the assistance provided by the Environment Agency Project Team we would also like to thank Neil Goulding and his Operations Team for all their help and assistance during the project.

Contents

1 Introduction

This project investigated the potential impacts on water quality and sedimentation at several water-level management structures on the tidal River Trent with fish access structures. These fish access structures had been installed to existing tidal flapped outfalls to allow the passage of migratory organisms, particularly fish (including eel), thereby restoring connectivity between the North Sea and the rivers that flow into it.

The fish access structures studied during the project had all been installed to enable obligations under the Water Framework Directive (WFD) and Eel Regulations to be achieved. During operation of the tidal structures there is the potential for changes in the water quality and sediment regime in the associated drains, which could affect the management regime and flood risk within these drains.

To understand the operational impacts of the fish access structures, detailed monitoring was undertaken at four tidal drains over several complete tidal cycles to monitor changes in water quality, turbidity (as a surrogate for changes in sediment dynamics) and, where possible, flow velocity through a fish access structure.

The results provided:

- details of the impacts of fish access structures on water quality and sediment dynamics within drains
- information about the potential impacts on the management regime within drains
- a more detailed understanding of the response of various types of fish access structure available.

Ultimately, the findings will feed into wider policy decisions within the Environment Agency and also within the INTERREG European Funded Living North Sea Project, helping to inform fish passage solutions across the North Sea region of Europe.

1.1 Report structure

The report is divided into five sections. Section 2 reviews some previous studies regarding fish access structures, while Section 3 provides an overview of the Humber Estuary and River Trent catchment and the sites surveyed during the project. Section 4 describes the monitoring methodology used during the work, Section 5 presents the results of monitoring at each of the five sites and Section 6 discusses the findings from the project and the conclusions reached from the monitoring.

2 Previous studies

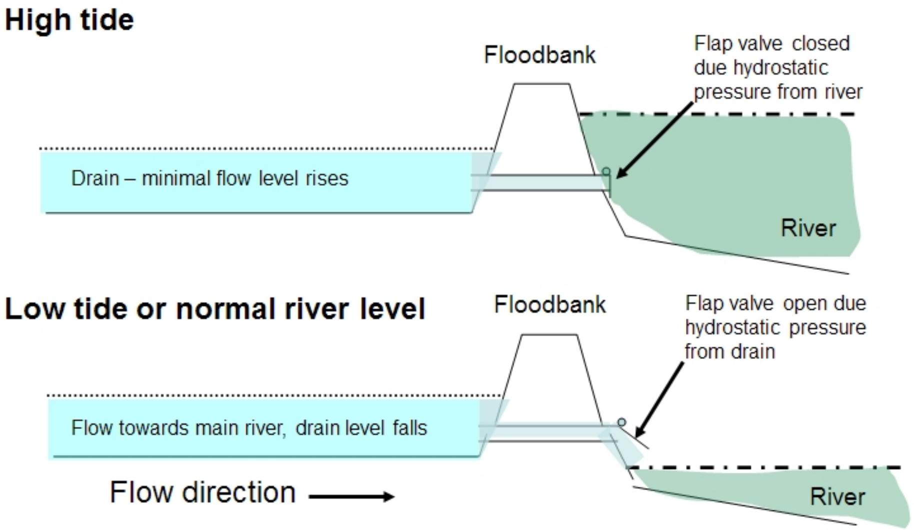
Only a small number of studies have investigated the impacts of flap valves and fish access structure. This section provides a brief overview of flap valves and their impacts on fluvial and estuarine processes and ecology.

2.1 Tidal flap valves

Many types of tidal flap valve are used to control the flow of water into a watercourse due to tidal changes. However, there are two main groups: traditional designs and modern designs. The former are composed of top hinged or chained flaps while the latter are composed of side or bottom hinged flaps and self-regulating structures (Giannico and Souder 2004, Patrik et al. 2009). Such structures have been used worldwide for several centuries for water control and in draining land for conversion to agriculture or urban areas (Giannico and Souder 2004).

Tidal flap valves are commonly mounted on the estuary-facing side of a culvert where a watercourse runs through a floodbank, dyke or levee to join the main river (Figure 2.1). They are used to control the ingress of tidal water and function automatically based on the change in water levels. When the water level outside the flapped watercourse is higher than in the drain, the flap valve will close preventing flooding of the drain and the surrounding land. When the water level inside the watercourse is higher than in the main river or the estuary, the flap valve opens allowing water to flow out of the watercourse (Figure 2.1). In this way flap valves maintain low tide conditions within a watercourse or prevent floodplain flooding behind a levee (Charland 1998, Patrik et al. 2009).

Figure 2.1 Example operation of a flap valve



Tidal flap valves are also used to provide ecological benefits such as:

- the creation of new inter-tidal habitats such as mudflats, salt marshes and supertidal wetlands (Charland 1998, Environment Agency, 2003)
- the creation of agricultural or urban land (Environment Agency 2011).

However, flap valves have a range of detrimental impacts on the natural environment, affecting hydrology, water quality, geomorphology, ecology and land use. Due to alteration of flow they can have a negative impact on the physical, chemical and biological properties of a watercourse (Giannico and Souder 2004).

Physical modifications are linked to the construction of a tidal structure and are accompanied by changes in channel morphology which can impact flow, sediment dynamics and ecology and habitats, for example via scour of the channel bed upstream of the flap valve (Giannico and Souder 2004).

The intrusion of water from the estuary can affect the chemical balance of the drain by causing upstream increases in water nutrient concentration and heavy metal suspension, and reductions in dissolved oxygen, pH and alterations in water temperature (Giannico and Souder 2004).

The biological effects of flap valves include:

- changes to the composition of aquatic plant communities
- modification of the ecological potential of a tidally flapped watercourse
- reductions in estuarine water quality, for example by the release of coliform bacteria into estuarine waters at low tides (Charland, 1998; Giannico and Souder, 2004).

However, an important impact of tidal flap valves is their impact on fish movement (see, for example, Charland 1998, Giannico and Souder 2004, Patrik et al. 2009, Solomon 2010).

2.2 Impact of tidal flap valves on fish passage and development of 'fish-friendly' flap valves

Fish find it difficult to bypass flap valves and to navigate culverts connected to flap valves (Charland 1998, Patrik et al. 2009). Research suggests that there are two main factors influencing the degree to which a flap valve is a barrier to fish passage (Giannico and Souder 2004):

- how long the flap valve is closed
- the size of the opening created between the flap valve and its mounting when open.

In addition, varying flow velocities created by the combination of the flow of water through the flap valve and the size of the opening can hamper the swimming ability of the fish (Giannico and Souder 2004).

A diverse range of 'fish-friendly' modifications to flap valves have been developed and utilised in order to overcome the impacts to fish passage (c.f. Charland 1998, Charland 2001, Solomon and Beach 2004, Solomon 2010, Environment Agency 2011), although Giannico and Souder (2004) argue that such designs are only 'fish-friendlier' as they still act as a barrier to fish passage.

Most designs for fish access structures are based on hinged flaps which are float or spring controlled, providing automatic operation based on changes in tidal levels. Such structures increase the length of time for which fish can access habitat behind a flap valve. This duration is controlled by a number of factors (Environment Agency, 2011):

- invert level of the flap

- diameter of the access structure
- float level
- level of water in the landward watercourse
- tidal cycle.

As a result many flap valves are either being replaced or being retrofitted with such fish access structures.

The three main types of fish access structure considered in this study (Retarder, ACE and Stoneman) are outlined below (see section 3.2 for a more detailed description).

Spring retarders are used to keep the flap valve open for longer periods on the flood tide and open earlier on the ebb tide than a normal flap valve to allow more backflow up the drain and longer durations of access for fish (including eel) (Environment Agency 2010, Black and Veatch 2011).

The Aquatic Control Engineering (ACE) fish assess structure is a bottom-hinged flap set within the main panel of a flap valve which is naturally open until lifted by a float. The design appears to have been originally proposed by Charland (1998). A number of similar models for bottom-hinged flaps have been, or are being, supplied to the Environment Agency, for example the access structure on the River Stiffkey in Norfolk (Solomon 2010).

The Stoneman device is a steel plate that rotates across the mouth of a circular-section culvert, its rotation effected by a weighted float. The system works so that the gate is closed at both high and low tides, but open at an intermediate stage so that the water passing landwards is saline rather than backed-up freshwater (Solomon 2010). A prototype, installed on the estuary of the River Axe in January 2009, has operated without significant problems (Solomon 2010).

2.3 Management impacts of flap valves and fish access structures

Available evidence suggests that the addition of fish access structures to flap valves is likely to alter the water quality of the drains in which they are installed, with increased water circulation due to the presence of a fish access structure possibly resulting in reduced water temperatures (Giannico and Souder 2004).

Changes in salinity within watercourses due to the addition of flap valves or fish access structures could also impact on local ecology and directly impact the use of abstracted water through changes to water quality – particularly if used for agriculture (Environment Agency 2011).

In addition flap valves and fish access structures also need to be checked regularly to ensure there are no problems involving the build-up of flotsam or debris behind or inside the structures which could affect the system's effectiveness (Charland 1998, Giannico and Souder 2004, Environment Agency 2011). Such blockages could lead to management problems such as increased risk of flooding due to failure of a flap valve.

3 Catchment and site overview

Five sites were selected for monitoring. These were located along the lower tidal reaches of the River Trent, upstream of its confluence with the Humber estuary. Details of the site selection process and overviews of each site are given below.

3.1 Site selection

The Environment Agency initially identified a list of 13 sites along the tidal River Trent. An initial site visit was made on 14 October 2011 by the project teams from the Environment Agency and Cascade Consulting (the contractor for the project), and Environment Agency operational staff. Most of the sites on the initial list were visited. An additional site, Burringham Reservoir Drain, was visited to assess the feasibility of using it as a control site.

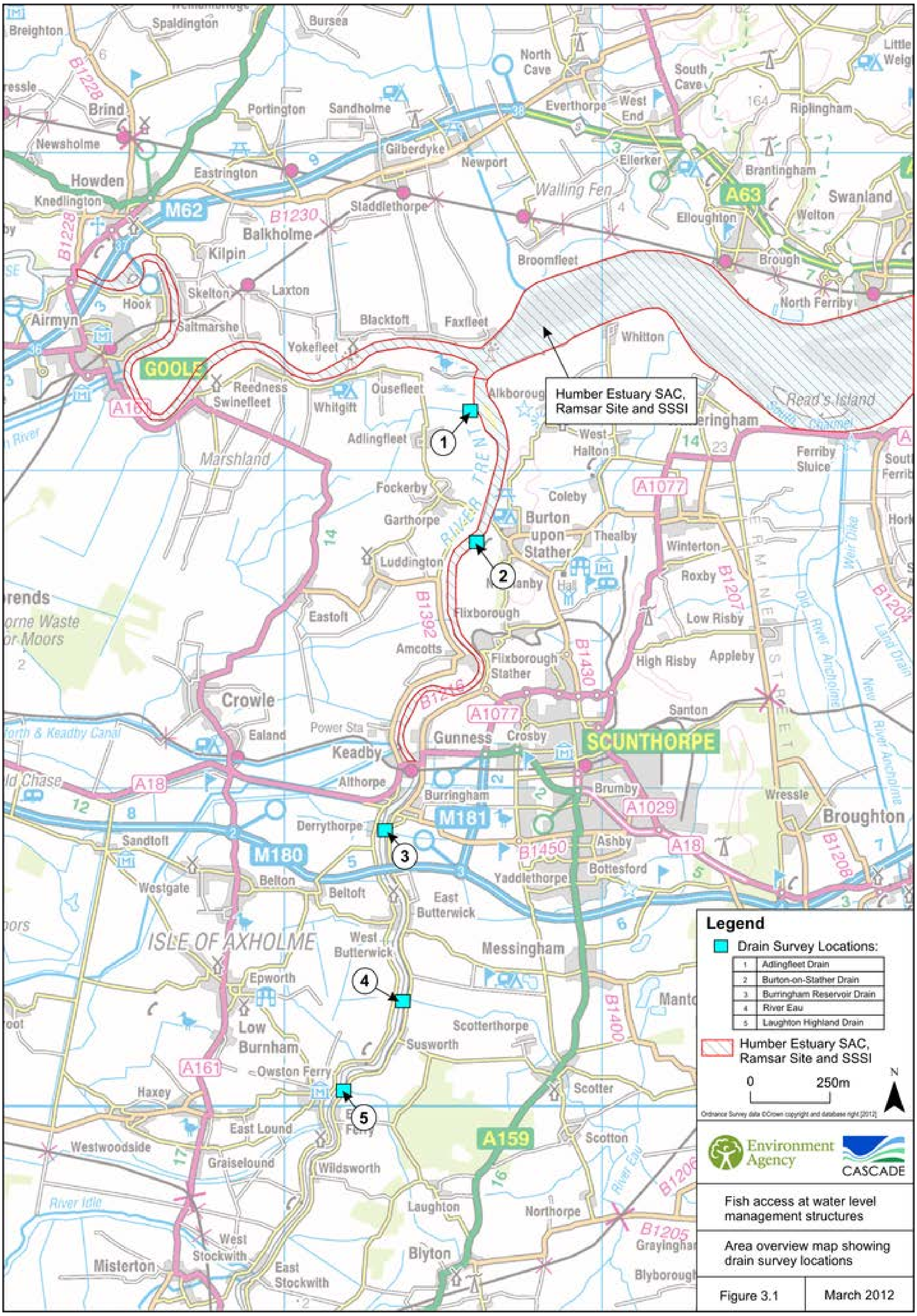
Based on the information gained from the initial site visit and the knowledge of the Environment Agency project team and operational staff, five sites were selected. In order upstream from the mouth of the River Trent (Figure 3.1) these sites were:

1. Adlingfleet Drain
2. Burton-on-Stather Drain
3. Burringham Reservoir Drain (control site)
4. River Eau
5. Laughton Highland Drain

Adlingfleet Drain was chosen for a short-term tidal flushing event study only and was not intensely monitored due to severe sedimentation problems at the tidal side of the tidal structure. The other four sites were chosen based on the following crucial factors:

- **Presence of a fish access structure.** Each site (apart from the control) had a different type of operational fish access structure. This provided a range of types of structure to assess, allowing a wider view of the potential management impacts of fish access structures.
- **Site maintenance.** Sediment deposition on the tidal side of many of the drains was very variable, with the fish access structure and flap valves of some drains silting up rapidly and becoming inoperable over a few tidal cycles, while others remained clear. The chosen sites either remained clear of sediment or could be rapidly cleared if required.
- **Upstream distance.** The sites were selected based on the presence of a long, upstream reach from the tidal structure that was unimpeded by other features such as water control structures.
- **Lack of interaction/impacts.** Sites were chosen where there were either no or very few impacts to flow, for example abstractions or discharges. This criterion was the most difficult to achieve as most of the drains had such interactions due to their anthropogenic nature, though the significance of any impacts was considered before the sites were selected.
- **Access.** An important aspect of site selection was ease of access. All the chosen sites could be accessed all along their banks, were safe to access in the dark and adequate off-road parking for vehicles was available.

Figure 3.1 Map showing drain survey locations



3.2 Fish access structures

The main aim of fish access structures is to increase the length of time during the flood and ebb periods of the tidal cycle when fish (including eel) can access a tidal flapped drain. The three types of fish access structures present on the drains surveyed were:

- Aquatic Control Engineering (ACE) fish access structure
- Stoneman fish access structure
- Retarder access device

The ACE and Stoneman fish access structures are fitted directly onto the drain outlet so as to completely replace an existing standard flap valve structure. These structures are therefore within the estuarine environment and are operated by the tidal regime. In contrast, the Retarder is retrofitted to the existing cabling of the flap valve, leaving the flap valve itself unaltered. The Retarder is installed above normal water level on the landward side of a tidal structure and is therefore not directly impacted by the tidal regime.

The ACE fish access structure is essentially a simple float operated, cat-flap like valve, which closes and opens based on the rising and falling tide. The float is rigidly attached to the top of the flap valve and can be set at different angles to allow varying rates of closure of the flap. The flap itself is hinged at its base. On the rising tide the float remains on the surface of the water, pushing the flap valve closed. On the falling tide, the level of the float drops with the tide, pulling the flap valve open.

The Stoneman fish access structure operates in the vertical plane in a scissor-like action. A flat metal plate is attached to a rigid metal arm, with a large cylindrical float on the opposite end. The arm is hinged above the plate. As the tide rises the float is pushed up, moving the plate horizontally and in a downwards direction across the fish access structure. As the tide falls, the float drops, allowing the plate to open horizontally in an upwards direction.

The Retarder consists of a large spring surrounded by a metal cage. This can be directly attached to the control wire mechanism of the flap valve and no modification of the flap is required. The cage is fully adjustable to control the spring tension and hence the period the main flap valve can be open. The Retarder operates by providing additional resistance to closure against the hydrostatic pressure of the rising tide and to allow the flap valve to overcome the hydrostatic pressure of the tidal waters during the falling tide before an equilibrium is reached between the tidal level and the water level within a drain.

3.3 River Trent catchment and site descriptions

This study focused on five drains located along the tidal section of the lower River Trent (Figure 3.1). The River Trent itself drains a large area of the UK. The section below provides an overview of the Trent catchment along with the four sites where monitoring was undertaken.

3.3.1 River Trent

Catchment description

The River Trent drains a total area of ~10,500km^2, including much of the Midlands, and flows for ~275km from its source on Biddulph Moor to its confluence with the River Ouse.

The tidal limit of the River Trent is at Cromwell Weir. At this point the river drains a catchment area of ~8,228km^2. Below Cromwell Weir the tidal section of the River Trent is ~69km in length.

Within the catchment average annual rainfall is 746mm (Institute of Hydrology 1999).

Altitudes vary greatly throughout the catchment from up to 630m in its northern region, which drains the Pennines, to near sea level at the mouth of the Trent. Median elevation is around 110m above sea level. The river itself follows a southerly course from its source, though Stoke and Burton-upon-Trent, flowing eastwards past Derby and through Nottingham, before altering course at Newark and flowing in a northerly direction past Gainsborough and Scunthorpe before flowing into the River Ouse at Trent Falls.

There are several significant tributaries of the River Trent, notably the Dove, Derwent, Erewash, Mease, Tame and Soar. The River Trent and River Ouse flow directly into the Humber Estuary and thence to the North Sea. The Humber Estuary is the second largest coastal plain estuary in the UK and possesses high sediment concentrations (JNCC 2012).

The geology of the Trent catchment is generally characterised by mudstones and sandstones of Triassic age (~248–206 million years ago), particularly downstream of Burton-upon-Trent in the mid-upper reaches of the catchment. Limestones and sandstones of Carboniferous age (~34–326 million years ago) characterise the geology of the upper areas of the catchment around the headwaters (BGS 2012). The geology of the catchment is of very low permeability, although there are areas of moderate and high permeability, most notably in the western and headwaters of the catchment (CEH 2012). Superficial geology within the catchment is dominated by a mixture of fluvial sands and gravels and glacial tills, although superficial deposits within the headwaters of the catchment are limited. The River Trent and its larger tributaries are underlain by extensive deposits of alluvium (BGS 2012).

Land use within the catchment is predominantly a mixture of grassland and arable and horticultural land. Urbanisation is significant, particularly around the southern, central and eastern areas of the catchment.

The selected sites fall within the stretch of the River Trent between Owston Ferry and the mouth of the River Trent (~27km in length) (Figure 3.1). Along this reach land use is predominantly low lying arable farmland interspersed with urban areas (Owston Ferry, West Butterwick, Burringham, Keadby and Burton-upon-Stather) and industrial development (wharves around Keadby, Gunness and Flixborough), particularly towards the lower reaches of the river. In this stretch the river is navigable and is frequently used by industrial transport craft (for example gravel barges) and pleasure craft. Below Keadby, larger draught cargo vessels are common. Individual site descriptions for each of the drains are given in sections 3.3.2 to 3.3.6.

Tidal regime

A significant feature of the Humber Estuary is the large tidal range. This is due to its position within the North Sea basin; producing a mean spring tidal range of 5.7m at Spurn Point. The tidal range is amplified as it propagates up the estuary due to the narrowing of the estuary in a westerly direction. At Hessle, ~45km inland from Spurn Point (and ~19km downstream from the mouth of the River Trent), the tidal range increases to 6.9m (Environment Agency 2009). Because of these large tidal ranges, the Humber is classified as a macro-tidal estuary.

The estuary of the River Trent is characterised by a semi-diurnal tide. This is a cycle which has two high and two low tides a day, this being due to the interaction between the luni-solar bulge in the World's seas and the rotation of the Earth. There is approximately 24 hours 50 minutes between two tidal crests (for example, high tide–low tide–high tide–low tide–high tide) and so one tidal cycle (that is, high–low–high) measures approximately 12 hours 25 minutes (Pethick 1993). In this regime, the two high tide levels are commonly unequal due the axial inclination of the Earth and orbital movement of the Moon. A complete tidal cycle from high tide to low tide to high tide is broken up into two distinct portions – the flood tide (the incoming tide when water levels are rising) and the ebb tide (the outgoing tide when water levels are falling).

Finally, there are two key variations in tides which occur over a 29-day cycle, namely spring and neap tides, with two spring and two neap tides occurring over this period. The spring tide is caused when the Moon and Sun are in alignment, that is, the Moon phase is at new or full. At this point the gravitational pull of both celestial bodies combines to create the highest tidal bulges and hence the highest tides. A neap tide is caused when the Moon is 90° or 270° out of alignment with the Sun (that is, the Moon phase is at first or last quarter). At this point the gravitational pull is reduced and tides are lower. During neap tides the tidal range is significantly reduced compared with those experienced during spring tides (that is, high tide levels are lower and low tide levels are higher). The maximum spring and neap tides occur approximately 1.5 days after new/full Moon or first/last quarter (Pethick 1993). The highest spring tides, those occurring at the equinoxes, did not occur during the study. These two variations are crucial to the study and the understanding the range of impacts of fish access structures on water quality and suspended sediment.

As noted above, the tide experienced in the River Trent estuary is a semi-diurnal tide with very pronounced spring and neap tides. In addition, the tidal cycle seen in the River Trent estuary is not perfectly symmetrical, that is, flood and ebb portions of the cycle are of unequal lengths. This is due to frictional resistance between oncoming and reflected tidal waves within the irregular coastline of the Humber estuary (Pethick 1993). In the River Trent the time between ebb slack and flood slack is approximately three hours, while the difference between flood slack and ebb slack is approximately nine hours, that is, a very rapid rise in tide level followed by a slow decline in the tide level. These times are obviously subject to natural variation, particularly due to weather and flow within the River Trent itself.

Tidal range in the River Trent estuary is lower than in the Humber estuary. At Keadby Bridge (Figure 3.1), the typical tidal range is between 0.6m above Ordnance Datum (AOD) to 4.7mAOD. There is an increasing time lag in the progress of the tide as one goes further inland: with high tide at Laughton Highland Drain (Figure 3.1) being approximately one hour after high tide at Burton-on-Stather Drain. These lags are dependent on a range of conditions, particularly meteorological conditions and freshwater flow in the River Trent, and can therefore differ significantly.

Salinity values in the River Trent estuary indicate predominantly freshwater to brackish water conditions (section 5), although these will be controlled by the flow within the River Trent. The presence of willows on the bankside of the River Trent estuary (a saline intolerant tree species) from before Keadby and upstream supports the observation that this section of the River Trent estuary is predominantly borderline freshwater to brackish water.[1]

Due to the large tidal range and morphological configuration of the Humber and Trent estuaries, the River Trent is one of only two rivers in England to have a tidal bore (the other being the River Severn). This is known as the Trent Aegir and occurs around spring tides.

Designations

The River Trent falls within the Humber River Basin Management Plan. Burringham Reservoir Drain, the River Eau and Laughton Highland Drain are all in the Lower Trent and Erewash catchment. This catchment covers an area of 2,045km^2, extending from the River Dove confluence with the River Trent, south-west of the city of Derby, to the Humber Estuary. Burton-on-Stather Drain falls within the Louth, Grimsby and Ancholme catchment which covers an area of 1,464km^2.

The section of the River Trent estuary from Keadby Bridge to the mouth has several significant conservation designations:

- Humber Estuary Special Area of Conservation (SAC) (UK0030170)
- Humber Ramsar site (UK11031)
- Humber Estuary Site of Special Scientific Interest (SSSI) (2000480)

From the mouth of the River Trent to ~2.4km upstream, the River Trent is additionally designated under the Humber Estuary Special Protection Area (SPA) (UK9006111), an Important Bird Area (Humber flats, marshes and coast, 90022) and an RSPB reserve, Blacktoft Sands. The WFD status of each site is discussed in sections 3.3.2 to 3.3.6.

The Humber Estuary is designated for its nationally and internationally important habitats and species, more specifically a diverse range of habitats from the estuary, mudflats, coastal lagoons, salt meadows and dunes (Annex I habitats in the SAC designation and also identified in the Ramsar citation). Several species of national and international importance are listed in the designations, notably sea lamprey (*Petromyzon marinus*), river lamprey (*Lampetra fluviatilis*), grey seal (*Halichoerus grypus*), red knot, Eurasian golden plover and other waterfowl. The Humber Estuary is also designated under the SSSI for its geology, namely South Ferriby Cliffs, and coastal geomorphology at Spurn Point.

Given the spatial extent of the designations, only Adlingfleet Drain and Burton-on-Stather Drain flow into designated stretches of the River Trent.

3.3.2 Burringham Reservoir Drain

Burringham Reservoir Drain was used as a control site, there being no fish access structure fitted to the tidal flap valve. It is located approximately 500m upstream of Burringham village (Figures 3.1 and 3.2). Although the catchment area of the drain is ~0.5km^2, this is significantly modified by the presence of a pumping station and water control structure. The annual rainfall in the catchment is 594mm (Institute of Hydrology 1999). The drain is characterised by a deep, trapezoidal profile with steep sides ~4m high, with a ~3.5m wide channel at the bottom of this profile (Figure 3.3). On the

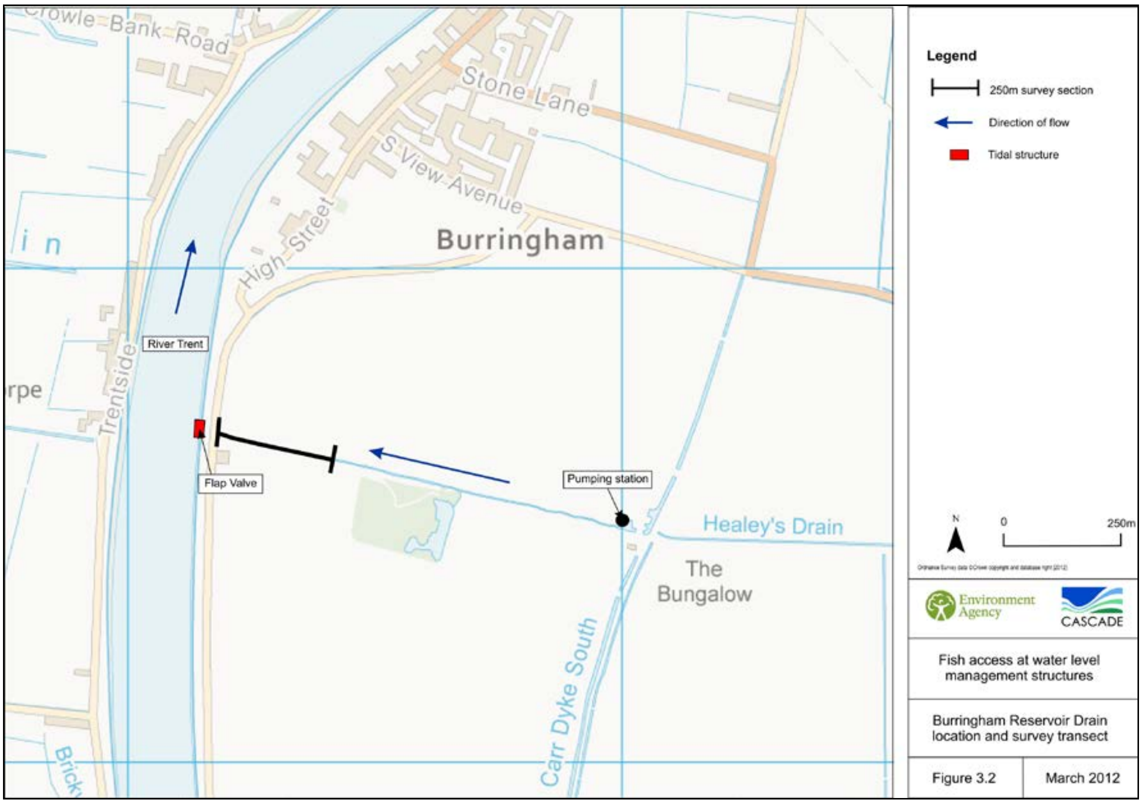
[1] Neil Goulding, Environment Agency, personal communication (2011)

landward side of the drain the tidal structure is a large stone block structure connected to the River Trent by way of a culvert ~40m long (Figure 3.4) which passes beneath a road and an embankment prior to the outfall on the River Trent estuary. A penstock is present on the landward side of the drain. On the estuary side the tidal structure is composed of concrete with a single flap valve (Figures 3.5 and 3.6).

The banks of the drain are variably vegetated, with grasses and tall herbs and reeds on the north (right) bank and dense shrub and scrub and trees on the south (left) bank.[2] The site is predominantly rural, surrounded by arable farmland. Soil types in and around the drain are wholly coastal flat loamy and clayey soils (NSRI 2012).

A pond is located on the south bank of the drain ~500m upstream from the penstock of the tidal structure (Figure 3.2). No flow path between this pond and the drain could be identified. It is therefore concluded that the pond is not in hydrological connectivity with the drain and does not influence flow in the drain.

Figure 3.2 Burringham Reservoir Drain location and survey section



There is single dwelling located on the south bank of the drain, immediately before the tidal structure and outfall to the River Trent estuary. The pumping station ~0.8km upstream of the discharge location into the River Trent is controlled by the local Internal Drainage Board. This on-line pumping station effectively prevents backflow to the drain beyond 0.8km and can also lead to increased water levels within the drain. Depths within the channel ranged between 0.1 and 1.1m, although the depth was generally around 0.3m, the larger depths being caused by pumping of water into the drain during water control operations at the upstream pumping station.

Burringham Reservoir Drain is located in a catchment of low, small and calcareous typology. For WFD purposes the drain is in the ‘Bottesford Beck’ water body, which is identified as being heavily modified for flood protection and urbanisation. The current WFD potential is bad status with a predicted overall objective of poor potential by 2015.

[2] Bank orientation is referred to here when facing in a downstream direction towards the tidal structure.

Less than good status for invertebrates, ammonia and dissolved oxygen and quantity and dynamics of flow all contribute to the reduced potential. The overall WFD objective is to achieve good potential by 2027.

Figure 3.3 Looking east upstream along Burringham Reservoir Drain

Figure 3.4 Burringham Reservoir Drain penstock and culvert to River Trent

Figure 3.5 View of flap valve (note valve is open)

Figure 3.6 Looking south-west upstream in the River Trent

3.3.3 Burton-on-Stather Drain

Burton-on-Stather Drain is the farthest downstream drain monitored over several tidal cycles[3] (Figures 3.1 and Figure 3.7). The drain is situated on the floodplain of the River Trent with the urban areas of Burton Stather and Burton-on-Stather to the north and east respectively; Burton-on-Stather is on an elevated plateau. On Ordnance Survey maps the drain is marked as ‘Burton and Flixborough Drain’ but this name is not used in this report.

The drain has a catchment area of ~3.2km^2 with an annual rainfall of 618mm (Institute of Hydrology 1999). It is characterised by a steep-sided trapezoidal channel, with a bankfull height of ~1–3m. Bank heights decrease upstream from the tidal structure at the end of the drain (Figure 3.8). The channel is ~1m wide. On the landward side of the drain, the tidal structure is a large sheet piled and concrete structure connected to the River Trent estuary by way of a culvert ~40m long (Figure 3.9) which passes beneath rough pasture and an embankment prior to the outfall on the estuary. A penstock is present on the landward side of the drain. On the estuary side the tidal structure is a small concrete structure with a single flap valve surrounded by gabions (Figures 3.10 and 3.11); this is located above the low tide level, meaning the flap valve becomes dry at low tide. At this site the standard flap valve has been replaced with an ACE flap valve incorporating a fish access structure (Figure 3.10).

[3] Adlingfleet Drain is further downstream but was only monitored during a single flushing event.

The banks of the drain are variably vegetated with grasses, tall herbs and reeds on the north (right) bank, and dense grasses, shrub and scrub and trees on the south (left) bank. The site is predominantly rural. The southern (left) bank is flanked by arable farmland and a large pond and marsh surrounded by deciduous trees. The north (right) bank is flanked by rough grassland with an extensive series of recreational angling ponds set back from the drain. Soil types in and around the drain are wholly coastal flat loamy and clayey soils (NSRI 2012).

Burton Stather Sewage Treatment Works (STW) discharges into the drain ~500m upstream from the tidal structure and outfall into the River Trent (Figure 3.4).

Several large ponds are located on both banks of the drain. Two ponds are located close to the drain on the south bank between ~130–250m upstream from the penstock while a large pond is located on the north bank between ~250–420m (neither are shown on Figure 3.4). No flow path between these ponds and the drain could be identified. It is therefore concluded that the ponds are not in hydrological connectivity with the drain and do not influence flow in the drain.

Burton-on-Stather Drain is located in a catchment of low, small and calcareous typology. For WFD purposes, the drain is located in the 'Winterton Beck from Source to the Humber' water body. The water body is not designated as being either heavily modified or artificial. The current WFD ecological quality is moderate status, with a predicted overall quality of good status by 2015. Less than good status for invertebrates contributes to the reduced potential.

At the point where the drain flows into the River Trent estuary, the receiving water is designed as the Humber Estuary SAC, Humber Estuary Ramsar and the Humber Estuary SSSI.

Figure 3.7 Burton-on-Stather Drain location and survey section

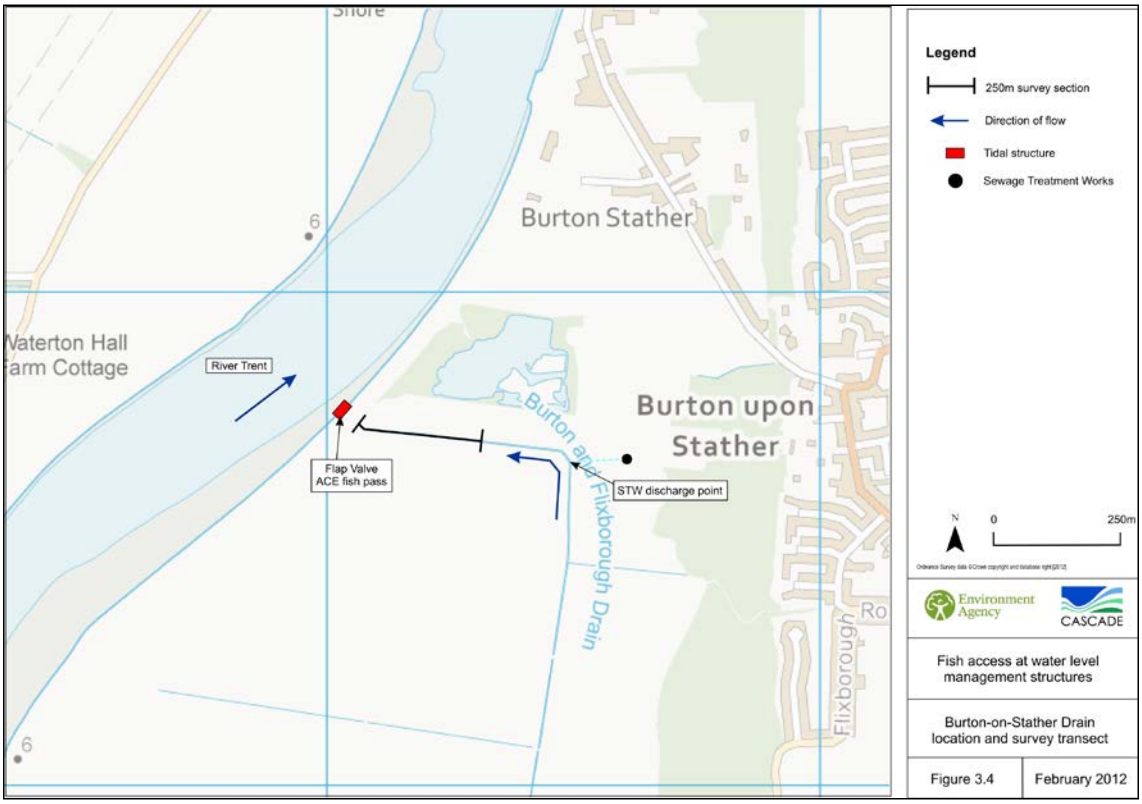


Figure 3.8 Burton-on-Stather Drain looking east upstream

Figure 3.9 Burton-on-Stather Drain penstock and culvert to River Trent

Figure 3.10 View of ACE flap-valve with fish access flap (open)

Figure 3.11 Looking north-west downstream in the River Trent

3.3.4 River Eau

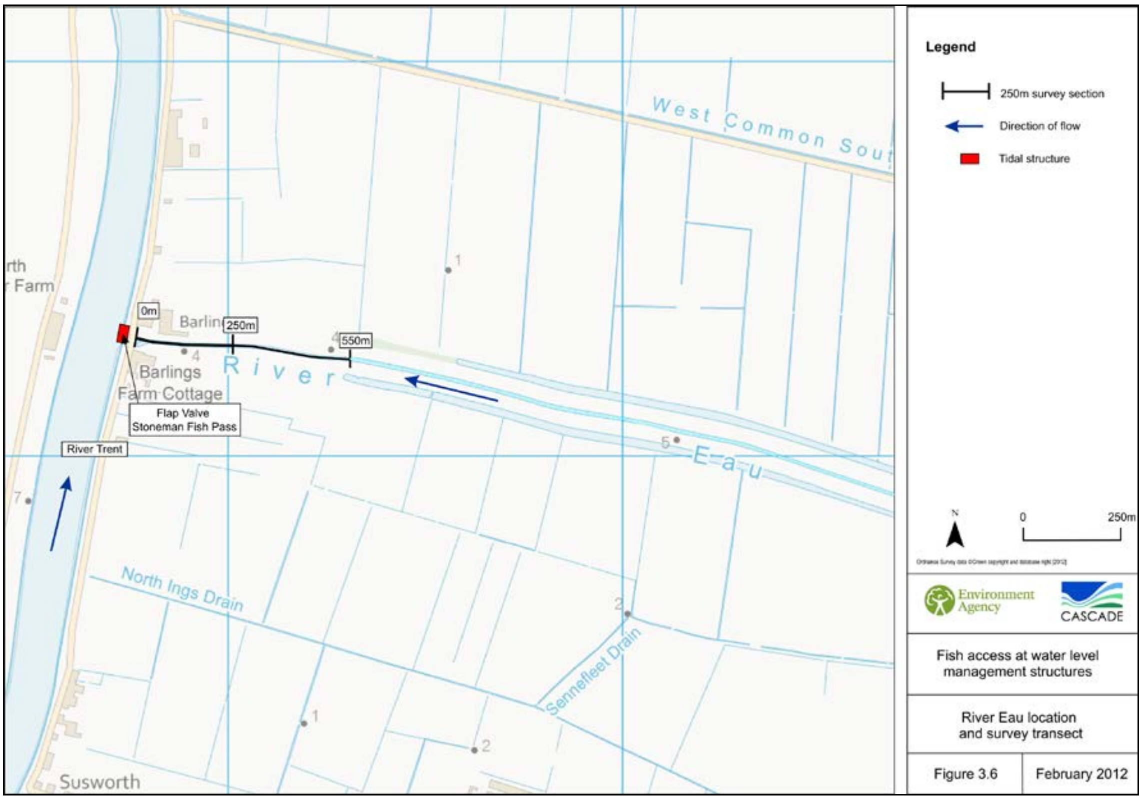
The River Eau was the largest watercourse studied in this project. The tidal structure is located at Susworth, a small hamlet, situated approximately 5km upstream of Burringham Reservoir Drain (Figures 3.1 and 3.12). The River Eau covers a catchment area of ~113.4km^2 with an annual rainfall of 609mm (Institute of Hydrology 1999). The river is surrounded by shallow sided banks with a box-shaped channel profile, with the lowest bank levels around 3.2mOD (Black and Veatch 2011). Bankfull height is ~1m (Figure 3.13) and the channel is ~10m wide.

On the landward side of the drain the tidal structure is extensive and consists of sheet piling and concrete (Figures 3.13 and Figure 3.14). The structure itself is composed of four individual penstock and outfalls arrangements which flow to the River Trent. These are arranged in two groups of two penstocks. There is an artificial island-like structure, which projects upstream from the centre of the tidal structure bifurcating the channel into two separate reaches with a single penstock group at each side of the island. This allows for control of the flow from the River Eau. Flow passes through the tidal structure by way of one of the four ~30m long culverts which pass beneath a main road and an embankment prior to the outfall to the River Trent estuary (Figure 3.14). On the estuary side the tidal structure is also extensive and composed of sheet piling and concrete. The two groups of flap valves are separated from each other by a vertical concrete wing wall (Figure 3.15).

In this study the penstock group and flap valves on the northern (right) side of the tidal structure were used and monitored. The northern most flap valve supported the Stoneman fish access structure (Figure 3.15). The southern bifurcation and southern group of flap valves were surrounded by sediment and would only become active at higher river levels.

Both banks of the drain are predominantly composed of rough grassland, with some trees towards the downstream end of the drain. The site is predominantly rural and surrounded by arable agricultural land with some grazing land towards the River Trent. Soil types in and around the drain are wholly coastal flat loamy and clayey soils (NSRI 2012). Next to the tidal structure is a house on the north (right) bank and a farm and associated outbuildings (Barlings Farm) on the south (left) bank. Gabions were also noted as composing the banks immediately around the tidal structure (Figure 3.12).

Figure 3.12 River Eau location and survey section



The River Eau is located in a catchment of low, medium and calcareous typology. For WFD purposes the river is located within the 'River Eau from Kirton Lindsey Trib. to R. Trent' water body. The water body is designated as being heavily modified for flood protection. The current WFD ecological potential is poor status with a predicted overall objective of good potential by 2027. Less than good status for fish, phytobenthos and phosphate contribute to the reduced potential.

Figure 3.13 River Eau looking east upstream (note island-like structure to right, with the main channel to left of image and a secondary channel off to the right)

Figure 3.14 River Eau, looking east upstream showing surrounding landscape

Figure 3.15 View of northern group of flap valves and Stoneman fish access flap (open and deactivated)

3.3.5 Laughton Highland Drain

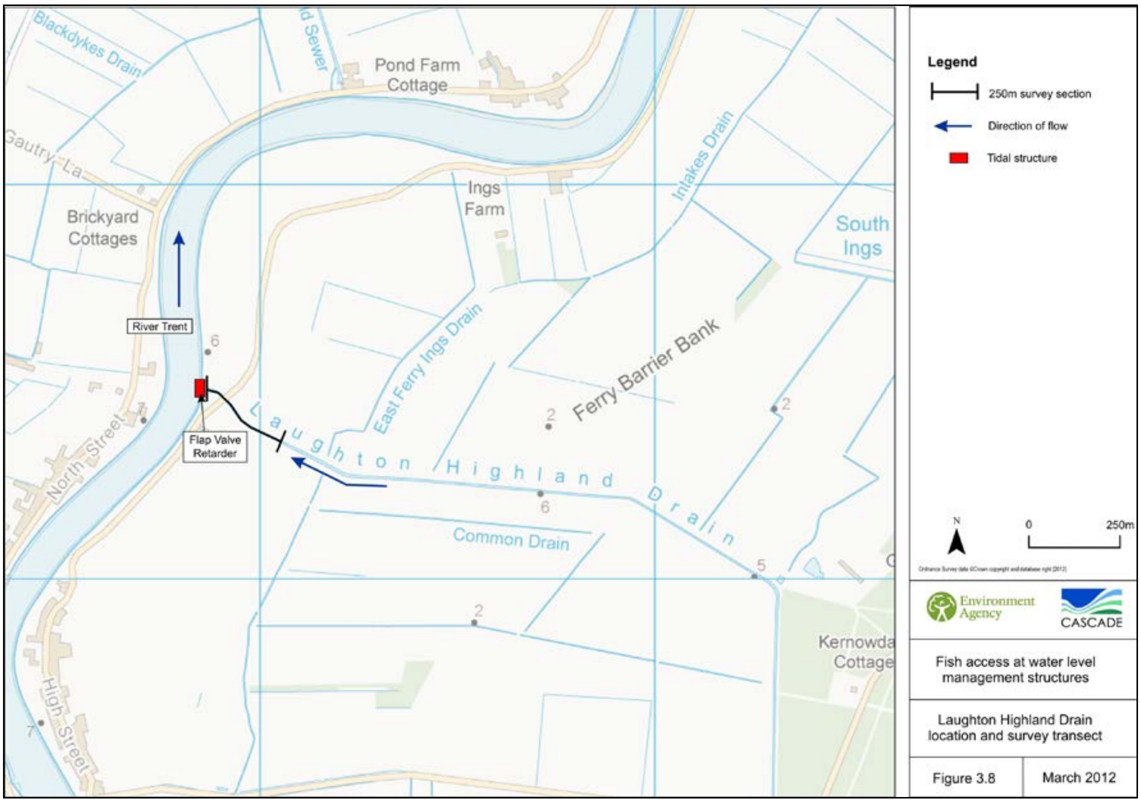
Laughton Highland Drain is located approximately 4km upstream in the River Trent from the River Eau (Figures 3.1 and 3.16). The catchment area of the drain is ~22.1km^2 with an annual rainfall of 596mm (Institute of Hydrology 1999). The drain is characterised by a steep, trapezoidal channel with a bankfull height of ~5m (Figure 3.17). The channel is ~2.5m wide.

On the landward side of the drain the tidal structure is a large sheet piling and concrete structure connected to the River Trent by way of a two culverts, both ~5m long (Figure 3.18). Two penstocks are present on the landward side of the drain, separated by a single vertical wing wall. On the estuary side the tidal structure is composed of sheet piling and concrete, both flap valves being separated by a single vertical wing wall (Figure 3.19). In this study the penstock and flap valve on the northern (right) side of the tidal structure was used, the northern most flap valve being fitted with a Retarder fish access device (Figure 3.20).

The site is predominantly rural and is surrounded by arable farmland. The banks of the drain are variably vegetated with grasses, tall herbs and scrub, and shrub and isolated trees on the north (right) bank and rough grass on the south (left) bank. Until approximately 50m upstream of the tidal structure, both banks are extensively covered with willow. Soil types in and around the drain are wholly coastal flat loamy and clayey soils (NSRI 2012).

There are two houses, Drainhead Cottages, located on the south (left) bank of the drain immediately upstream of the tidal structure. These houses are located next to a road carried over the drain via a bridge (Figure 3.16). There is extensive evidence of past dredging and weed cutting on the banks of the drain, particularly close to the outfall with the River Trent. Gabions were also noted as composing the banks immediately around the tidal structure.

Figure 3.16 Laughton Highland Drain location and survey section



Laughton Highland Drain is located in a catchment of low, small and calcareous typology. For WFD purposes the drain is within the ‘Laughton Drain from Source to River Trent’ water body. The water body is identified as being heavily modified for land drainage. The current WFD potential is poor status with a predicted overall objective of good potential by 2027. Overall potential remains unchanged in 2015. Less than good status for invertebrates, phytobenthos, dissolved oxygen and phosphate all contribute to the reduced potential.

Figure 3.17 Laughton Highland Drain, looking east upstream

Figure 3.18 Laughton Highland Drain penstocks and culverts to River Trent (right most penstock in photo used during all studies)

Figure 3.19 View of flap valves – the Retarder controls the flap at bottom left

Figure 3.20 Looking south-west upstream in the River Trent

3.3.6 Adlingfleet Drain

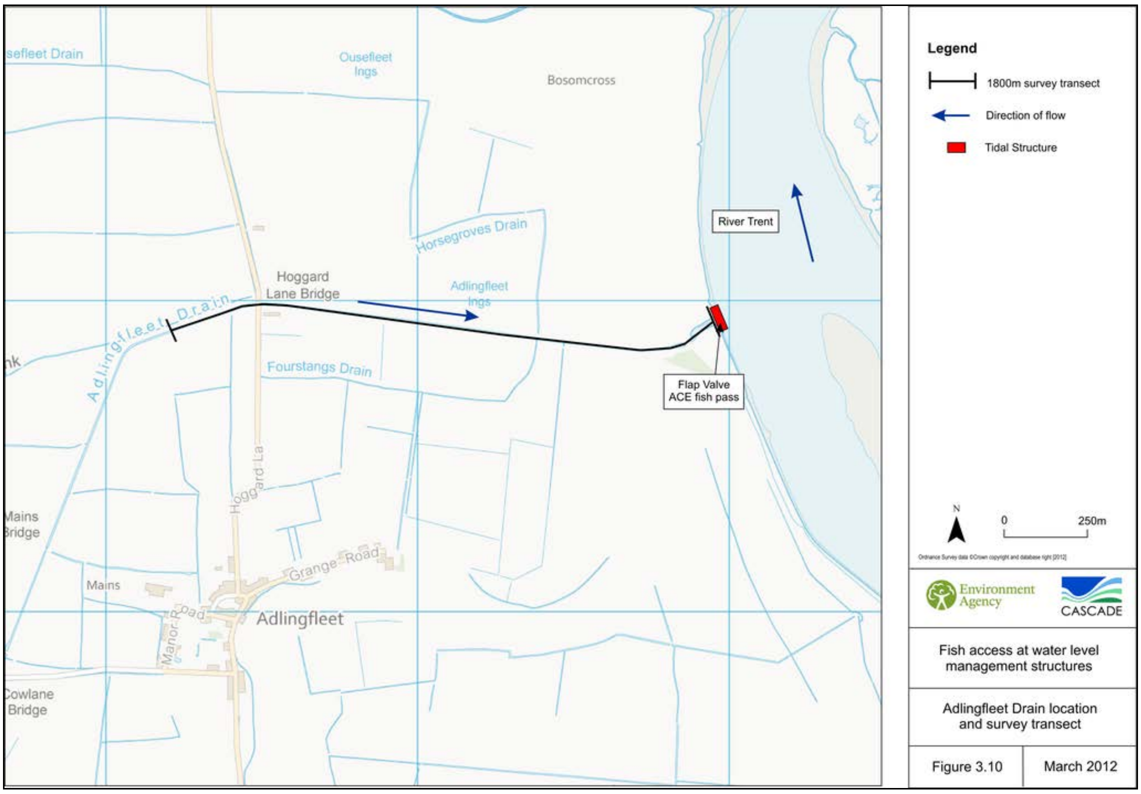
Adlingfleet Drain is ~1.2km from the mouth of the River Trent estuary (Figures 3.1 and 3.21). The catchment area of the drain is ~7.2km^2 with an annual rainfall of 595mm (Institute of Hydrology 1999). The drain is characterised by a moderately steep trapezoidal channel with a bankfull height of ~5m (Figure 3.22). The channel is ~7m wide.

On the landward side of the drain the tidal structure is a large sheet piling and concrete structure connected to the River Trent estuary by way of two culverts of ~10m in length (Figure 3.23). Two penstocks are present on the landward side of the drain. These differ from previous sites, being mounted above one another in the vertical plane rather than located side by side in the horizontal plane. On the estuary side the tidal structure is composed of sheet piling and concrete. This site is also unusual in that it flows into a small reed fringed creek, ~130m long, before flowing into the River Trent estuary. This creek is regularly filled with sediment to several metres deep, burying both flap valves (Figure 3.24) and requiring constant maintenance. The lower penstock and flap valve was fitted with an ACE fish access structure, but given the burial of the flap valve, this site was not considered for study over several tidal cycles.

The site is rural and surrounded by arable farmland. The banks of the drain are variably vegetated, predominantly with grasses, tall herbs and reeds along with isolated trees and bushes. Soil types in and around the drain are wholly coastal flat loamy and clayey soils.

A track runs alongside the drain on its south (right) bank for ~1.3km between a road and the tidal structure, providing access to the tidal structure itself. A single house is present on the south (right) bank at the junction between the access track and road (Figure 3.21). Also at this point a bridge, Hoggard Lane Bridge, crosses the drain. There is extensive evidence of past dredging and weed cutting on the banks of the drain, particularly close to the outfall with the River Trent.

Figure 3.21 Adlingfleet Drain location and survey section



Adlingfleet Drain is located in a catchment of low, small and calcareous typology. For WFD purposes the drain is in the ‘Adlingfleet Drain Upper Catchment’ water body. The water body is identified as being artificial due to land drainage. The current WFD potential is moderate, with a predicted overall objective of good potential by 2027. Overall potential remains unchanged in 2015. Less than good status for ammonia all contribute to the reduced potential.

Figure 3.22 Adlingfleet Drain, looking west upstream

Figure 3.23 Top most flap valve (other valve is buried beneath sediment)

Figure 3.24 Looking east into tidal creek and River Trent beyond

Adlingfleet Drain was monitored in this study to understand changes in salinity and turbidity during the inflow portion of a tidal flushing event.

The tidal flushing event is a management option and not a natural event and is known as ‘warping’. The technique is used to supply sediment to farmland surrounding a drain or to clear sediment from a drain. In the case of Adlingfleet Drain the tidal flushing event was used to remove sediment deposited in a creek on the estuary side of the drain tidal structure. A tidal flushing event comprises of two stages, the inflow stage and outflow stage.

- **Inflow stage.** This stage is undertaken during a rising tide, preferably on a high spring tide. At or around the ebb slack, the flap valve and penstock of the selected tidal structure on the selected drain are opened. As the flood tide commences, water will flow into the drain from the estuary and fill up the drain. When either sufficient water has entered the drain or the flood slack period of the tide has been reached, the flap valve and/or penstock is shut. The water will remain in the drain until the outflow stage.

- **Outflow stage.** This stage is undertaken during a low tide, preferably on the ebb tide. When tide levels are below water levels in the selected drain, the flap valve and penstock are opened to allow the water stored in the drain (from the inflow stage) to flow out of the drain and into the estuary. The significant hydrodynamic force generated by the outflow of water from the drain acts to clear sediment from the estuary side of the drain or the drain itself. When water levels in the drain have dropped to a level whereby flow ceases or the aims of the tidal flushing have been achieved, the flap valve and penstocks are shut.

Only the inflow stage of the tidal flushing event was monitored during this study.

4 Survey methodology

Two monitoring programmes were carried out to collect the necessary data. The main study (Section 4.1) consisted of a long-term tidal cycle programme involving the measurement of salinity, turbidity and flow velocity at specific locations along the selected drain. Alongside the main study a single individual event study (Section 4.2) was undertaken to understand the impacts of tidal flushing on the ingress of salinity and turbidity into a drain. The methodologies of each survey are discussed in detail below. The results are discussed in Section 5.

4.1 Primary methodology

Burringham Reservoir Drain (control site), Burton-on-Stather Drain (ACE fish access structure), the River Eau (Stoneman fish access structure) and Laughton Highland Drain (Retarder fish access device) were chosen for study to assess the impacts of the various fish access structures on salinity and turbidity within a drain under varying tidal cycles.

4.1.1 Tidal cycles

To fully understand the influence of fish access structures on salinity and turbidity within a drain, measurements were undertaken over both spring and neap tides with the fish access structures activated (open and operational) and deactivated (closed and locked shut and non-operational). This resulted in four surveys:

- spring tide, fish access structure activated (spring-open)
- neap tide, fish access structure activated (neap-open)
- spring tide, fish access structure deactivated (spring-closed)
- neap tide, fish access structure deactivated (neap-closed)

Surveys where the fish access structure was activated are known as the ‘open surveys’ while the surveys where the fish access structure was deactivated are known as the ‘closed surveys’.

The most appropriate survey dates (Table 4.1) were selected based on:

- tide tables
- information supplied by the Environment Agency[4]
- consideration of available daylight hours

The survey dates (and predicted high water levels) chosen did not represent the most extreme values of spring or neap tides, but were chosen so that spring and neap tides were approximately similar in magnitude for both the closed and open surveys.

In addition, all monitoring was undertaken over a single tidal cycle from low tide to high tide to low tide in order to observe the behaviour of the water throughout the full tidal range and to maintain consistency between sampling occasions.

[4] Neil Goulding, Environment Agency, personal communication (2011)

Table 4.1 Dates and times of surveys

Date of survey	Site surveyed	Start time	End time	Survey	Approximate high water level (mAOD)
23 November 2011	River Eau	11:40	00:30 (24 Nov)	Spring-open	3.6*
	Laughton Highland Drain	11:34	23:20		3.6*
24 November 2011	Burringham Reservoir Drain	12:53	00:23 (25 Nov)	Spring-open	4.4**
	Burton-on-Stather Drain	13:35	23:21		4.6***
1 December 2011	River Eau	08:34	20:00	Neap-open	2.2*
	Laughton Highland Drain	09:10	20:29		2.2*
2 December 2011	Burringham Reservoir Drain	09:20	19:40	Neap-open	3.2**
	Burton-on-Stather Drain	07:40	17:02		3.7***
12 December 2011	River Eau	04:42	16:37	Spring-closed	3.2*
	Laughton Highland Drain	05:08	16:26		3.2*
13 December 2011	Burringham Reservoir Drain	05:03	15:58	Spring-closed	4.2**
	Burton-on-Stather Drain	04:49	15:29		4.5***
19 December 2011	River Eau	10:50	21:26	Neap-closed	2.5*
	Laughton Highland Drain	10:58	22:18		2.5*
20 December 2011	Burringham Reservoir Drain	11:11	22:38	Neap-closed	3.5**
	Burton-on-Stather Drain	08:55	19:08		4.1***

Notes: High water levels obtained from Admiralty Easy Tide website (http://easytide.ukho.gov.uk/EASYTIDE/EasyTide/index.aspx)

*Owston Ferry; **Keadby; ***Burton Stather

The surveys were undertaken by two teams of two surveyors. This allowed monitoring at all four sites to be undertaken over a two-day period. It also allowed measurements to be taken when tidal conditions were broadly similar, which would not have been the case if monitoring was undertaken over longer time periods by fewer surveyors.

For the surveys where the fish access structures were closed, each structure was deactivated in a specific manner. At Burton-on-Stather Drain, the ACE fish pass was locked shut with a locking mechanism supplied by the manufacturer. At the River Eau the Stoneman pass could not be locked. Instead, the penstock behind the Stoneman pass was closed, deactivating it, and the adjacent penstock was opened (Figure 3.15). At Laughton Highland Drain, the Retarder device was removed from the flap valve control cable, allowing the flap valve to operate as normal. Environment Agency Operations staff performed the deactivation procedures on the fish access structures.

4.1.2 Water quality and turbidity monitoring

Water quality and turbidity measurements were undertaken at each of the four sites using YSI 6600V2 series sondes. The relevant calibration certificates for both sondes used during the survey are shown in the Appendix. A range of determinands were measured:

- salinity in parts per thousand (ppt)
- conductivity (μS/cm)
- temperature (°C)
- flow depth (m)
- turbidity as nephelometic turbidity units (NTU)

Measurements were taken following a simple method which balanced the need for very detailed spatial coverage along a drain with the time available to measure and capture all possible changes in water quality and turbidity over a tidal cycle.

A single measurement was taken in the River Trent estuary adjacent to the flap valve of a drain as far away from the valve as possible so as not to measure outflow from the drain. The distance between the penstock on the landward side of the drain and the flap valve on the River Trent estuary varied with each site. At Burringham Reservoir Drain and Burton-on-Stather Drain this distance measured ~40m, while at the River Eau it measured ~30m and at Laughton Highland Drain ~5m.

Within the drain, measurements were taken at 0, 10, 50, 100, 175 and 250m upstream from the penstock (a single survey section). These sampling sites were measured prior to undertaking a survey and marker stakes were driven into the ground at the correct location to ensure exactly the same sites were sampled each time. For the River Eau only, additional upstream sites were added during tidal ingress into the drain as significantly elevated levels of turbidity were noted at 250m during surveys when the fish access structure was open. To better understand the upstream impact additional sites at 300, 350, 400, 450, 500 and 550m upstream were also surveyed. These additional sites were measured when tidal ingress had begun and were stopped after flood slack.

On the River Eau the measurements at 0 and 10m were taken in the main, north (right) bifurcation of the channel (section 3.3.4) while in Laughton Highland Drain the measurements at 0m were taken in front of the north (right) penstock on the tidal structure (section 3.3.5).

Measurements were always taken in an upstream direction from the tidal structure penstock so that, if bed disturbance had occurred, results would not be impacted by downstream movement of sediment such would be the case if results were taken in a downstream direction. Care was also taken not to touch the bed with the sonde so as to prevent displacement of bed sediments into the water column and impacting on measured turbidity values. If this did occur, the sediments displaced into the water column were allowed to travel downstream before measurements were undertaken again or a measurement was taken slightly upstream out of the field of the displaced sediment.

On an initial site visit on 31 October 2011 (and again during the subsequent monitoring), several measurements were taken across the width and also at various depths (surface, mid-depth and bottom) in each drain to ascertain whether there was any vertical or horizontal variation in the determinands being studied. No vertical or horizontal variation in any of the determinands was recorded. This was also found to be the case in the margins of the main River Trent.

Accordingly, at each measurement site in the drain, measurements were taken at a distance of approximately 1.5m away from the channel banks (facilitated by the use of extendable poles) and with the sonde fully immersed.

A single survey section of the channel took ~30–40 minutes. This equated to approximately one full survey section of a drain per hour, though this was varied according to conditions, that is, additional runs were made if tidal inflow had begun immediately after one run had been completed.

A complete survey of one drain was undertaken over one complete tidal cycle (low tide–high tide–low tide) of 12 hours 25 minutes, resulting in approximately 9–12 complete survey sections per complete tidal cycle. The exact duration of a complete survey was determined in the field by analysing water quality results in real time. If the determinands measured over two or three consecutive runs in a drain showed little to no variation from the determinands measured in a drain prior to the commencement of the flood tide (and inflow of estuarine water into the drain), monitoring was stopped as no further variability was occurring. Cessation of monitoring always occurred when there was no tidal influence on the drain and water was flowing out of the drain. This was particularly the case at Burton-on-Stather Drain when surveys were ended before the end of a complete tidal cycle as the flap valve and fish access structure were dry and out of water around 1.5h before the end of the tidal cycle due to the elevated location of the tidal structure and flap valve on the bank side.

Values for each determinand at a measurement site were recorded directly onto record sheets. The times of all measurements were recorded as Greenwich Mean Time and are presented in 24-hour clock format, for example, 01:00 (1.00am).

4.1.3 Velocity measurements

Velocity measurements were carried out to attempt to understand flow velocities through the fish access structures during tidal inflow and outflow. This knowledge will allow the potential for fish and eel to pass through the access structures to be understood, based on known swimming speeds.

Flow velocities were measured, using a Valeport 801 magflowmeter, immediately upstream of the penstock located on the upstream side of the tidal structure. Measurements were taken at a depth of ~60% of the flow depth at the time of measurement. The flow meter was held still during a velocity measurement and, if the probe indicated a high standard deviation, velocities were immediately re-measured. Care was taken not to place the flowmeter probe into a turbulent stream of water so as not to give unrepresentative results.

Due to problems in safely accessing the penstocks of each structure, only a limited number of flow velocity measurements were undertaken for Burringham Reservoir Drain, Burton-on-Stather Drain and Laughton Highland Drain. No measurements could be taken at the River Eau or on the estuary side of the tidal structure around the flap valve and fish access structure.

4.2 Adlingfleet Drain methodology

Adlingfleet Drain was chosen as a site where monitoring of a single tidal flushing event could be undertaken. The site was chosen due to the size of the drain and the ongoing problems with sedimentation in the creek on the estuary side of the tidal structure. This sedimentation necessitated frequent sediment removal by filling the drain with incoming tidal water, holding it during the ebb and releasing it a low tide, thus flushing away the sediment in the creek. This technique is known as ‘warping’ and has been utilised for several purposes including land management. This study was undertaken to attempt to understand the impact of inflow of saline and turbid waters into the drain. A more detailed description of the tidal flushing event is provided in Section 3.3.6.

This event based study was undertaken on 21 November 2011 during a spring tide; monitoring began at 11:00 and ended at 17:23. Monitoring was carried out **only** during the inflow of tidal water into the drain, that is, the first stage. For safety reasons, flushing was required to be undertaken during daylight hours only.

4.2.1 Water quality and turbidity monitoring

Monitoring consisted of three individual runs:

- a baseline run carried out before the start of tidal inflow (from 11:00 to 11:57)
- a run carried out during the tidal inflow (13:12 to 15:05)
- a run carried out after the tidal inflow had ceased (15:52 to 17:23)

Water quality and turbidity data were collected using the same sondes as described in section 4.1.2.

Water quality and turbidity measurements were taken over a 1,800m stretch of Adlingfleet Drain, starting at the upstream face of the tidal structure to the point on the drain where the drain changes course to the south east (Figure 3.21). On the baseline run, measurements were only taken to 1,400m upstream due to there being very little change in salinity and turbidity.

Measurements were taken at 100m intervals in an upstream direction, starting at 0m at the penstock of the tidal structure. Between 0m and 1,400m, samples were taken from the south (right) bank and, between 1,400m and 1,800m, samples were taken from the north (left) bank. At each measurement interval, salinity (ppt) and turbidity (NTU) were recorded. Given the width of the channel, measurements were taken approximately 1.5m away from the edge of the water (facilitated by the use of extendable poles) with the sonde fully immersed. Measurements of salinity and turbidity taken at the penstock of the tidal structure before and at the start of the tidal inflow flushing showed no vertical variation in salinity or turbidity.

4.3 Notable issues

A range of notable issues were present during the surveys.

4.3.1 All sites

Because there had been very little rainfall in the months preceding the surveys, outward freshwater flow in the drains and the River Trent were unseasonally low. Flows in the River Trent were actually near to summer flows.[5] Flows in the River Eau were particularly affected given the impacts on flow from abstractions further upstream at Scotter for the purposes of turf cultivation.[6] This suggests that the condition of the

[5] Neil Goulding, Environment Agency, personal communication (2012)
[6] Neil Goulding, Environment Agency, personal communication (2011)

drains and the determinands measured may not be wholly representative of normal flow conditions.

Leakage around the flap valves and penstock structures at high tide levels was also identified as an issue at all sites, particularly the River Eau and Laughton Highland Drain. At the River Eau leakage was also occurring through the tidal structure itself and was noticeably increasing turbidity around the 10m measurement site, with most flow coming from the south penstock group on the south channel bifurcation (section 3.3.4).

There were additional issues with measurement sites at some of the drains. At Burton-on-Stather Drain and the River Eau, the presence of mud bars prevented some measurements being taken and during some surveys measurements could only be reliably taken when levels within the drain had increased after tidal inflow. Furthermore, due to dangerous access, very few measurements were taken at 10m upstream in Laughton Highland Drain.

4.3.2 Burringham Reservoir Drain – water level variation

Burringham Reservoir Drain was chosen as a control site. However, during all but the spring-open survey, the water level in the drain rose significantly, even with the flap valve closed. This was attributed to the action of the pumping station located on the reach (section 3.3.2) transferring water from surrounding drains into Burringham Reservoir Drain. This change in level mostly occurred midway through the survey and always when the main flap valve was shut and no inflow of water from the River Trent could occur.

Despite the increase in flow depths only minor changes in salinity were recorded and turbidity was unaffected. The major impact of increasing depth was to force the flap valve open slightly earlier on the ebb tide, allowing outflow to begin sooner. However, since there were only minor changes in salinity and no changes in turbidity the use of the drain as a control site remained valid.

5 Results

The results of the surveys are presented below for each drain using an array of time series plots. On these plots the determinands measured at each measurement site (section 4.1.2) are plotted against the time from the start of the survey (Table 4.1), each measurement site being illustrated as a single line on the plot. The tidal cycle is detailed on the background of each graph, with the flood tide (the period between ebb slack and flood slack) displayed as a light grey background and the ebb tide (the period between flood slack and ebb slack) displayed as a dark grey background.

In addition the approximate time which the flap valves on each drain were noted to have closed on the flood tide and opened on the ebb tide are marked as small squares at the top of each plot (and marked as 'Closed' and 'Open' in the plot legend).

The clear trends in the data collected, which are visible over the entire period of survey at all sites, show that the sondes were operating correctly. This provides significant confidence in the measurements and the conclusions derived from them.

5.1 Burringham Reservoir Drain – control site

Burringham Reservoir Drain was chosen as a control site in order to understand how a drain with a flap valve without a fish access structure responded.

5.1.1 Salinity

Analysis of spring-open and neap-open data

Figures 5.1 and Figure 5.2 display the trends in salinity measured in Burringham Reservoir Drain during the spring and neap tides respectively. During this period the fish access structures at each of the other drains were activated.

Salinity levels measured in Burringham Reservoir Drain during the spring-open (Figure 5.1) and neap-open (Figure 5.2) surveys were largely invariant, averaging 0.76ppt for the spring-open survey and 0.53ppt for the neap-open survey – essentially freshwater to brackish water.

Spring-open

During the spring-open survey, salinity from 50m to 250m upstream of the penstock remains constant throughout the entire survey at ~0.79ppt (Figure 5.1), with the inflow or outflow of water to and from the drain having no impact. At 0m and 10m away from the penstock, salinity is lower at 0.66ppt, similar to that measured in the River Trent. After closure of the flap valve at ~50 minutes, salinity at both sites climbs towards ~0.81ppt at 203 minutes, slightly higher than further upstream, before declining again towards 0.66ppt until the end of the survey. The initial rise noted at 0m and 10m is attributed to the cessation of inflow due to closure of the flap valve, preventing continual dilution. The subsequent decline, in contrast to the salinity measured upstream between 50m to 250m, suggests that leakage through the structure is causing dilution of the water in the drain.

The flap valve was noted to be open at ~560 minutes (towards the ebb slack), although this did not noticeably affect the salinity at any measurement site.

Figure 5.1 Salinity measured in Burringham Reservoir Drain during the spring-open survey

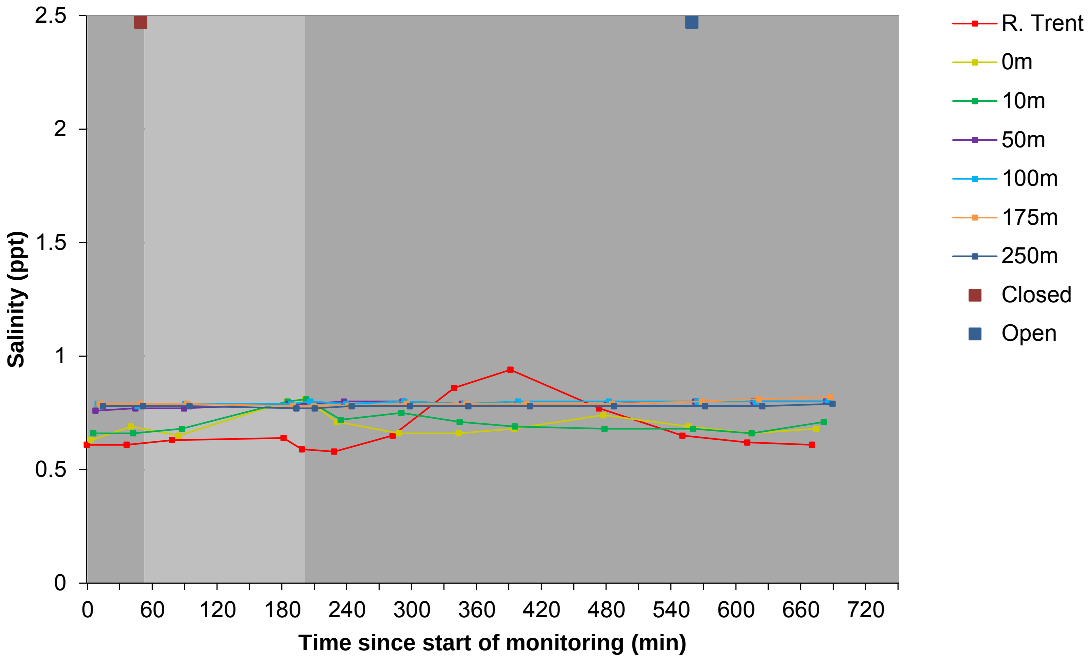
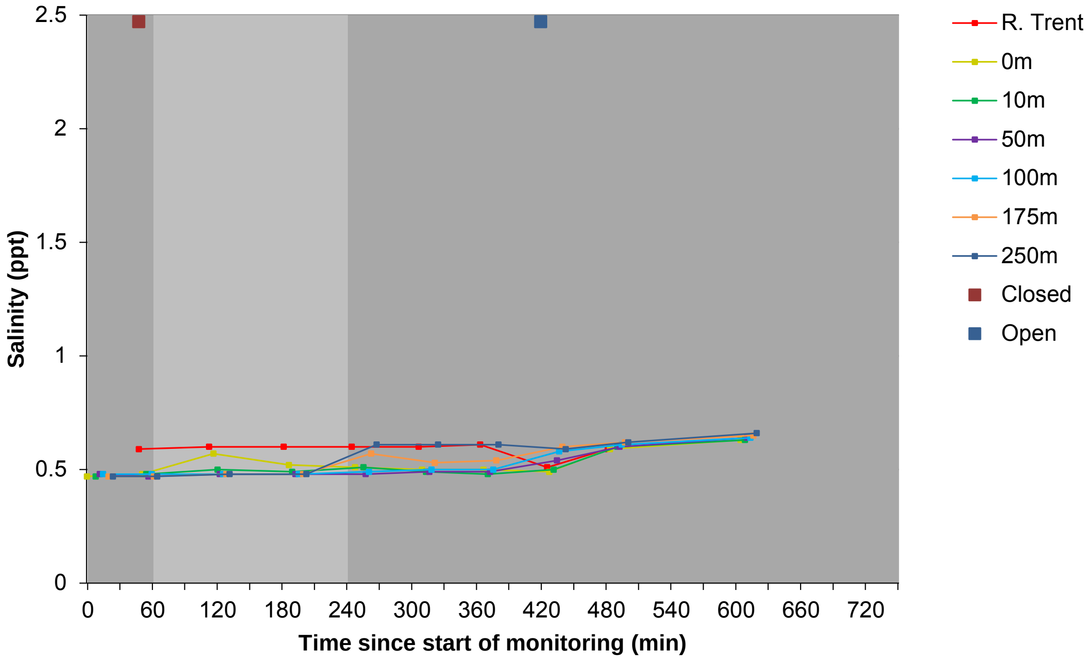


Figure 5.2 Salinity measured in Burringham Reservoir Drain during the neap-open survey



Neap-open

During the neap-open survey (Figure 5.2), salinity measured ~0.48ppt throughout the drain prior to the start of the flood tide at ~50 minutes. The flap valve was noted to have shut very rapidly (at ~50 minutes, essentially closed with the rising tide), with very little inflow into the drain noted. The slight increase in salinity at 0m, towards a peak of 0.57ppt at 117 minutes, is likely to be linked with the small volume of inflow to the drain before closure of the flap valve and leakage through it (given the similarity between the peak measurement of salinity at 0m and that in the River Trent, ~0.59ppt). Thereafter, at 0m, salinity declines towards 0.48ppt.

It is notable that salinity at 175m and 250m increases (~0.60ppt at 265 minutes) despite the flap valve being shut and no evidence of the upstream movement of an area of increased salinity. At this time the level within the drain was notably higher than at the start, due to the operation of a pumping station upstream (sections 3.3.2 and 4.3.1). This could have drawn water of increased salinity into the drain, accounting for the noted increases.

At ~420 minutes the flap valve was observed to have opened, allowing flow out of the drain and causing the salinity to vary. Unusually, and in contrast to most salinity measurements during the study, salinity increases above its pre-flood levels to ~0.63ppt. It is possible that this reflects the input of more saline water due to the action of the pumping station upstream.

Analysis of spring-closed and neap-closed data

Figures 5.3 and 5.4 display the trends in salinity measured in Burringham Reservoir Drain during the spring and neap tides respectively. During this period the fish access structures at each of the other drains were deactivated. Both spring-closed (Figure 5.3) and neap-closed (Figure 5.4) surveys show little variation in salinity levels throughout the drain over an entire survey.

Spring-closed

Throughout the spring-closed survey (Figure 5.3) salinity measured at sites 50m to 250m was relatively invariant at ~0.80ppt. Salinity at sites 0m and 10m declined from 0.80ppt to minima of 0.59ppt at 323 minutes and 0.60ppt at 444 minutes respectively. Although the flap valve had been noted to have shut at ~150 minutes, the offset between the minima for the 0m and 10m sites is taken to represent the slow movement upstream of both initial inflow prior to closure of the valve as well as leakage (particularly as salinity in the River Trent was measured at ~0.40ppt). Salinity measured at 0m and 10m increased to ~0.80ppt rapidly after the flap valve opened at 508 minutes, further suggesting that leakage through the structure was a contributing factor to varying salinity at these sites.

Neap-closed

Throughout the neap-closed survey (Figure 5.4), salinity was generally invariant at ~0.71–0.77ppt throughout the drain. The flap valve was noted to close at ~30 minutes and open again at ~530 minutes. Most variation in salinity occurred at the 0m and 10m sites in the period between the closure and opening of the flap valve. This, coupled with the rapid closure of the flap valve and limited ingress of water from the River Trent, suggests that variation in salinity can be attributed to leakage through the valve.

Figure 5.3 Salinity measured in Burringham Reservoir Drain during the spring-closed survey

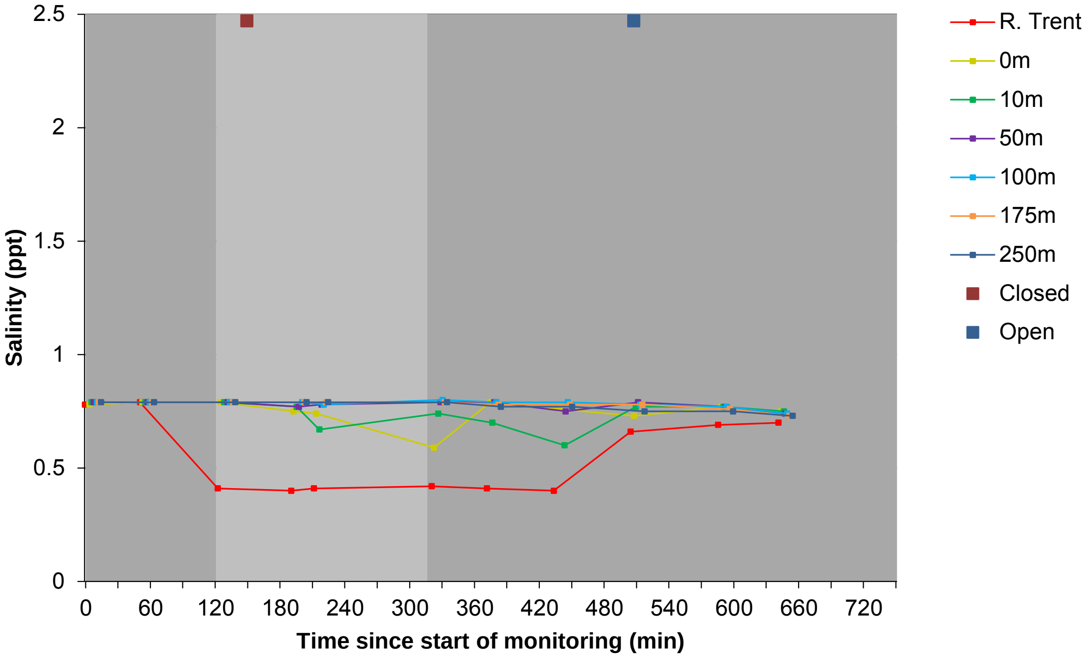
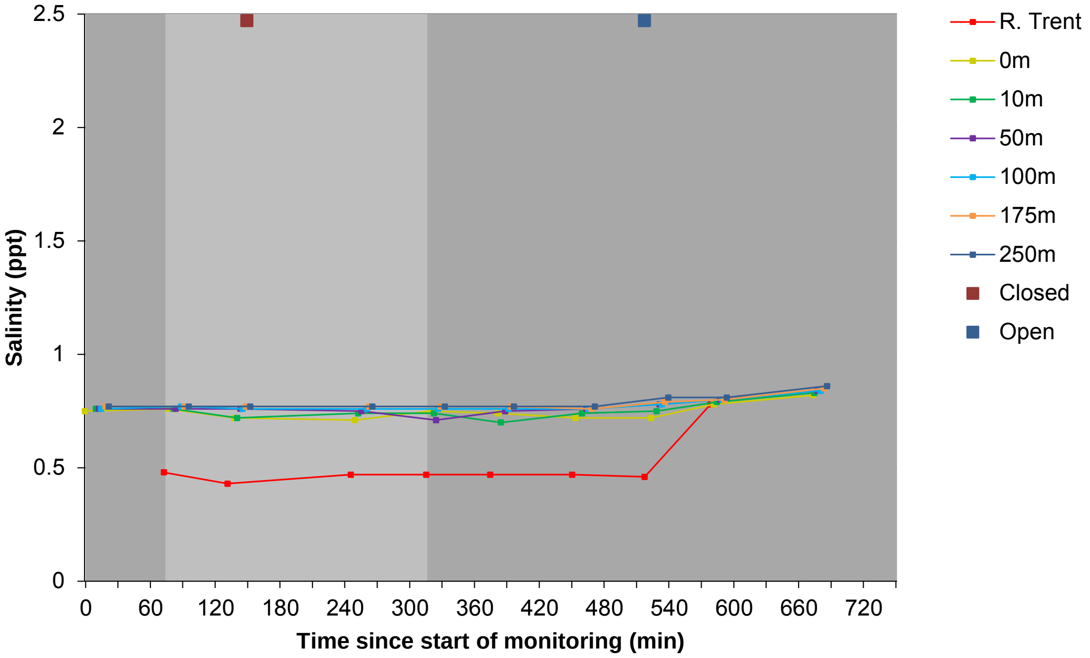


Figure 5.4 Salinity measured in Burringham Reservoir Drain during the neap-closed survey



5.1.2 Turbidity

Analysis of spring-open and neap-open data

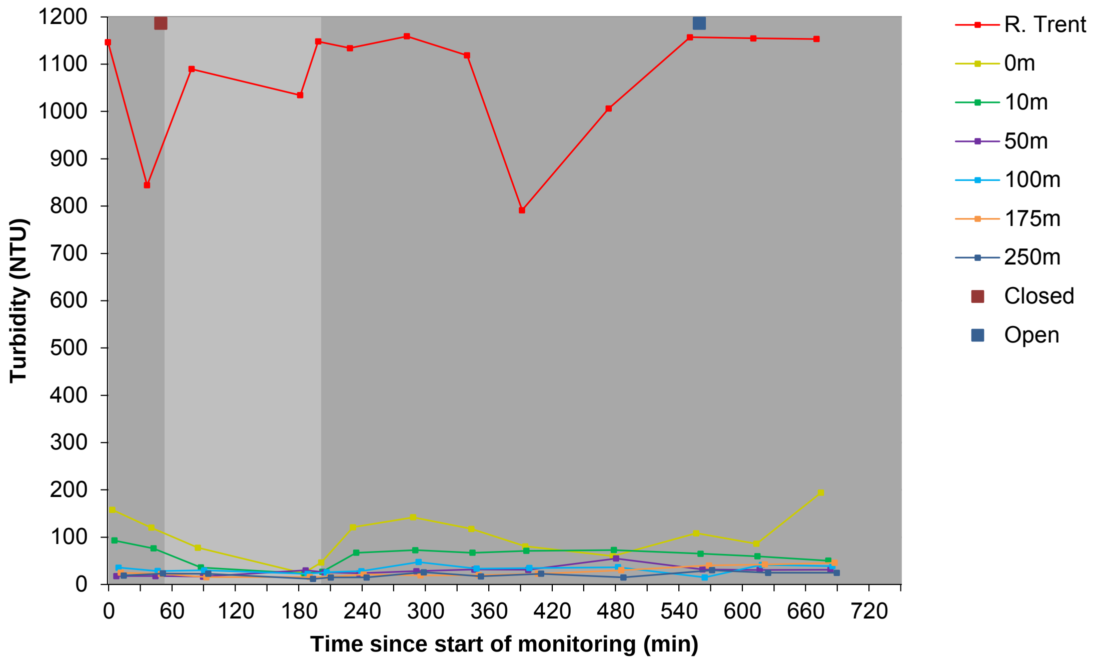
Figures 5.5 and 5.6 display the trends in turbidity measured in Burringham Reservoir Drain during the spring and neap tides respectively. During this period the fish access structures at each of the other drains were activated.

Spring-open

Turbidity measured within Burringham Reservoir Drain during the spring-open survey (Figure 5.5) shows a general trend of low turbidity throughout the drain, with 18–55NTU measured at the 50m to 250m sites, increasing slightly to 71–194NTU at the 0m to 10m sites.

When water was flowing out of the drain (ebb slack tide), prior to the closure of the flap valve at 50 minutes, turbidity measured at 0m and 10m was relatively high (188NTU and 93NTU at six minutes respectively) compared with further upstream (around 18NTU). Turbidity measured in the River Trent at this time was1146NTU. Turbidity measured at these sites continued to decline until after the closure of the flap valve. The elevated values at 0m and 10m during the outflow period are attributed to high suspended sediment loads due to downstream flow and re-suspension or re-entrainment of sediment transported into the drain during previous inflow events.

Figure 5.5 Turbidity measured in Burringham Reservoir Drain during the spring-open survey



At ~200 minutes when the flap was closed and there was minimal flow in the drain, increases in turbidity are once again noted at 0m and 10m, which continue until the end of the survey. Given the very high turbidity levels within the River Trent over the monitoring period and the low upstream levels (18NTU at 250m), these elevated levels are directly attributed to the impacts of leakage through the flap valve. After the flap valve opened at ~560 minutes, there is an increase turbidity measured at 0m. This is attributed to movement of unsettled sediment in the water column generated by leakage. Turbidity between 50m to 250m remains low and relatively invariant throughout the survey at 18–55NTU.

Turbidity levels within the River Trent were very high during the survey (800–1,100NTU) but had relatively little influence on turbidity within the drain, the only influence being due to leakage.

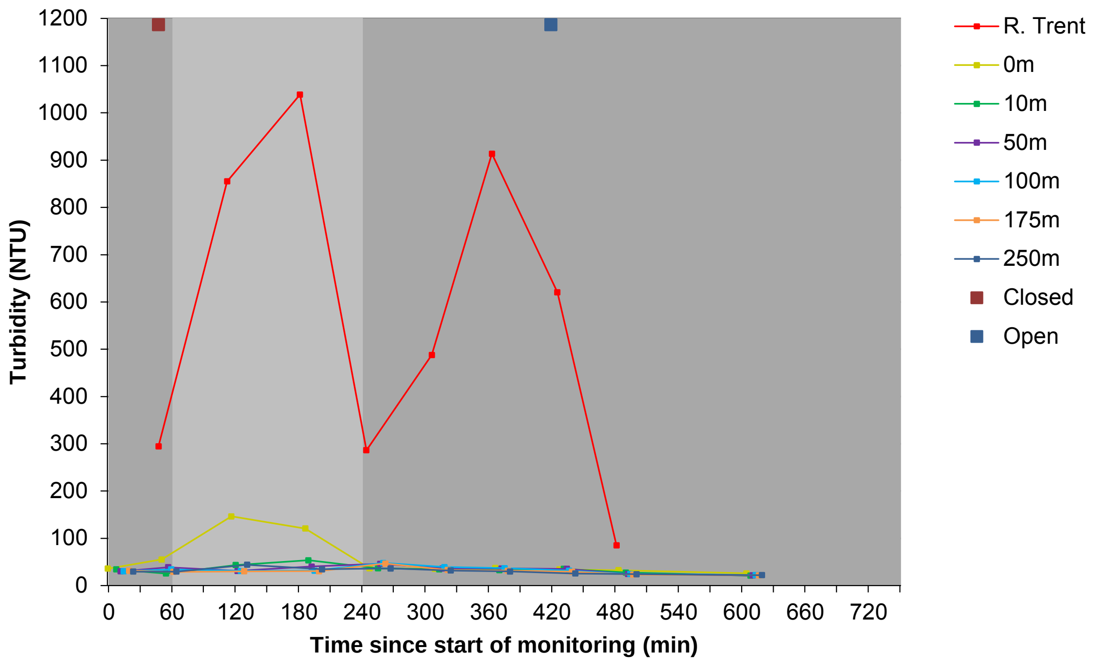
Neap-open

Turbidity measured within Burringham Reservoir Drain during the neap-open survey (Figure 5.6) shows similar trends to the spring-open survey, with a general trend of low and invariant turbidity throughout the drain, with 30–50NTU measured at the 10m to 250m sites, increasing slightly to a peak of 146NTU at the 0m site. Turbidity values in the River Trent ranged between 85 and 1,038NTU.

Prior to the closure of the flap valve at 48 minutes, turbidity was seen to increase at 0m to 55NTU at 51 minutes. This initial rise is attributed to increasing suspended sediment entering the drain from the River Trent during the initial stages of the flood tide when water was flowing into the drain prior to closure of the flap valve. There is a continual rise after closure of the valve to an initial peak of 146NTU at 117 minutes, followed by a decrease towards 250 minutes. Similarly, between 121 minutes and 200 minutes, a rise in turbidity was noted at 10m. The rises at both 0m and 10m are attributed to the impact of leakage through the structure.

With the exception of slight increase in turbidity between 121 minutes and 200 minutes, turbidity remains invariant throughout the drain between 10m to 250m during the entire survey.

Figure 5.6 Turbidity measured in Burringham Reservoir Drain during the neap-open survey



The bimodal response in turbidity within the River Trent during the survey (Figure 5.6) is due to the tidal cycle, with both peaks occurring during the highest flow velocities in the flood and ebb tidal periods when most sediment will be in transport. This response is not seen in the River Trent during the spring-open survey during which turbidity levels remained high throughout, perhaps reflecting the additional energy of the system during the spring tide. Despite the elevated levels in turbidity, the River Trent exerted no significant influence on turbidity within the drain apart from due to leakage.

Analysis of spring-closed and neap-closed data

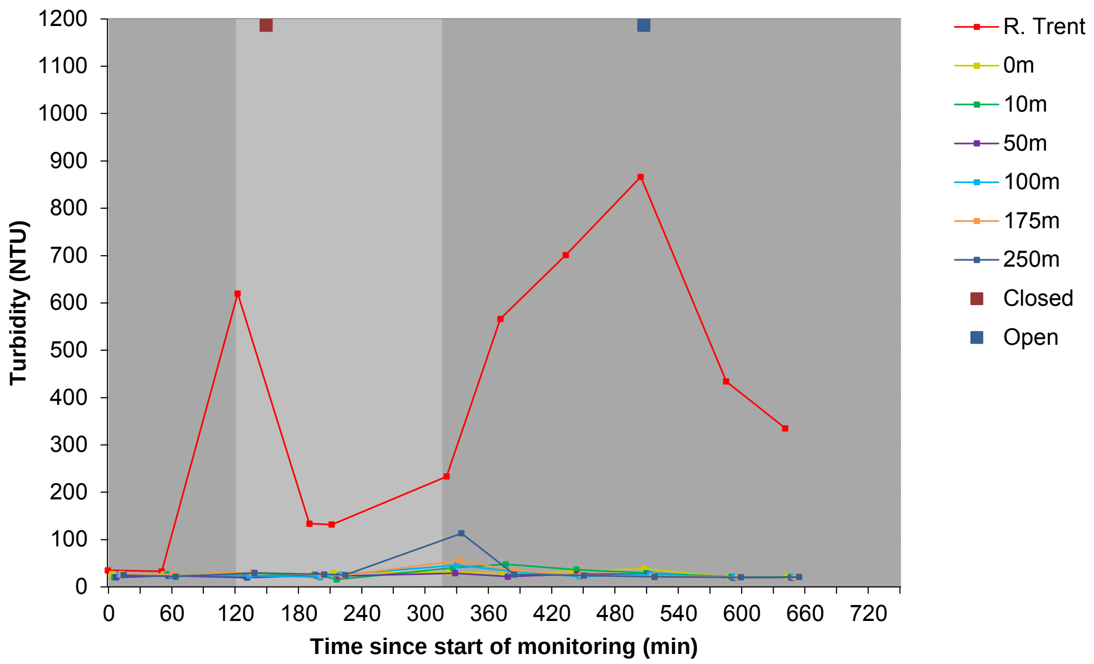
Figures 5.7 and 5.8 display the trends in salinity measured in Burringham Reservoir Drain during the spring and neap tides respectively. During this period the fish access structures at each of the other drains were deactivated.

Turbidity levels within Burringham Reservoir Drain during the spring-closed survey (Figure 5.7) and neap-closed survey (Figure 5.8) are similar to those measured during the spring-open survey (Figure 5.5) and neap-open survey (Figure 5.6), but show even less variation in turbidity within the drain.

Spring-closed

During the spring-closed survey (Figure 5.7), turbidity varied little throughout the drain, measuring between 20 and 56NTU. The only variation from the trend was noted when turbidity climbed to 113NTU at 335 minutes. Given there are no other values at this level before, during or after the time period, it is likely that this represents disturbance of the bed by the sonde during measurement. The flap valve was noted to close at 150 minutes into the survey and open at 508 minutes, and no changes in turbidity were associated with the opening of closure of the valves.

Figure 5.7 Turbidity measured in Burringham Reservoir Drain during the spring-closed survey

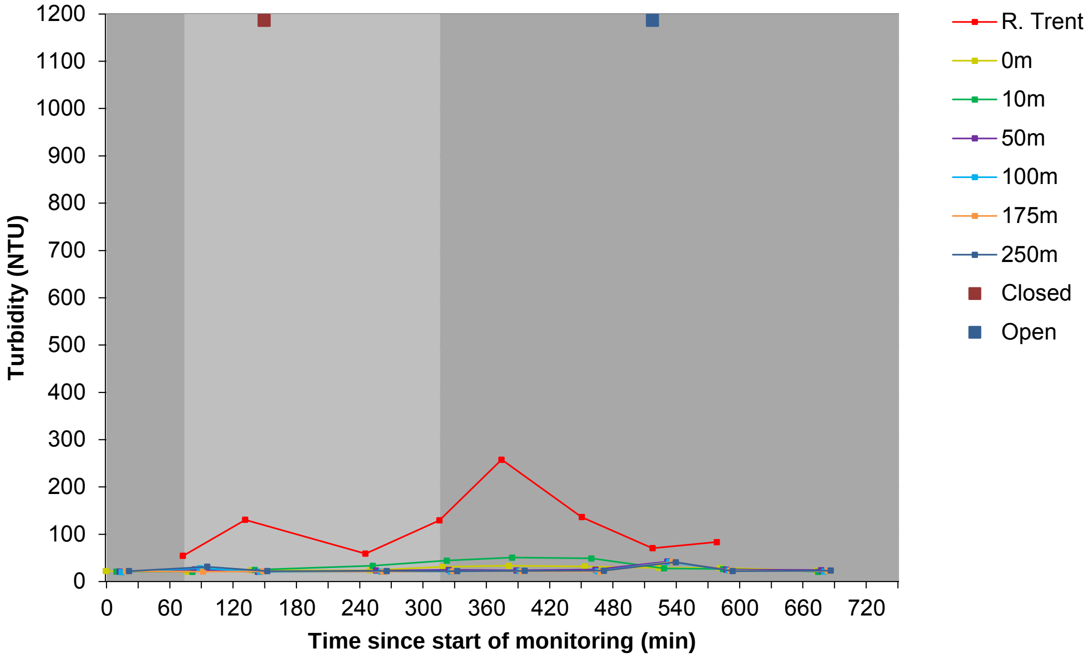


Neap-closed

During the neap-closed survey (Figure 5.8), turbidity was similar to that measured during the spring-closed survey, varying little throughout the drain, measuring between

20 and 50NTU. The flap valve closed at 30 minutes into the survey and opened at 530 minutes. A slight variation in turbidity was noted at the lower sites, 0m to 50m, when the valve opened. This is due to movement of sediment around and immediately upstream of the penstock.

Figure 5.8 Turbidity measured in Burringham Reservoir Drain during the neap-closed survey



Turbidity within the River Trent between spring and neap surveys

Turbidity measured in the River Trent between the spring-open and neap-open surveys (Figures 5.5 and 5.7) and the spring-closed and neap-closed surveys (Figures 5.7 and 5.8) was very different. These differences are due to wider factors occurring between surveys such as:

- varying meteorological conditions
- differences in the spring and neap tides themselves
- changes in sediment dynamics throughout the River Trent and wider Humber estuary.

These differences also account for the differences in variability in turbidity within the drain during the open and closed surveys. Similarly, this is the case with leakage, with higher rates of leakage and changes in turbidity in the drain occurring during the open surveys when turbidity, and hence suspended sediment loads, were higher in the River Trent than during the closed surveys.

5.2 Burton-on-Stather Drain

5.2.1 Salinity

Analysis of spring-open and neap-open data

Figures 5.9 and 5.10 display the trends in salinity measured in Burton-on-Stather Drain during the spring and neap tides respectively, when the ACE fish access structure was activated.

With the exception of step changes in salinity at the start of the flood tide and at around 400 minutes, salinity measured during the spring-open (Figure 5.9) and neap-open (Figure 5.10) surveys were largely invariant, averaging 0.76ppt for both surveys, essentially freshwater to brackish water.

Figure 5.9 Salinity measured in Burton-on-Stather Drain during the spring-open survey

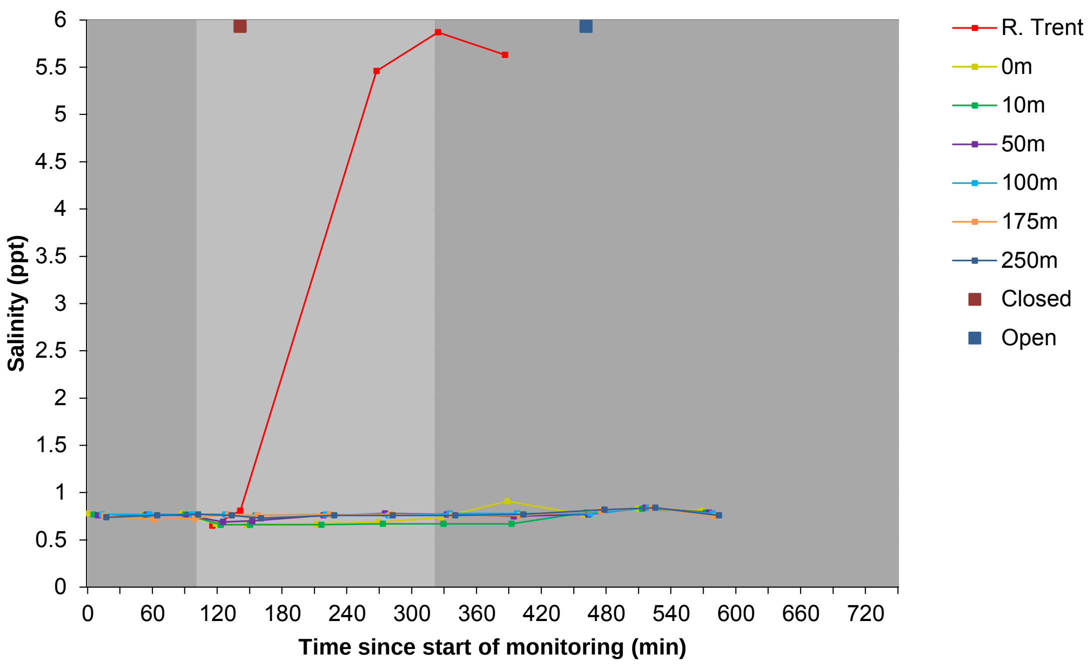
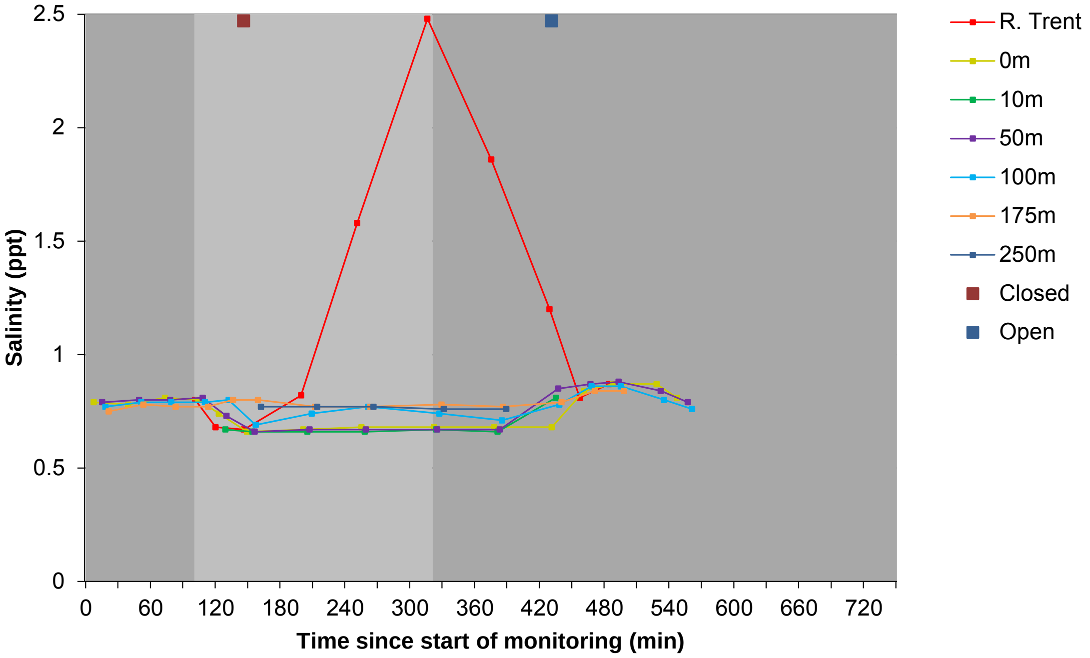


Figure 5.10 Salinity measured in Burton-on-Stather Drain during the neap-open survey



Spring-open

During the spring-open survey (Figure 5.9), salinity measured ~0.76ppt throughout the drain for ~100 minutes prior to the start of the flood tide. At this point salinity declined slightly at the lower sites, 0m to 50m upstream, from 0.76ppt to 0.67ppt, due to the inflow of water from the River Trent (where salinity was also measured at 0.67ppt) and subsequent dilution of water in the drain. At ~142 minutes the flap valve and ACE fish access structure shut. After this, salinity remained invariant from 50m to 250m upstream for the remainder of the survey, the rapid closure of the flap valve and ACE during the rising spring tide preventing the movement of significant levels of estuarine water upstream. Salinity remained at 0.67ppt at 10m until ~460 minutes when it increased and stabilised at the pre-flood tide level. This is attributed to the flap valve and ACE structure opening at 462 minutes and 479 minutes respectively and allowing the drain to begin to flow into the River Trent. Salinity at the 0m site remained unchanged at 0.67ppt until ~270 minutes when salinity measured at this site began to increase to a maximum of 0.91ppt at 389 minutes. Given the higher salinity values recorded in the River Trent at this time (greater than 5ppt) and the fact that the flap valve and ACE structure were shut, this increase is attributed to leakage through the structure.

Prior to the decline in salinity recorded at the 0m and 10m sites at the beginning of the flood tide, salinity in the River Trent was low (0.67ppt). However, immediately after the closure of the flap valve and ACE structure, salinity in the River Trent greatly increased to a peak of 5.87ppt at 325 minutes. This was the largest salinity value recorded throughout the entire study and would have probably caused significant increases in salinity within the drain had the flap valve and ACE not shut.

Neap-open

During the neap-open survey (Figure 5.10), salinity measured ~0.79ppt throughout the drain for ~100 minutes prior to the start of the flood tide. At this point salinity declined at the lower sites, 0m to 50m upstream, from 0.79ppt to 0.67ppt, due to the inflow of water from the River Trent (where salinity was also measured at 0.67ppt) and subsequent dilution of water in the drain. Salinity also declined slightly at 100m from 0.79ppt to 0.69ppt. At ~147 minutes the flap valve and ACE fish access structure shut. After this, salinity remained invariant from at 0m to 50m at 0.67ppt. There was some variation in salinity from 100m to 250m upstream, although this did not significantly deviate from the pre-flood levels. At ~430 minutes the flap valve and ACE structure opened, causing an increase in salinity towards the pre-flood values at all sites other than 0m, where salinity remained slightly lower (0.68ppt at 432 minutes). This is attributed to dilution of the flow at 0m due to outflow of water from the upstream catchment of the drain.

Compared to the spring-open survey (Figure 5.9), a reduction in salinity was noted further upstream in the neap-open survey (50m compared with 10m in the spring-open survey). This reflects the extended period the flap remained open (approximately seven minutes longer), which will have allowed more water to enter the drain and therefore travel further upstream increasing dilution.

Like the spring-open survey (Figure 5.9), salinity in the River Trent was low (0.67ppt). prior to the decline in salinity recorded at the 0m, 10m and 50m sites at the beginning of the flood tide. However, immediately after the closure of the flap valve and ACE structure, salinity in the River Trent greatly increased to a peak of 2.48ppt at 317 minutes, though less than half the salinity observed during the spring-open survey. It is possible that there would have been a significant increases in salinity within the drain had the flap valve and ACE not shut.

Analysis of spring-closed and neap-closed data

Figures 5.11 and 5.12 display the trends in salinity measured in Burton-on-Stather Drain during the spring and neap tides respectively, when the ACE fish access structure was deactivated.

Figure 5.11 Salinity measured in Burton-on-Stather Drain during the spring-closed survey

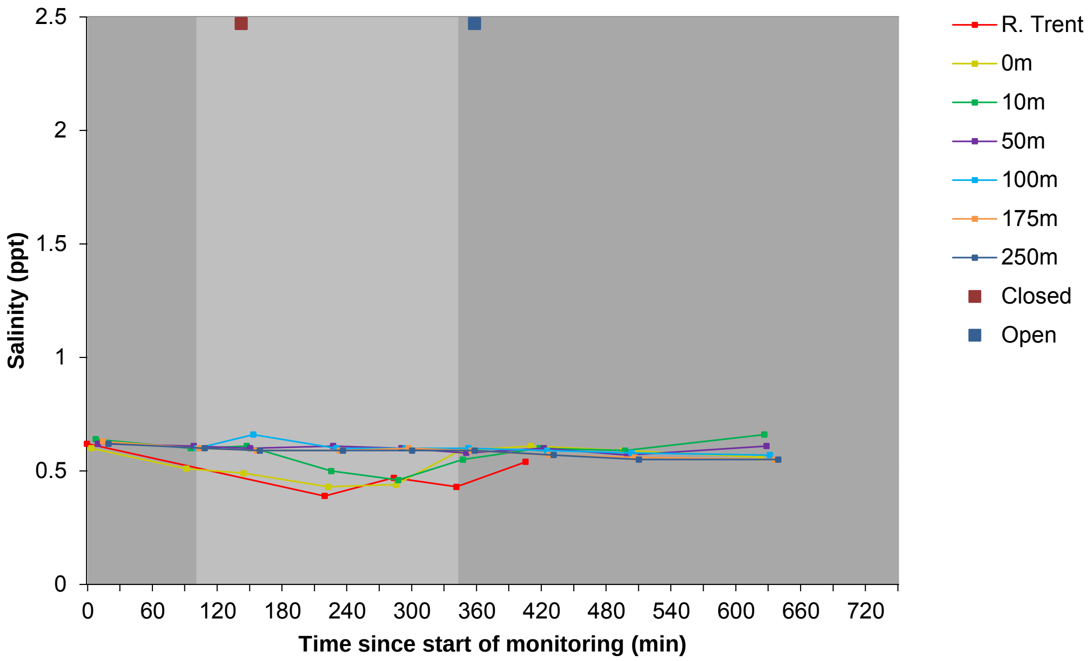
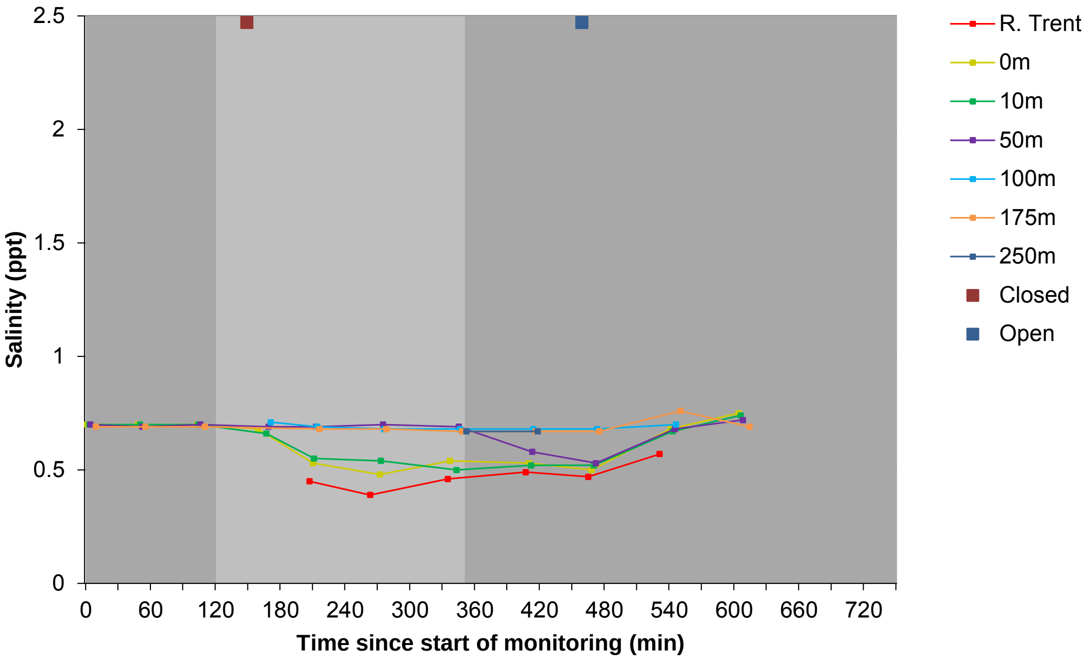


Figure 5.12 Salinity measured in Burton-on-Stather Drain during the neap-closed survey



Both spring-closed (Figure 5.11) and neap-closed (Figure 5.12) surveys showed similar trends in salinity, namely a decrease in salinity from a pre-flood tide level followed by a increases in salinity to pre-flood levels.

Spring-closed

Throughout the spring-closed survey (Figure 5.11) salinity measured at sites 50m to 250m was relatively invariant at ~0.58ppt, with only sites 0m and 10m exhibiting any changes in salinity. Salinity at sites 0m and 10m declined from 0.58ppt to minima of 0.43ppt at 223 minutes and 0.46ppt at 288 minutes respectively. The trends in salinity at 0m and 10m closely followed those measured in the River Trent, highlighting the dilution effect on salinity from the inflow. The flap valve was noted to have shut at 143 minutes, although salinity still continued to decrease, probably due to the volume of water that had entered the drain prior to closure. The offset in the minimum salinity value measured at 10m is attributed to the slow upstream movement of the less saline water input from the River Trent. At both sites salinity is shown to increase towards the pre-flood levels after the flap valve opened at 359 minutes on the ebb tide. This reduction is attributed to the outflow of less saline water from the drain.

Neap-closed

The salinity trends for the neap-closed survey (Figure 5.12) were very similar to those for the spring-closed survey (Figure 5.11). For ~130 minutes prior to the start of the flood tide, salinity measured ~0.70ppt throughout the drain during the neap-closed survey (Figure 5.12). Immediately after the start of the flood tide, salinity at sites 0m and 10m declined from 0.70ppt to minima of 0.48ppt at 273 minutes and 0.50ppt at 344 minutes respectively. The trends in salinity at 0m and 10m followed those measured in the River Trent, which again highlighted the dilution effect on salinity from the incoming flow. The flap valve was noted to have shut at 150 minutes, although salinity still continued to decrease, once again attributed to the volume of water that had entered the drain prior to closure. The offset in the minimum salinity value measured at 50m is attributed to the slow upstream movement of the less saline water input from the River Trent.

A reduction in salinity was noted further upstream in the neap-closed survey than in the spring-closed survey (Figure 5.11). This reflects the extended period the flap remained open (approximately seven minutes longer), which will have allowed more water to enter the drain and therefore travel further upstream, increasing dilution. This trend was also noted during the neap-open survey (Figure 5.10).

At both sites, salinity is shown to increase towards the pre-flood levels after the flap valve opened at 460 minutes during the ebb tide. This reduction is attributed to the outflow of less saline water from the drain.

5.2.2 Turbidity

Analysis of spring-open and neap-open data

Figures 5.13 and 5.14 display the trends in turbidity measured in Burton-on-Stather Drain during the spring and neap tides respectively, when the ACE fish access structure was activated.

Figure 5.13 Turbidity measured in Burton-on-Stather Drain during the spring-open survey

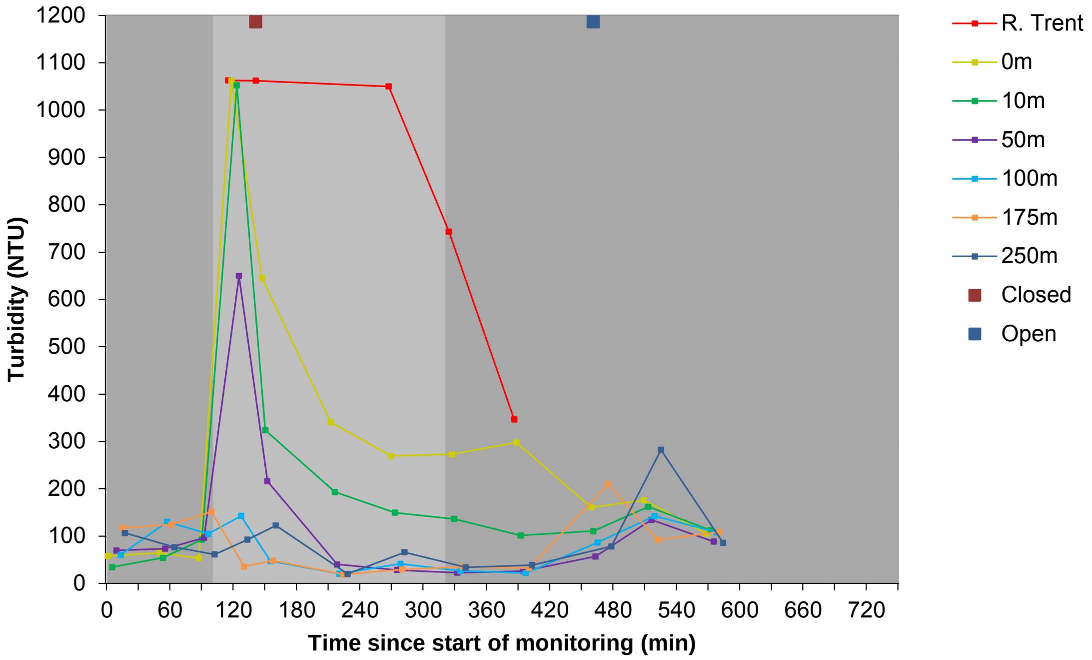
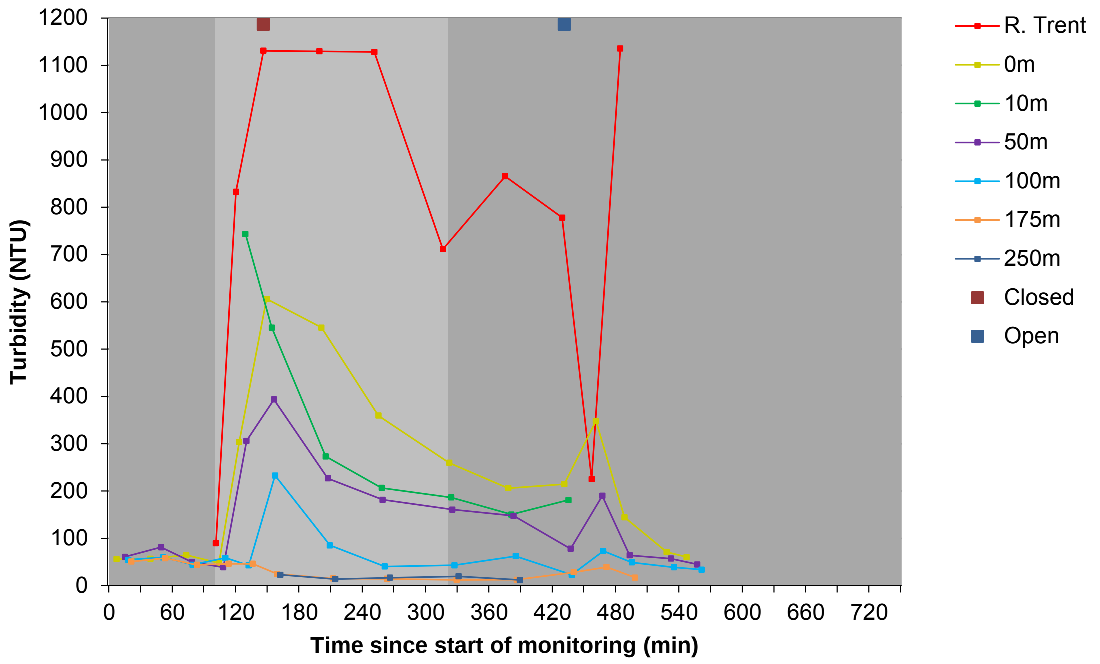


Figure 5.14 Turbidity measured in Burton-on-Stather Drain during the neap-open survey



Spring-open

The spring-open survey (Figure 5.13) displays a general trend of a steep increase in turbidity in the drain during the flood tide from around 100NTU peaking at ~1,000NTU, a value similar to that in the estuary. There is then an initial steep decrease in turbidity followed by a more gradual decrease during the ebb tide back to the values of ~100NTU recorded prior to the flood. The trend is only clear in the drain up to 50m; more upstream survey points show less fluctuation.

During the first 90 minutes of the monitoring period (ebb tide), there was very little variability in turbidity across the 250m measurement site. Turbidity was low at between 40 and 130NTU. At 100 minutes (flood slack), there was a steep increase in turbidity with measurements at 0 and 10m of over 1,000NTU, similar values to those recorded in the estuary. Turbidity also increased at 50m to ~650NTU. However, changes in turbidity upstream of 50m were greatly reduced suggesting the influence of the incoming tide declines rapidly beyond this point. The rapid increase in turbidity indicates that both sediment from the River Trent and scour around the ACE structure and penstock contributed to the increase.

The fish flap and ACE valve were noted as being completely closed at 142 minutes due to the rapid rise of the spring tide. Following the closure, the turbidity measurements in the drain dropped rapidly. The drop in turbidity at 0m was less than at 10m, measured at 645NTU and 323NTU respectively. Turbidity at 50m remained slightly higher than recorded prior to the tidal flood. Turbidity remained high, above 1,000 NTU in the estuary throughout the flood tide. Following the initial steep decline in turbidity in the drain, the decline continued and by 220 minutes turbidity at 50m had returned to the values measured prior to the flood. Turbidity remained elevated at 0m compared to 10m, but both measurements continued to decline until approximately 460 minutes. However, this did not drop as low as pre-flood levels with measurements of approximately 205NTU and 150NTU at 0m and 10m respectively. At the more upstream sampling locations (over 100m) in the drain, by 220 minutes the turbidity had decreased below that measured prior to the flood. This is due to downstream movement of turbid water and replacement with water of reduced turbidity from upstream.

From 400 minutes, turbidity gradually increased across the length of the drain, apart from at the penstock (0m). Following the opening of the valve and fish pass at 462 minutes, the increase in turbidity continued and began to increase around the penstock once again until turbidity peaked at approximately 520 minutes. This increase is attributed to the opening of the flap valve followed by the ACE fish access structure and subsequent outflow of water from the drain, disturbing the bed and settled sediments.

Once the flap valve had opened, the water in the estuary was too low to measure and therefore there are no estuarine measurements for the rest of the ebb tide. The disturbance of the bed and settled sediments could be accentuated upstream in the drain compared with at the flap valve due to discharge from Burton Stather STW. The spike in turbidity at 250m measured at 526 minutes is also indicative of the influence of a discharge on the drain, likely from the STW.

The final measurements at approximately 580 minutes suggest the drain is no longer under tidal influence with little variability along the 250m survey section. Due to the elevation of the drain at Burton compared with the estuary, the flushing out of the drain is rapid taking only 120 minutes. The drain is largely uninfluenced by the tide for some of the tidal cycle.

Neap-open

The neap-open survey (Figure 5.14) displays a similar trend to that observed during the spring-open monitoring (Figure 5.13). There is very little variability in turbidity along the drain during the ebb tide. Following the flood tide there is a steep increase in turbidity from around 100NTU to 600NTU and 700NTU at 0m and 10m respectively. The flap valve noted to have closed at 147 minutes. The increase does not reach the levels measured in the estuary of ~1,100NTU as during the spring-open monitoring. The increase is evident further upstream during the neap-open monitoring than the spring-open with an increase to ~200NTU at 100m.

At the neap tide lower suspended sediment concentrations were expected due to the lower energy of the tide. However, the tidal influence further upstream in the drain during the neap tide could be explained by a slower rise in tide meaning the ACE valve remains open longer.

The peak in turbidity further upstream at 50m and 100m was delayed by approximately 20 minutes. Following this peak there was a more gradual decline compared to that observed during the spring-open monitoring. At 100m the turbidity declined back to values measured during ebb tide by ~260 minutes, at flood slack. Turbidity around the penstock, 10m and 50m, did not decrease back to values measured during the ebb tide, declining to around ~200NTU at ~380 minutes. Turbidity in the estuary remained constantly high during the flood tide (at ~1,100NTU) and began to decline following flood slack.

The valve and fish pass were recorded as open at 432 minutes. Following the opening there is a small rise in turbidity at all sites. This peak is probably due to bed disturbance resulting from the rapid outflow of water from the drain. The scour at the penstock is particularly significant and this scour appears to extend to the estuarine side of the valve. The dramatic peak in turbidity in the estuary recorded at 480 minutes results from the low levels of water that remain around the penstock in the estuary and the high volume of water flowing out of the flap valve and fish access structure creating much disturbance and scour. Following this peak around 480 minutes, turbidity decreases once again to levels around ~80NTU as recorded during the ebb tide prior to the flood.

Analysis of spring-closed and neap-closed data

Figures 5.15 and 5.16 display the trends in turbidity measured in Burton-on-Stather Drain during the spring and neap tides respectively, when the ACE fish access structure was deactivated.

Spring-closed

The spring-closed survey data (Figure 5.15) are in complete contrast to the spring-open survey (Figure 5.16) with turbidity levels significantly reduced.

Levels of turbidity remained fairly constant from the ebb tide through the flood tide for all measurement sites. The same general trends of an increase in turbidity at the start of the flood tide were not observed. Turbidity levels were slightly elevated, between 30 and 50NTU at 0m compared with other survey locations between 0 minutes and ~280 minutes. This elevation is probably due to localised scour, possibly due to leakage around the penstock. A similar trend in turbidity was observed in the estuary with a gradual increase during the flood tide followed by a decrease at flood slack and through the ebb tide. The levels of turbidity were not as high, peaking at 693NTU compared with 1,062NTU in the spring-open survey. The flap valve was noted to have closed at 143 minutes. Lower turbidity levels are likely to be due to less concentrated flows around the penstock, during both inflow and outflow, causing reduced bed disturbance and sediment erosion and entrainment.

There was a spike in turbidity at ~500 minutes for all survey locations, as was observed in the spring-open survey. The flap valve opened at 359 minutes and turbidity began to increase following the opening. This peak is attributed to the rapid flushing (a depth reduction of ~10cm over 10 minutes was observed in the field) of the drain causing bed disturbance. The peak was particularly significant at 175m and 250m suggesting that there were also upstream influences from the STW discharge.

Figure 5.15 Turbidity measured in Burton-on-Stather Drain during the spring-closed survey

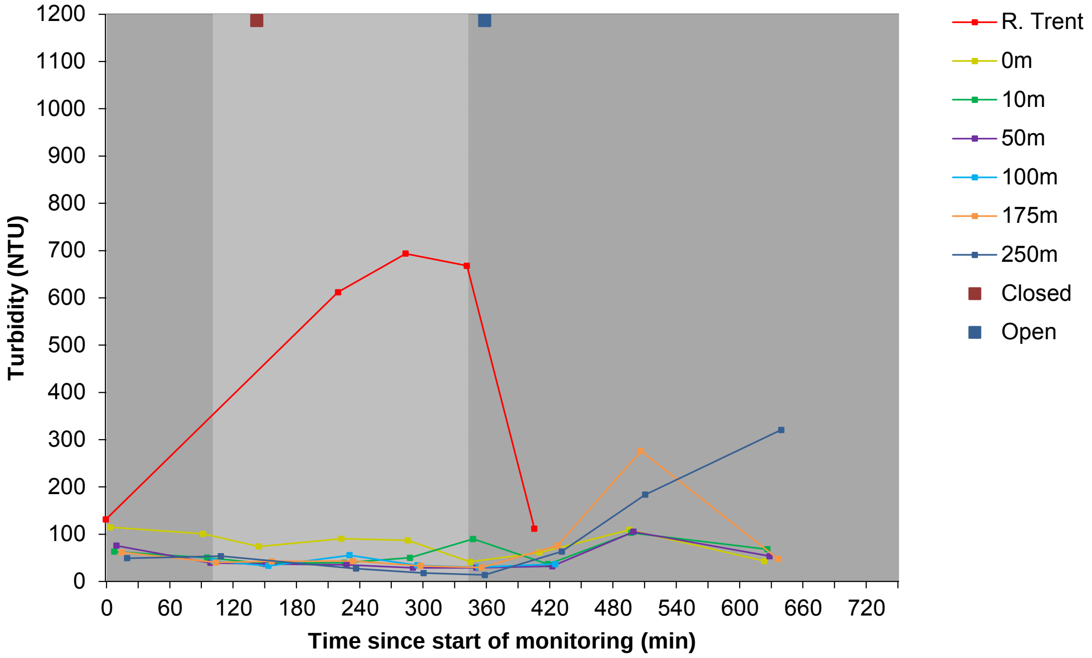
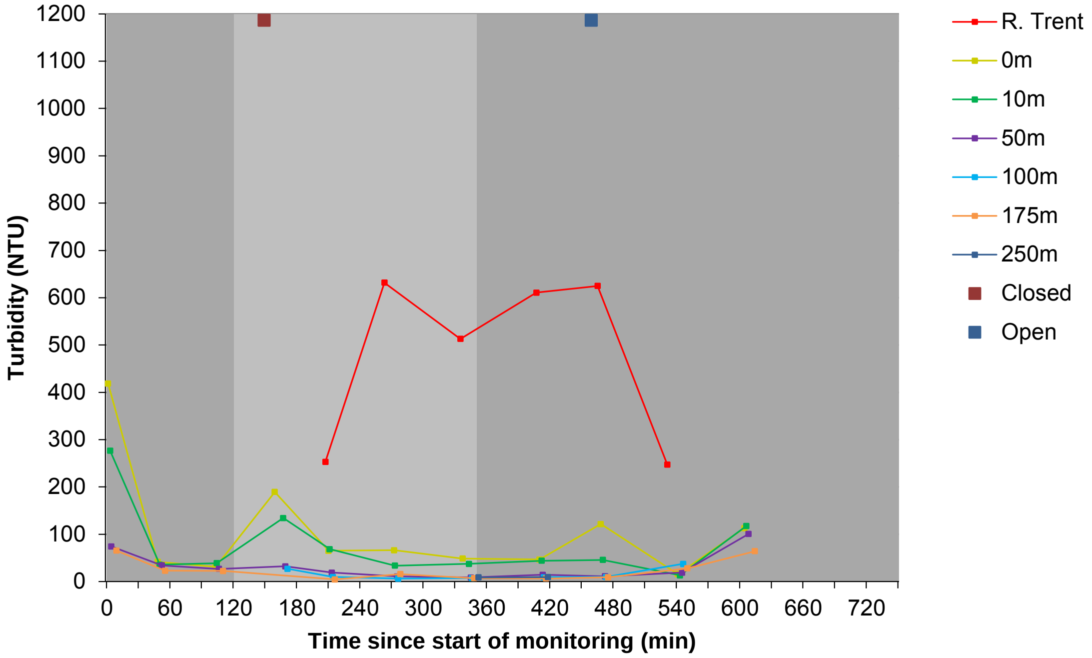


Figure 5.16 Turbidity measured in Burton-on-Stather Drain during the neap-closed survey



Neap-closed

With the exception of the 0m and 10m measurement sites, turbidity measured in the drain at ebb tide during the neap-closed survey (Figure 5.16) were low with little variability, as was observed during the neap-open survey. The high turbidity values of

418NTU and 276NTU at 0m and 10m respectively at the beginning of the survey were localised around the penstock, although a slight elevation further upstream suggests that this was not due to bed disturbance. It is a possible that a plume of sediment travelled down the drain as a result of a discharge from the STW, but this was not observed during field measurements. It can be concluded that this peak is not a result of tidal influence though more data would be required to draw any further conclusions regarding its source.

The flap valve closed at 150 minutes. During the flood tide the same increase in turbidity was observed as for the neap-open survey, although the level of turbidity was less and the extent of the increase upstream limited to measurement sites 0m and 10m. The decrease in turbidity following the peak is gradual with a return the ebb tide value by ~280 minutes. At 460 minutes the valve opened and there was a small peak in turbidity at 0m before turbidity decreased back to the levels recorded prior to the flood. At 600 minutes there was another small peak in turbidity at all measurement sites in the drain. This could also be attributed to the STW as described for the turbidity peak at 0m, but no firm conclusions can be drawn from these data.

Both spring-closed (Figure 5.15) and neap-closed (Figure 5.16) graphs show significantly different trends in turbidity compared with the spring-open (Figure 5.13) and neap-open (Figure 5.14) graphs. Although there are likely to be some differences caused by changes in the magnitude of the tides, the available sediment in the estuary and changes in flow in the drain, it is highly unlikely that these variables can account for the differences measured. In this case it is very probable that the ACE fish access structure is responsible for the differences.

At 0m the peak turbidity measured during the spring-open survey was 1,062NTU compared with 100NTU at the spring-closed survey. Similarly, for the neap-open survey, a peak turbidity of 606NTU at 0m was recorded compared with 189NTU for the neap-closed survey. This suggests that ~91% of the turbidity levels recorded when the ACE was active on the spring tide and ~69% on the neap tide were related to the action of the ACE.

Upstream influence of the ACE fish access structure

Both spring-closed (Figure 5.15) and neap-closed (Figure 5.16) graphs show significantly different trends in turbidity compared with the spring-open (Figure 5.13) and neap-open (Figure 5.14) graphs. Although there are likely to be some differences caused by changes in the magnitude of the tides, the available sediment in the estuary and changes in flow in Burton-on-Stather Drain, it is highly unlikely that these variables can account for the differences measured. In this case it is very probable that the ACE fish access structure is responsible for the majority of the differences.

At 0m the peak turbidity measured during the spring-open survey was 1,052NTU, decreasing to 115NTU during the spring-closed survey. Similarly, for the neap-open survey, a peak turbidity of 545NTU was recorded at 0m, decreasing to a peak of 418NTU during the neap-closed survey (although most values are below 200NTU). This suggests that ~90% of the turbidity levels recorded during the spring surveys and ~25% of the turbidity levels recorded during the neap surveys in the Burton-on-Stather Drain when the ACE fish access structure was active are very probably related to the action of the ACE. Given that the average turbidity within the drain during the neap-closed surveys was mostly below 200NTU, it is likely that the influence of the ACE during the neap surveys could be significantly higher.

During the spring-open survey the upstream limit of observed changes in turbidity was >250m, decreasing to 250m during the spring-closed survey. During the neap-open and neap-closed surveys, the upstream limits were 250m and 50m respectively. This suggests that ingress of sediment into the drain could occur 200m further upstream of the penstock when an ACE fish access valve is fitted compared with the standard flap valve.

5.3 River Eau

5.3.1 Salinity

Analysis of spring-open and neap-open data

Figures 5.17 and 5.18 display the trends in salinity measured in the River Eau during the spring and neap tides respectively, when the Stoneman fish access structure was activated.

Salinity levels during both the spring-open (Figure 5.17) and neap-open (Figure 5.18) surveys were largely invariant, ranging between 0.54ppt and 0.61ppt and averaging 0.57ppt, essentially freshwater to brackish water.

There are no apparent trends associated with the opening or closing of the Stoneman or flap valve in the spring-open survey. During the neap-open survey, salinity values are shown to increase from 0.54ppt to 0.62ppt at the start of the flood tide when estuarine water is flowing into the drain, increasing salinity over its pre-flood tide value of 0.54ppt. Salinity remained at and around 0.62ppt until ~550 minutes when it began to decrease toward 0.56ppt and pre-flood tide levels. This probably represents the outflow of estuarine water from the River Eau and the replacement of this water by freshwater from upstream. It is important to note that the salinity in the drain is almost identical to that in the River Trent.

Figure 5.17 Salinity measured in the River Eau during the spring-open survey

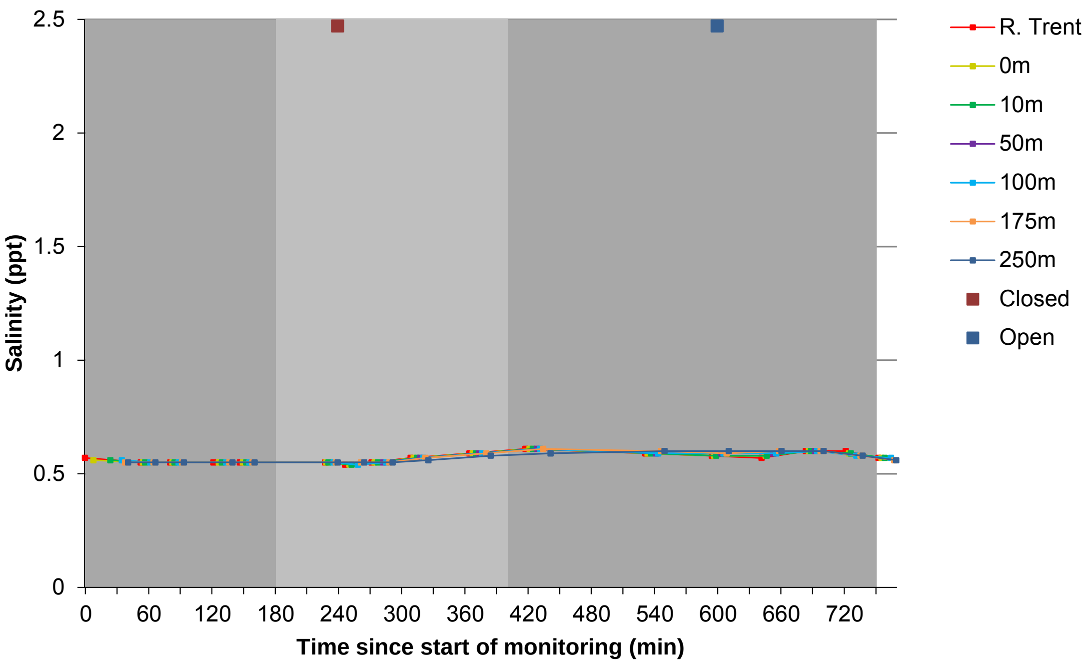
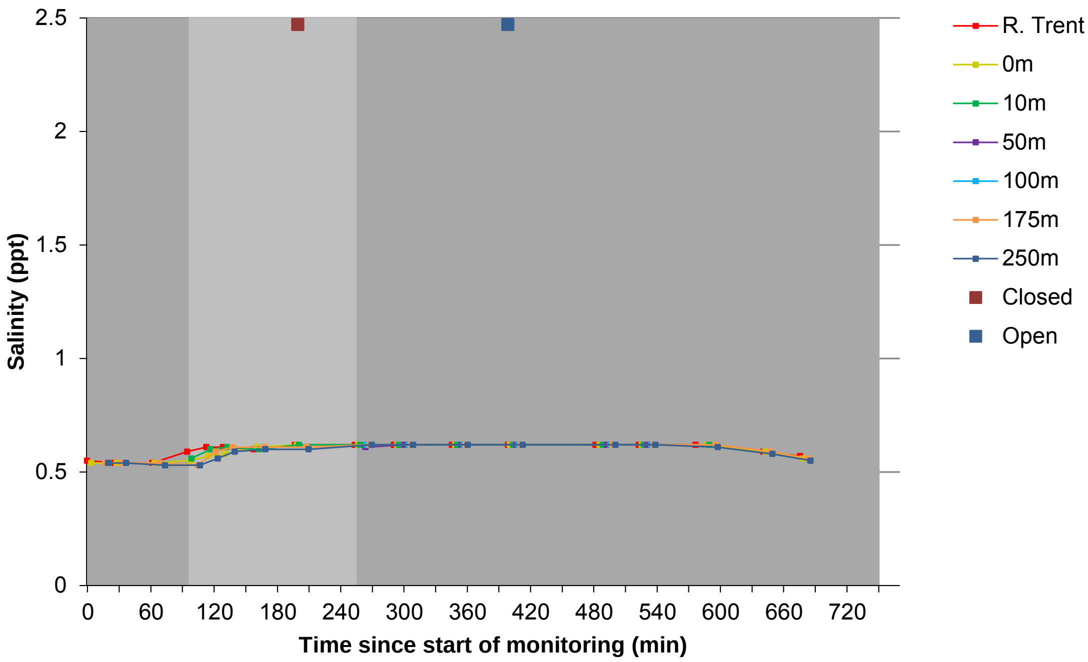


Figure 5.18 Salinity measured in the River Eau during the neap-open survey



Analysis of spring-closed and neap-closed data

Figures 5.19 and Figure 5.20 display the trends in salinity measured in the River Eau during the spring and neap tides respectively, when the Stoneman fish access structure was deactivated.

Figure 5.19 Salinity measured in the River Eau during the spring-closed survey

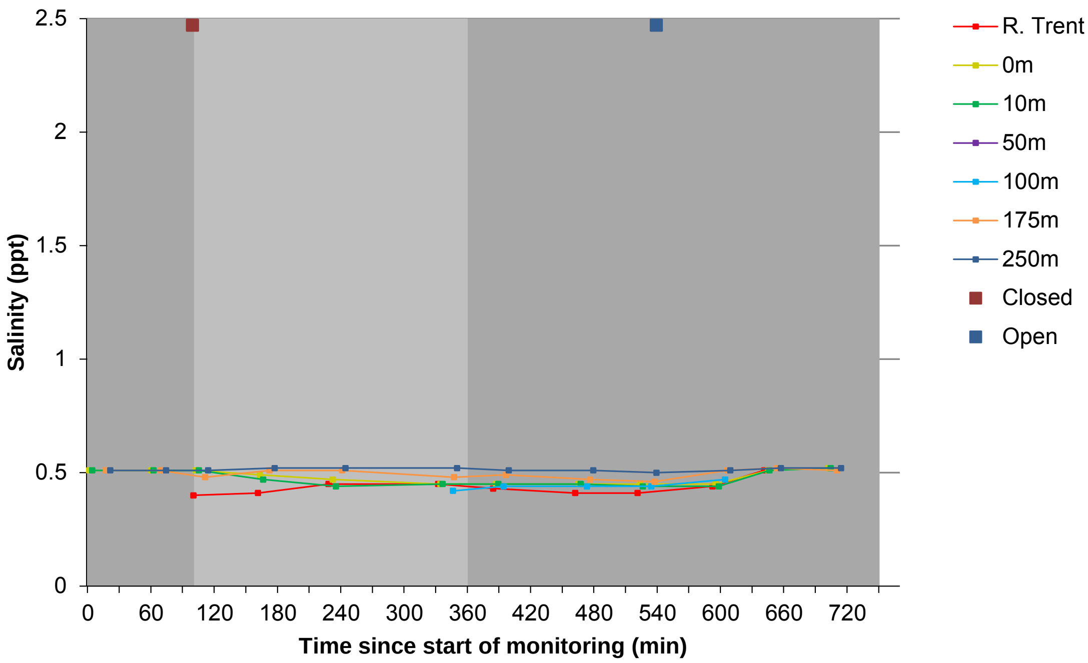
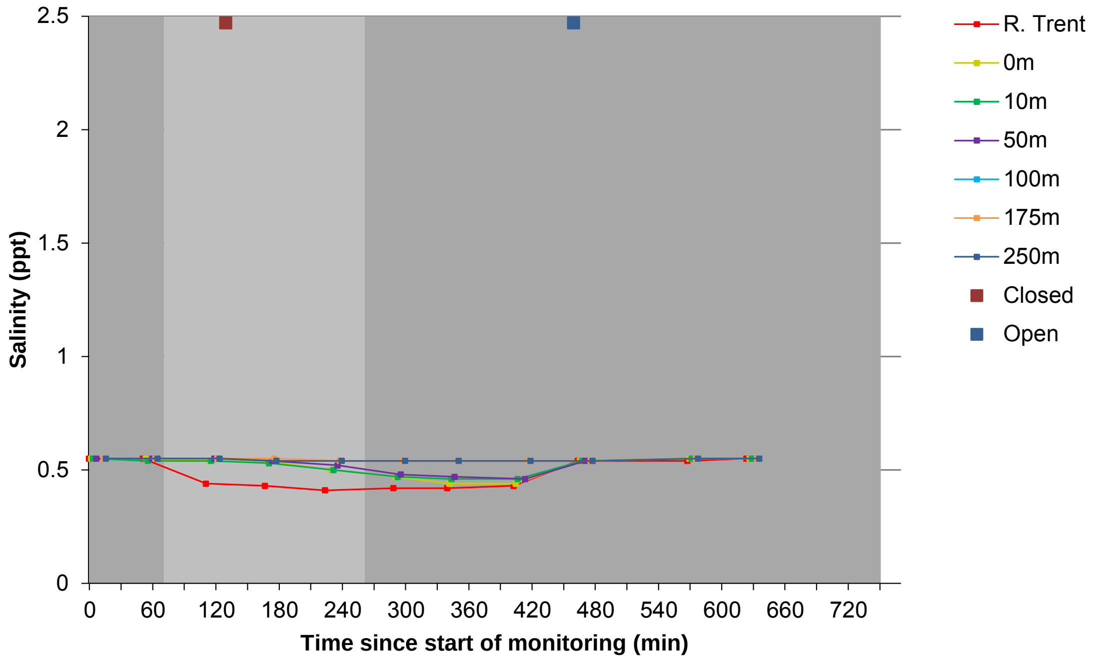


Figure 5.20 Salinity measured in the River Eau during the neap-closed survey



Salinity levels during both the spring-closed (Figure 5.19) and neap-closed (Figure 5.20) surveys ranged between 0.40ppt and 0.52ppt, lower than measured in the River Eau during the spring-open and neap-open surveys.

Spring-closed

Prior to the flood tide, Figure 5.19 shows that salinity within the River Eau at all sites (0m to 250m) was measured at 0.51ppt while salinity in the River Trent was measured at 0.41ppt. At the start of the flood tide, salinity in the River Eau between 0m to 100m decreased rapidly toward 0.41ppt. This suggests that the inflow of water from the River Trent, prior to the flap valve shutting, increased dilution of water in the River Eau, reducing salinity. At around ~540 minutes, when the flap valve reopened and the outflow to the River Trent began, salinity climbs back to its pre-flood tide level of 0.51ppt. Salinity measured at 175m upstream is higher than that measured between 0m and 100m (at 0.47ppt), while at 250m upstream, salinity remained essentially invariant over the whole monitoring period at 0.51ppt, suggesting that the upstream extent of the impact begins to decline after 100m.

Neap-closed

Figure 5.20 shows the same trend in salinity as Figure 5.19, although the decrease in salinity in the River Eau is much less rapid with salinity at 0m and 10m only approaching that in the River Trent (0.43ppt) at 400 minutes, long after the flap valve has shut. This suggests that these reductions in salinity are due not only to the initial input of water from the estuary causing dilution of water in the River Eau but also to extensive leakage through the penstocks and tidal structure itself. These reductions in salinity are also confined to the first 50m of the river and are not manifest further upstream, further supporting dilution by leakage. Salinity returned to pre-flood levels around 430 minutes. This is attributed to the opening of the flap valve and outflow of the lower salinity water from the River Eau.

5.3.2 Turbidity

Analysis of spring-open and neap-open data

Figures 5.21 and 5.22 display the trends in turbidity measured in the River Eau during the spring and neap tides respectively, when the Stoneman fish access structure was activated.

Figure 5.21 Turbidity measured in the River Eau during the spring-open survey

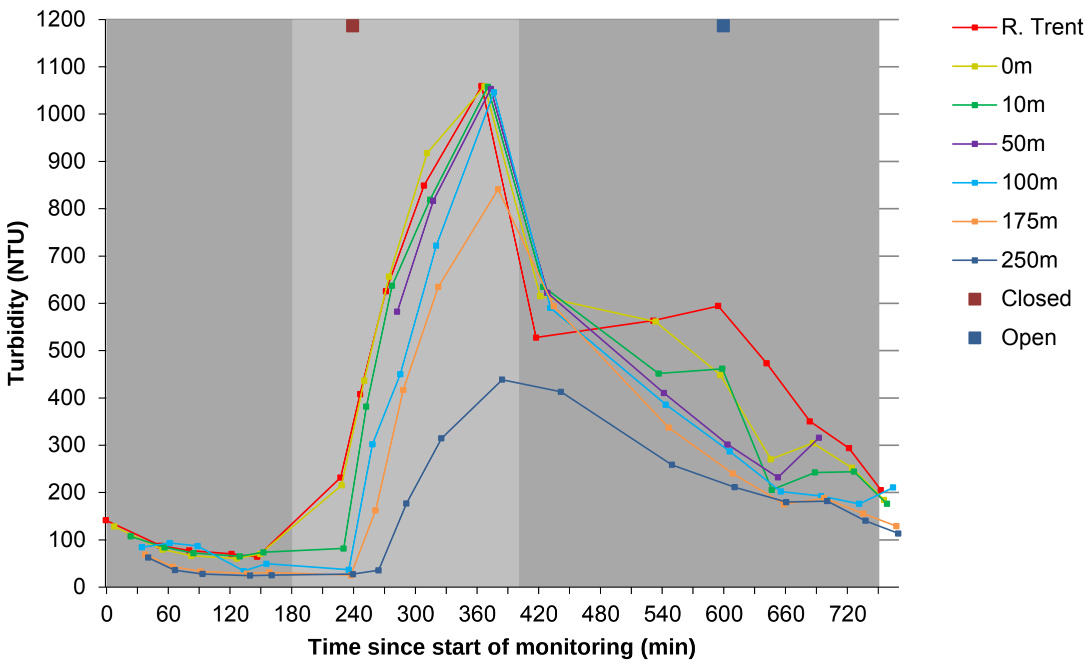
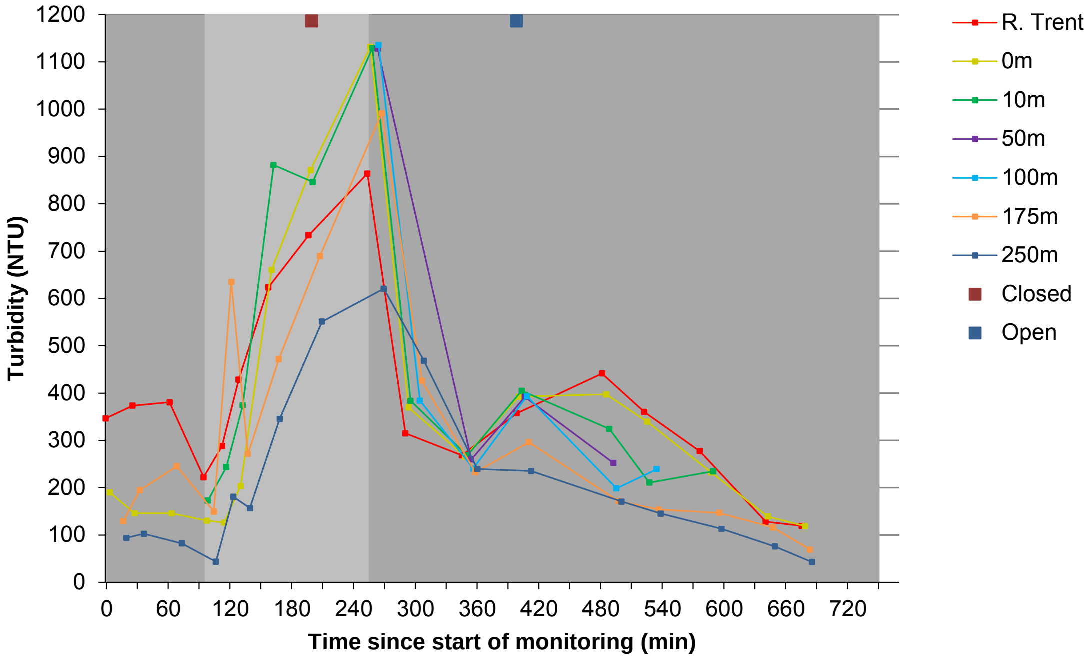


Figure 5.22 Turbidity measured in the River Eau during the neap-open survey



Spring-open

Figure 5.21 displays a general trend of a steep rise in turbidity during the flood tide, from around 150NTU, peaking around the start of flood slack at ~1,100NTU, and then a gradual decrease in turbidity during the ebb tide to turbidity measurements of around 200NTU at ebb slack. This trend is apparent at all measurement sites, although the trend is subdued slightly at 250m.

Prior to commencement of the flood tide at ~160 minutes, turbidity values ranged from 147NTU in the River Trent and at 0m to 25NTU at 250m upstream. Upon commencement of the flood tide, water rapidly flowed into the drain, causing a rapid increase in turbidity up to a maximum of 1,059NTU recorded in the River Trent and at the 0m to 100m measurement sites. The initial rapid rate of increase in turbidity between 160 minutes to 240 minutes at 0m and 10m, coupled with the fact that the rate of increase in turbidity was similar to that in the River Trent, suggests that both sediment input from the River Trent and scour around the penstock contributed to the very high levels of turbidity observed.

During the survey it was noted that the Stoneman concentrated flow into a turbulent jet, which was directed up the channel that contributed to bed scour. At around 240 minutes the Stoneman fish access structure and flap valve were noted as having closed, although turbidity was still increasing due to both the volume of sediment input through the Stoneman and flap valve and the amount of re-entrained sediment due to scour from the inflowing water. The closures of the Stoneman and flap valve were rapid due to the rapid rise of the spring tide. Lower rates of increase in turbidity during the incoming flood tide were noted for the 175m and 250m measurement sites, these peaking at 841NTU and 439NTU respectively. Although this reflects their distance upstream, their elevated levels above the pre-flood tide values show that the influence of the inflowing tidal water and scour near to the penstock was rapidly transferred upstream.

Immediately after peak turbidity was recorded, values declined to around 590NTU at ~430 minutes at all measurement sites between 0 and 175m. This decrease represents the settling of coarser sediment particles from the flow as well as the influence of flow moving downstream from unaffected upper reaches. The elevated turbidity levels noted around 0m at ~500 minutes (560NTU compared with 451NTU at 10m) are due to the larger concentration of fine sediment which has not settled out of suspension. In addition, these elevated levels may also be due to constant re-suspension of sediment via leakage through the penstocks.

This decline in turbidity continued for these measurement sites until around 600 minutes when an increase in turbidity is noted at survey points 0m and 10m from ~270NTU to 315NTU. These increases are related to opening of the flap valve and Stoneman resulting in additional scour of the previously disturbed bed and settled sediments as the water begins to flow out of the River Eau and into the River Trent.

Despite having being draining out for nearly 200 minutes, turbidity levels within the River Eau by the end of the spring-open survey were still above those recorded prior to the flood tide and inflow of water into the River Eau, that is, 140–250NTU compared with 25–147NTU. This suggests that, under incipient conditions, it may take longer than a single tidal cycle for sediment within the River Eau to either be evacuated from the river or to settle out of suspension.

Neap-open

Figure 5.22 displays a relatively similar trend in turbidity during the neap-open monitoring to that observed during the spring-open monitoring (Figure 5.21) except for the sharp decrease in turbidity noted after the peak at around 300 minutes. There was a steep rise in turbidity during the flood tide, from around 150NTU, peaking around the start of flood slack at ~1,100NTU, followed by a rapid decrease in turbidity to ~240NTU. This was followed by subsequent increases in turbidity as the Stoneman and flap valves opened and began to drain out during the ebb tide. It is important to note that deposits of mud, particularly in marginal bars, had increased markedly between the spring-open and neap-open surveys. This suggests that large volumes of sediment had entered the River Eau between the open and closed surveys and that these had not been re-entrained and transported back into the River Trent during outflow.

Prior to commencement of the flood tide at ~90 minutes, turbidity values ranged from 220NTU in the River Trent, 130NTU at 0m and 44NTU at 250m upstream. These values are slightly higher than those shown in Figure 5.21 recorded prior to the inflow of the spring flood tide (and could possibly be related to the earlier inference about the time the River Eau requires for sediment to be evacuated or settled). Upon commencement of the flood tide, water rapidly flowed into the drain causing a rapid increase in turbidity up to a maximum of 1,059NTU recorded between the 0m and 100m measurement sites. In contrast, turbidity values recorded in the River Trent were significantly lower than those recorded at 0m to 100m in the River Eau (846NTU). This is also in significant contrast to the data recorded during the spring-open survey.

The difference indicates that much of the suspended sediment in the River Eau that was recorded at 0m to 100m is derived from bed scour, in addition to input from the River Trent. Reduced suspended sediment concentrations are expected during the lower energy neap tides, but the increase in scour in the River Eau is possibly related to the lower energy and slower rise of the neap tide, allowing the Stoneman and flap valve to shut later than on a spring tide. This increases the volume and length of time water could flow though the structures and into the River Eau, consequently maintaining a high level of scour. The concentration of flow into a jet by the Stoneman noted during the spring-open survey still occurred during the neap-open survey, although the apparent strength of the jet had declined. At around 200 minutes, the Stoneman and flap valve shut (having possibly been open for 15–20 minutes longer than during the spring tide).

Lower rates of increase in turbidity during the incoming flood tide were noted for the 175m and 250m measurement sites, these peaking at 991NTU and 620NTU respectively (Figure 5.22). The lower rate of increase reflects their distance upstream, although the measured turbidity is significantly higher than observed during the spring-open survey (841NTU and 439NTU respectively). This is likely to be related to the increased time over which the Stoneman and flap valves were open compared with the spring-open survey, allowing water to flow into the drain and drive the suspended sediment scoured from around the penstock and derived from the River Trent, further up the River Eau.

Immediately after peak turbidity was recorded at ~265 minutes, values declined sharply to around 355–425NTU at ~305 minutes at all measurement sites between 0m and175m, although turbidity at 250m upstream remains slightly elevated for longer. This decrease represents the settling of coarser sediment particles from the flow. A further decline in turbidity to around 240NTU follows at ~360 minutes and is noted at all sites between 0m and 250m. At ~400 minutes an increase in turbidity was recorded at sites between 0m and 100m, increasing from ~240NTU to ~390NTU. These increases are caused by the Stoneman and flap valve opening and additional scour of the previously disturbed bed and settled sediments as the water begins to flow out of the River Eau and into the River Trent. It should be noted that opening occurred up to ~60–100 minutes earlier than during the spring tide. In contrast to observations during the spring-open survey, turbidity values measured at all survey points at the end of the neap-open survey had returned to levels seen prior to the flood tide. This is possibly indicative of the longer period when water could flow out of the River Eau due to the flap valve being open for longer.

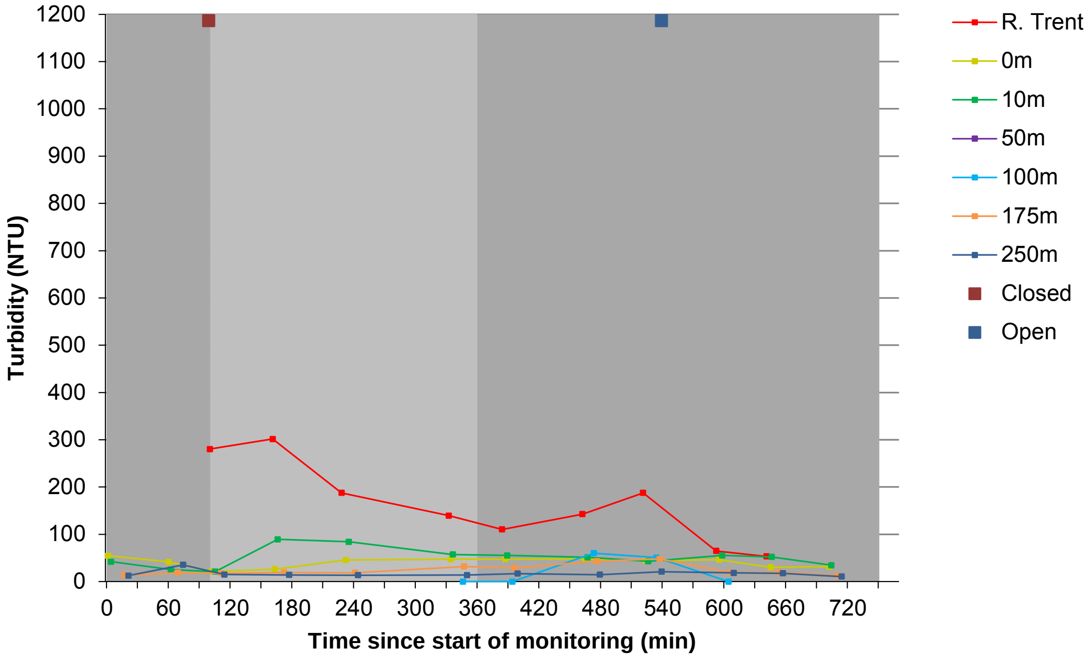
Passage of sediment past 250m upstream during spring-open

In addition to measurements taken up to 250m upstream, measurements of turbidity were also taken at 50m intervals up to 550m upstream. For clarity these are not shown on Figure 5.21. However, the data show that at ~520 minutes, 80 minutes before the Stoneman and flap valve opened on the ebb tide, turbidity levels measured 190NTU at 550m upstream, being 523NTU higher than those recorded at 250m prior to the flood tide and the inflow of water into the River Eau. This increase is caused by the upstream passage of a turbid plume through the generally slack water of the River Eau over the survey period. If this value is extrapolated (noting the decline in turbidity measured over the survey section) it suggests that the upstream impact on turbidity during the inflow of tidal waters could extend up to ~800m during a spring-open scenario.

Analysis of spring-closed and neap-closed data

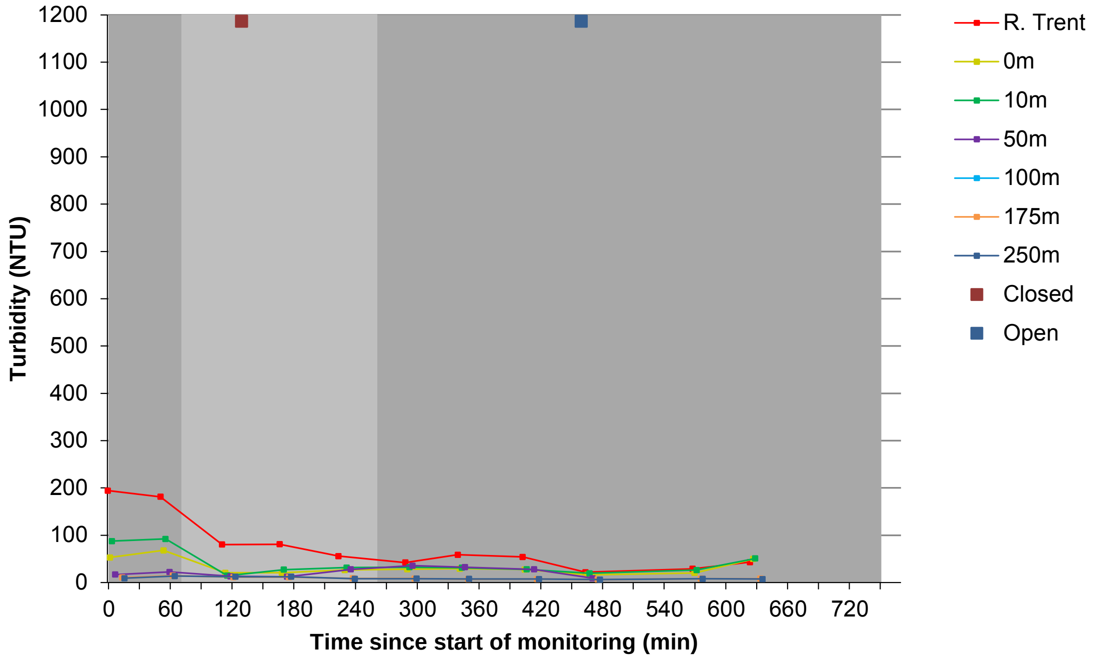
Figures 5.23 and 24 display the trends in turbidity measured in the River Eau during the spring and neap tides respectively, when the Stoneman fish access structure was deactivated (section 4.1.1).

Figure 5.23 Turbidity measured in the River Eau during the spring-closed survey



1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Turbidity (NTU)
0
60
120
180
240
300
360
420
480
540
600
660
720
Time since start of monitoring (min)
R. Trent
0m
10m
50m
100m
175m
250m
Closed
Open

Figure 5.24 Turbidity measured in the River Eau during the neap-closed survey



Spring-closed

The levels shown in Figure 5.23 are in distinct contrast to those from the spring-open survey (Figure 5.21), with turbidity reduced by a significant amount. However, the graphs still possess the same general trend, albeit very subdued. This is a rise in turbidity during the flood tide, peaking around the start of flood slack and then decreasing during ebb slack. On the whole turbidity values are very low, not exceeding 100NTU at any of the measurement sites.

Prior to commencement of the flood tide at ~100 minutes, turbidity values ranged between 40NTU at 0m and 12NTU at 250m upstream (Figure 5.23). No sample could be taken in the River Trent as it was too low and the water surface could not be accessed from the bankside. Upon commencement of the flood tide water flowed into the drain and the flap valve shut rapidly within a matter of minutes (at ~100 minutes). Turbidity within the drain increased slightly (up to ~100NTU) at sites 0m and 10m, although in the River Trent turbidity was measured at 301NTU (the rising flood tide allowing measurements to be taken in the river). This demonstrates that the suspended sediment within the River Eau was probably entirely derived from the River Trent. Measured turbidity levels at 0m, 10m, 50m and 100m showed slow decreases after the flap valve shut, representing gradual settling of suspended sediment. Turbidity is shown to marginally increase at 175m upstream, from ~20NTU at 200 minutes to 48NTU at 540 minutes. This is attributed to the slow upstream movement of a turbid plume.

At ~540 minutes the flap valve reopened, allowing outflow from the River Eau. This is noted in the data by a small increase in turbidity at that time from ~40NTU to 55NTU at the measurement sites at 0m and 10m (Figure 5.23). After this increase, turbidity fell back to the levels measured before the start of the flood tide.

Turbidity was measured as being higher at 10m than at 0m despite the flap value being shut. This is attributed to the significant leakage through the south penstock group, which was observed to cause sediment laden water to flow into the main channel, entering immediately upstream of the 10m measurement site. This is further supported by the gradual decrease in turbidity measured at 10m between ~180–500 minutes as tidal levels in the River Trent declined and reduced leakage through the penstocks.

Neap-closed

The turbidity levels measured during the neap-closed survey (Figure 5.24) show very low turbidity along the upstream survey section, with most measurement sites showing turbidity around and below 50NTU. Turbidity in the River Trent was also low at the start of the flood tide, measuring around 100NTU. The only significant deviations from this were recorded at 0m and 10m between 0–65 minutes when turbidity was ~100NTU. As the flap valve shut after ~130 minutes this increase in turbidity is postulated to be linked to scour during downstream movement of flow from the drain as flows were slightly elevated on the day of the neap-closed survey compared with previous surveys, due to rain.

No significant increases in turbidity were identified during the inflow of water from the River Trent during the flood tide, with only minor increases in turbidity recorded at 0m and 10m. The flap value opened at around 460 minutes into the survey and was accompanied by a very minor increase in turbidity at 0m and 10m. All variability in turbidity in the River Eau between the time of closing and opening of the flap valve was confined to between 0m and 50m upstream.

Upstream influence of the Stoneman fish access structure

Both spring-closed (Figure 5.23) and neap-closed (Figure 5.24) graphs show significantly different trends in turbidity compared with the spring-open (Figure 5.21) and neap-open (Figure 5.22) graphs. Although there are likely to be some differences caused by changes in the magnitude of the tides, the available sediment in the estuary and changes in flow in the River Eau, it is highly unlikely that these variables can account for the differences measured. In this case it is very probable that the Stoneman fish access structure is responsible for the majority of the differences.

At 0m the peak turbidity measured during the spring-open survey was 1,059NTU compared with 55NTU during the spring-closed survey. Similarly, for the neap-open survey, a peak turbidity of 1,128NTU was recorded at 0m compared with 68NTU during the neap-closed survey. This suggests that ~95% of the turbidity levels recorded in the River Eau when the Stoneman was active are directly related to the action of the Stoneman.

During the spring-open survey the upstream limit of observed changes in turbidity was over 550m from the penstock, decreasing to 175m during the spring-closed survey. During the neap-open and neap-closed surveys, the upstream limits were +250m to 50m respectively. This suggests that significant turbidity ingress could occur 200–550m higher upstream with a Stoneman access valve is fitted compared with a standard flap valve.

5.4 Laughton Highland Drain

5.4.1 Salinity

Analysis of Spring-open and Neap-open data

Figures 5.25 and 5.26 display the trends in salinity measured in Laughton Highland Drain during the spring and neap tides respectively, when the Retarder fish access device was activated.

Apart from two step changes, salinity levels measured during the spring-open (Figure 5.25) and neap-open (Figure 5.26) surveys were largely invariant, ranging between 0.58ppt for both surveys, essentially freshwater to brackish water.

Figure 5.25 Salinity measured in Laughton Highland Drain during the spring-open survey

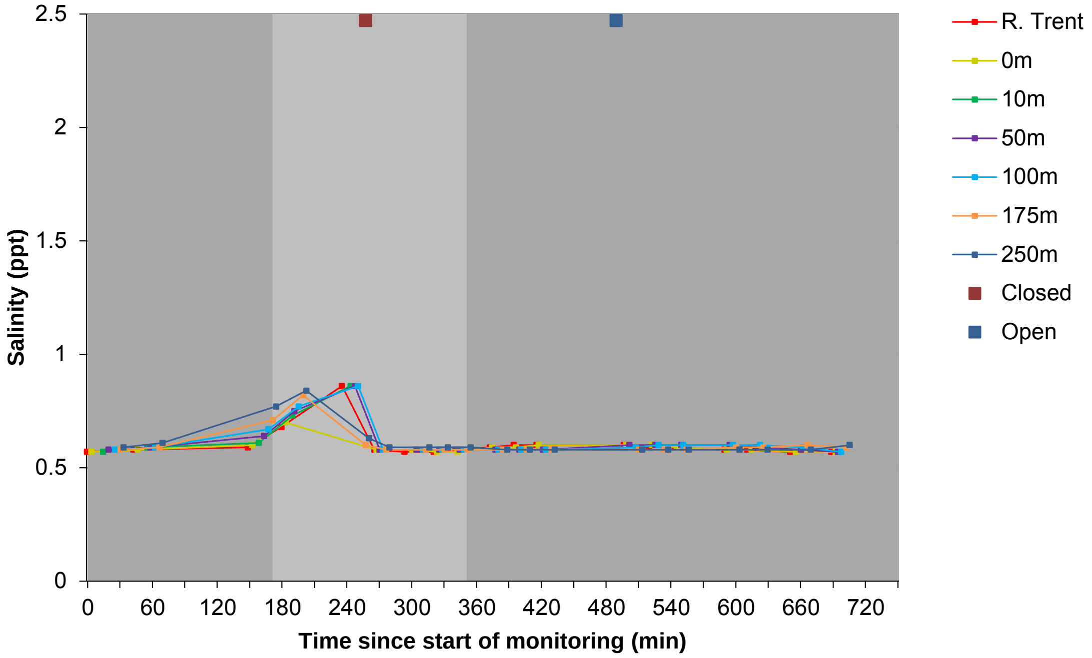
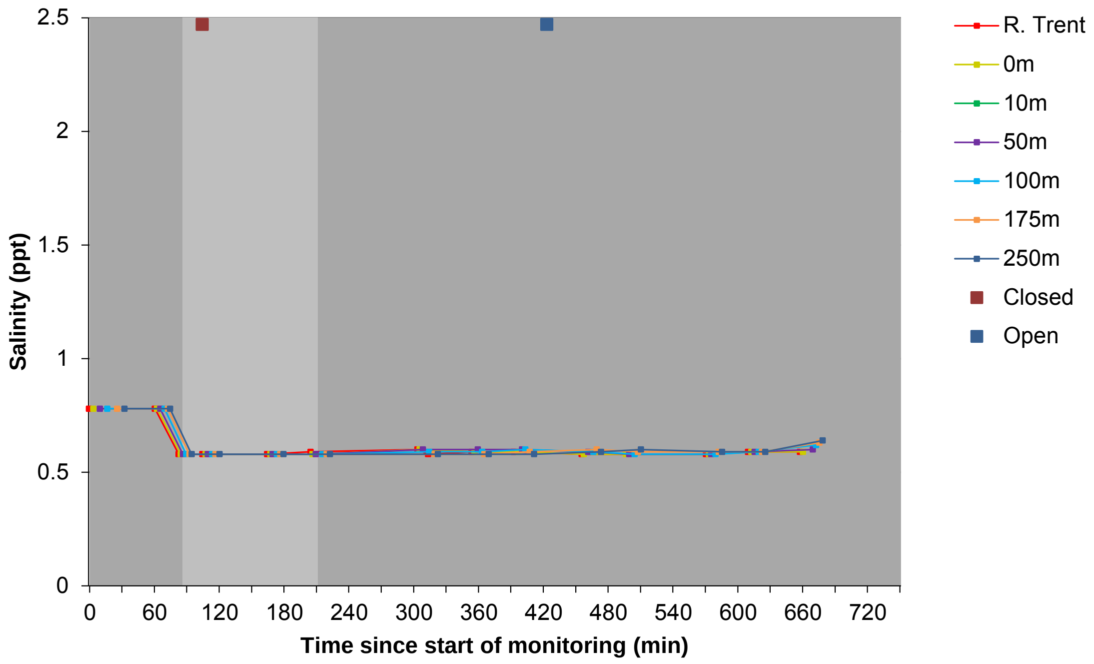


Figure 5.26 Salinity measured in Laughton Highland Drain during the neap-open survey



Spring-open

For ~190 minutes prior to the start of the flood tide, salinity measured ~0.60ppt throughout the drain during the spring-open survey (Figure 5.25). At the start of the flood tide at around 190 minutes, salinity rose at the lower sites, 0m to 100m upstream, from 0.60ppt to 0.86ppt, due to the inflow of water from the River Trent (which also measured 0.86ppt). At ~260 minutes the flap valve shut, after which salinity rapidly declined to ~0.58ppt, slightly below the pre-flood tide level, and remained essentially constant throughout the remainder of the survey. The rapid increase in salinity is attributed to the input of higher salinity water from the River Trent and the following rapid decline in salinity reflects the speed at which the flap valve shut due to the higher energy and rapid rising spring tide, preventing inflow of large volumes of water from the River Trent. The salinity of this water was then diluted by upstream flow. No change in salinity was detected when the flap valve opened at ~490 minutes.

At 200 minutes, prior to the peak in salinity close to the penstock, salinity levels at 175m and 250m upstream were measured as being higher (at 0.84ppt) than those measured at 0m to 100m upstream and also in the River Trent. This suggests that there could be an upstream influence on salinity which was undetected during the survey. Two drains are located perpendicular to Laughton Highland Drain (Figure 3.16, one drain is named East Ferry Ings Drain), ~370m upstream from the penstock and tidal structure. However, no apparent inflow points from these drains to Laughton Highland Drain were observed during a survey on 31 October 2011.

Neap-open

During the neap-open survey (Figure 5.26), salinity in the River Trent and throughout the drain was invariant at ~0.78ppt prior to the start of the flood tide. Salinity was shown to decrease throughout the drain to 0.58ppt as water from the River Trent entered the drain. This decrease ended at ~105 minutes when the flap valve shut. The decrease is due to dilution. The timing of the decrease in salinity suggests that the upstream progression of the inflowing tidal water took ~12 minutes to reach the 250m measurement site. After the decrease, salinity remained invariant at 0.58ppt for all sites in the drain and the River Trent. No change in salinity was detected when the flap valve opened at ~420 minutes.

The decrease in salinity recorded prior to the closure of the flap valve is unusual in that the decrease in salinity is noted in both the drain and the River Trent concurrently. This could potentially be related to the displacement of more saline waters in the River Trent by the incoming tide, although no vertical changes in salinity were noted in the River Trent at this point when measurements were taken.

At around 670 minutes (Figure 5.26) there is a rise in salinity between 50m to 250m upstream from 0.58ppt to ~0.64ppt. As there is no longer a tidal influence to the drain, this increase is attributed to outflow of lower saline waters from the drain or be due to an influx of higher salinity waters from upstream.

Analysis of spring-closed and neap-closed data

Figures 5.27 and 5.28 display the trends in salinity measured in Laughton Highland Drain during the spring and neap tides respectively, when the Retarder fish access device was deactivated.

Both spring-closed (Figure 5.27) and neap-closed (Figure 5.28) surveys showed similar trends in salinity, namely a decrease in salinity from a pre-flood tide level which is shown to propagate upstream, after which salinity increases towards the pre-flood tide salinity levels.

Figure 5.27 Salinity measured in Laughton Highland Drain during the spring-closed survey

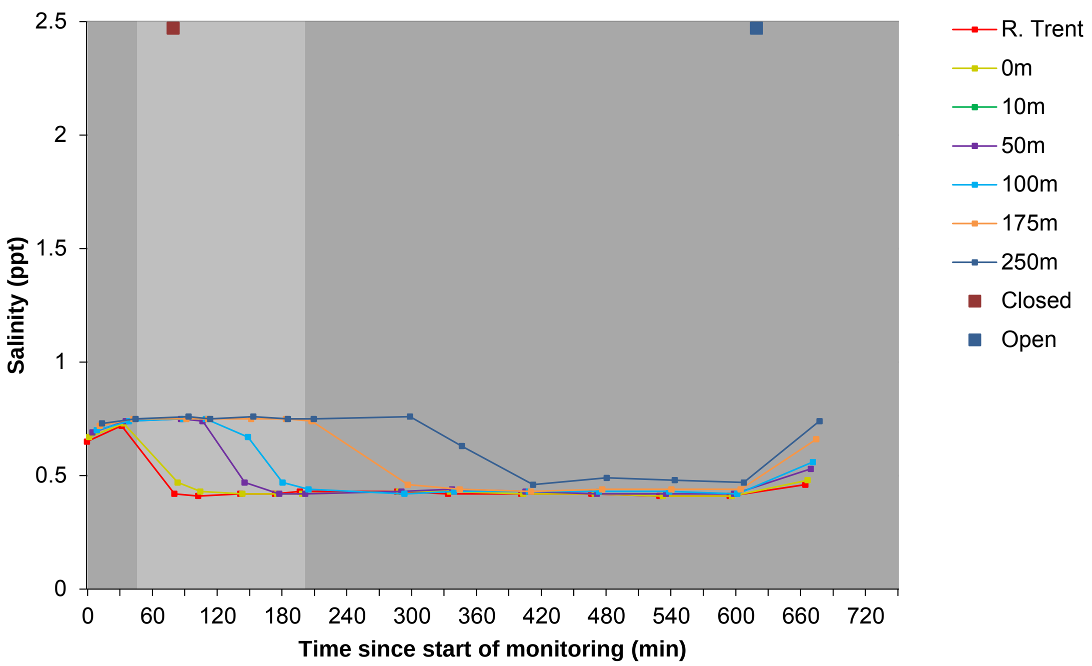
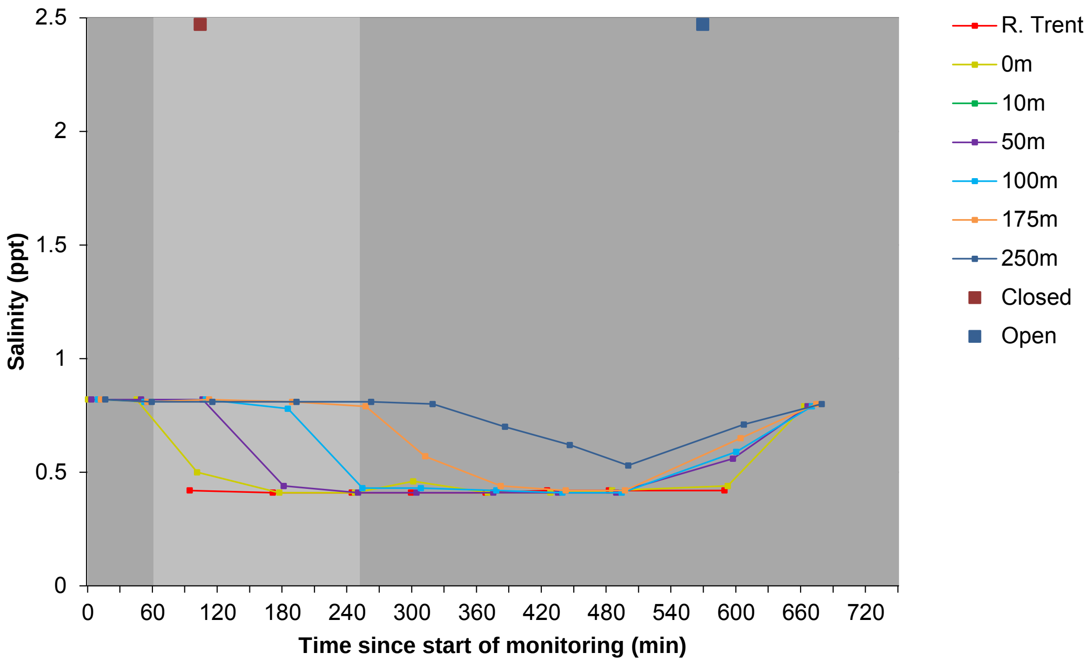


Figure 5.28 Salinity measured in Laughton Highland Drain during the neap-closed survey



Spring-closed

For ~50 minutes prior to the start of the flood tide, salinity measured ~0.72ppt throughout the drain during the spring-closed survey (Figure 5.27). Salinity declined at the start of the flood tide to ~0.44ppt, with the initial decline being measured at 0m upstream and then at each subsequent measurement site upstream (to 250m). This occurred over a total time of ~370 minutes despite the flap valve closing at ~70 minutes. This subsequent upstream decline represents the upstream movement of inflowing water of lower salinity than that previously present in the drain. At ~620 minutes the flap valve opened and outflow from the drain began. At this point, salinity values increased to ~0.74ppt, particularly those at 175m and 250m. This suggests that the less saline water input during the flood tide is displaced downstream and replaced with more saline water from upstream. Furthermore, salinity measured at the 250m measurement site does not decline to the same level as other sites (~0.48ppt compared with ~0.44ppt). This additionally suggests that upstream flow from the drain contributes to increasing salinity.

Neap-closed

The salinity trends for the neap-closed survey (Figure 5.28) show a very similar trend to those for the spring-closed survey (Figure 5.27). For ~60 minutes prior to the start of the flood tide, salinity measured ~0.82ppt throughout the drain during the neap-closed survey (Figure 5.28). Salinity declined at the start of the flood tide to ~0.41ppt, with the initial decline being measured at 0m upstream and then at each subsequent measurement site upstream (to 250m). This occurred over a total time of ~441 minutes despite the flap valve closing at ~105 minutes. This subsequent upstream decline represents the upstream movement of inflowing water of lower salinity than that previously present in the drain. The time taken to travel upstream is greater than that calculated for the spring-closed survey due to the lower energy of the neap tide. At ~570 minutes the flap valve opened and outflow from the drain began. At this point, salinity values increased to ~0.80ppt. As for the spring-closed survey, this increase suggests that the less saline water input during the flood tide is displaced downstream and replaced with more saline water from upstream. Similar to the spring-closed survey, salinity measured at the 250m measurement site did not decline to the same level as other sites (~0.48ppt compared with ~0.44ppt) suggesting that downstream flow from the catchment of the drain contributed to increasing salinity.

The pattern of slow upstream propagation of the incoming water from the River Trent visible in the spring-closed (Figure 5.27) and neap-closed (Figure 5.28) surveys differs from that seen on the spring-open (Figure 5.25) or neap-open (Figure 5.26) survey data. This suggests that the Retarder allows the flap valve to be open for longer, allowing a greater volume of water with a larger momentum to inflow more rapidly into the drain. This water would flow quickly upstream, rapidly reducing salinity in the drain. In contrast, when the Retarder is deactivated the flap valve shuts more rapidly, allowing only a smaller volume of water of lower momentum to flow into the drain. This water would therefore flow much slower (than the water input when the Retarder was active) and take significantly longer to travel upstream, leading to much slower reductions in salinity with upstream distance.

5.4.2 Turbidity

Analysis of spring-open and neap-open data

Figures 5.29 and 5.30 display the trends in turbidity measured in Laughton Highland Drain during the spring and neap tides respectively, when the Retarder fish access device was activated.

Figure 5.29 Turbidity measured in Laughton Highland Drain during the spring-open survey

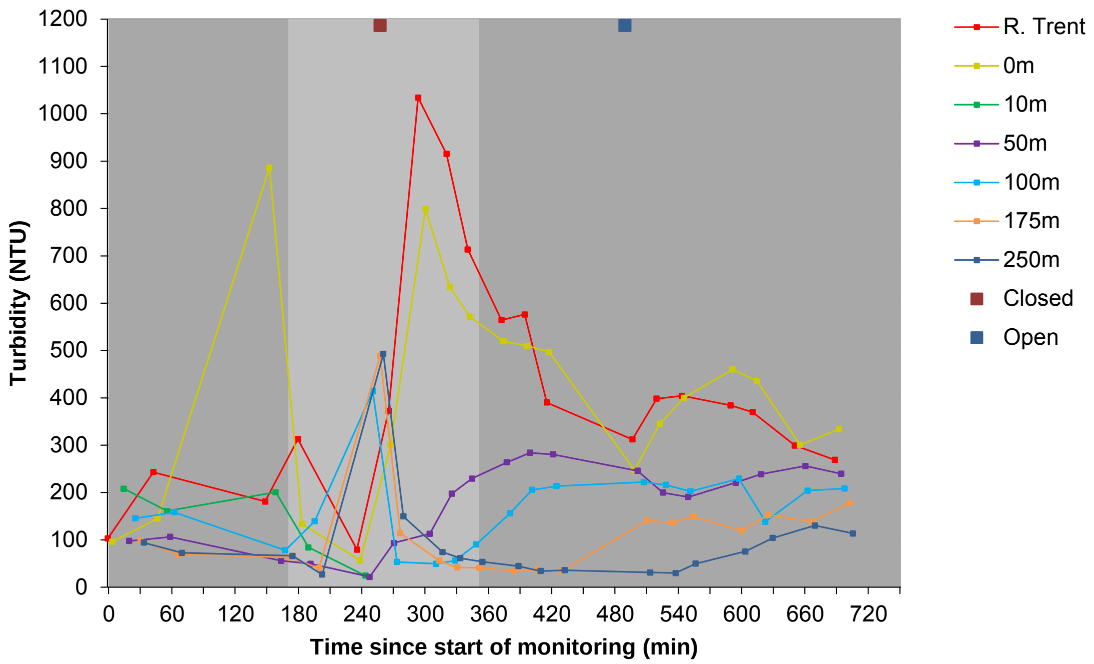
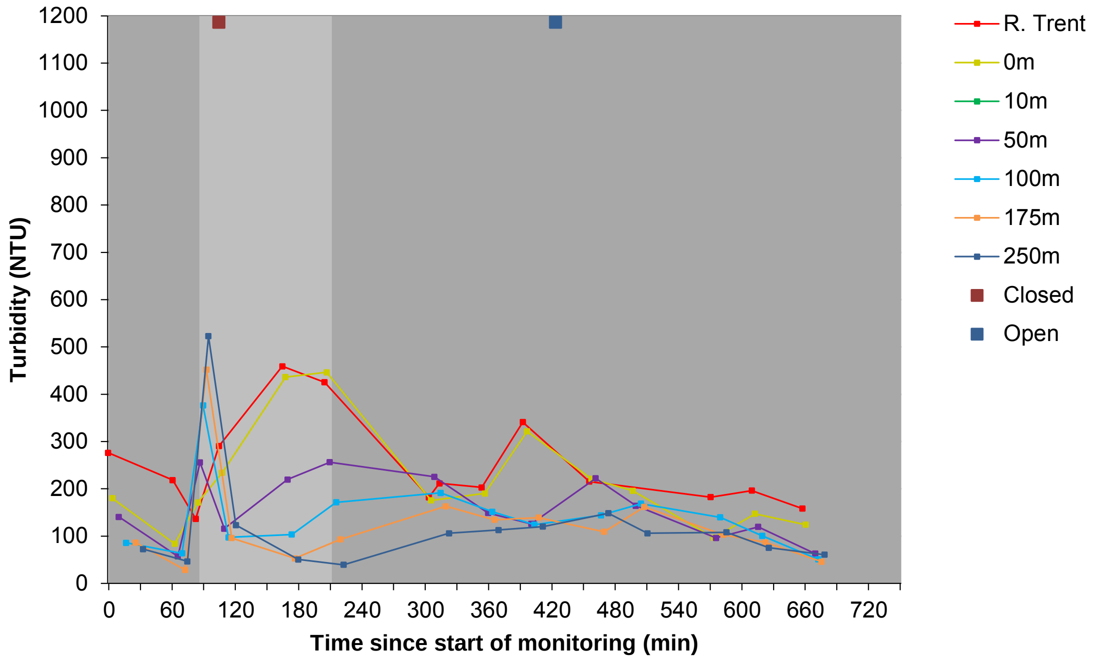


Figure 5.30 Turbidity measured in Laughton Highland Drain during the neap-open survey



Spring-open

Turbidity measured within Laughton Highland Drain during the spring-open survey (Figure 5.29) displays a general trend of a steep rise in turbidity during the flood tide, from around 150–200NTU, peaking around the start of flood slack at ~800NTU, and then a decrease in turbidity values during the ebb tide to around 200–400NTU at ebb slack. This trend is apparent at all measurement sites, although becomes increasingly subdued with upstream distance.

Prior to the commencement of the flood tide at ~200 minutes, turbidity values range from between 160NTU close to the penstock to 70NTU at 250m upstream. A significant increase in turbidity (886NT) was recorded at 153 minutes at 0m. Given the magnitude of the remaining turbidity data this value is attributed to bed disturbance by the sonde during measurement.

Upon commencement of the flood tide, water rapidly flowed into the drain, causing a rapid increase in turbidity up to a maximum of 799NTU at 0m at ~300 minutes, 235NTU lower than the 1,034NTU recorded in the River Trent. The flap valve was noted to have shut at ~258 minutes after the start of the flood tide. The difference in turbidity between that measured at 0m and in the River Trent during the initial rapid rate of increase suggests that sediment in the drain is predominantly derived from the River Trent with a contribution from re-entrainment from scour around the flap valve and penstock. Although the flap valve closed at ~258 minutes, turbidity was still increasing due to the volume of sediment present in the drain. Measurement sites further upstream, notably 50m and 100m, began to slowly increase from pre-flood tide levels as turbid water moved upstream. At ~420 minutes, 120 minutes after the increase in turbidity was noted at the 50m and 100m sites, turbidity began to increase at 175m and 250m upstream.

Turbidity at 0m declined from a peak of 799NTU at 300 minutes to a low of 247NTU at ~490 minutes. At this time the flap valve was noted to have opened and water was flowing out of the drain. This led to increasing turbidity, 430–460NTU between 590–610 minutes, due to removal of suspended sediment and scour from around the penstock. Turbidity measured at 50m and 100m upstream also showed slight increases after 550 minutes. These increases are predominantly due to outflow of turbid water and settling of sediments, which had been moving upstream, from the drain. Despite outflow from the drain having begun at ~490 minutes, turbidity levels continued to rise at 175m and 250m, representing the continuing slow movement of turbid water further upstream.

Immediately after the flap valve shut at ~258 minutes, there were noticeable peaks in turbidity at 175m and 250m of ~480NTU and a lower peak of 410NTU at 100m. These are not related to the inflow of water from the River Trent as they are too far upstream to have been affected in such as short space of time. These measurements instead suggest that an upstream input of turbid water has led to the increase. This could potentially be the drains suggested in section 5.4.1 (spring-open survey) in the analysis of the salinity measurements for Laughton Highland Drain. At least one drain (East Ferry Ings Drain, Figure 3.16) is connected to the River Trent several hundred metres further downstream from the confluence of Laughton Highland Drain and the River Trent and therefore would have received inflow of water from the River Trent earlier than the confluence of Laughton Highland Drain. East Ferry Ings Drain does indeed possess a penstock structure at its downstream end but its state at the time of survey could not be ascertained.

Neap-open

Turbidity measured within Laughton Highland Drain during the neap-open survey (Figure 5.30) displays similar trends to the spring-open survey. However, peak turbidity values are significantly lower, highlighting the lower energy of the neap tide. A sharp rise in turbidity is noted during the flood tide, from around 150–200NTU, peaking around the start of flood slack at ~450NTU, and then decreasing during the ebb tide to around 200NTU. This trend is apparent at all measurement sites, although becomes increasingly subdued with upstream distance.

Prior to the commencement of the flood tide at ~70 minutes, turbidity values range from between 180NTU close to the penstock to 75NTU at 250m upstream. Upon commencement of the flood tide, water flowed rapidly into the drain, causing an increase in turbidity up to a maximum of 450NTU at 0m at ~165–200 minutes, slightly higher than measured in the River Trent. This suggests that sediment was predominantly derived from the River Trent with scour around the flap valve and penstock contributing to the elevated levels. The flap valve closed at ~105 minutes, although turbidity at measurement sites further upstream (50m, 100m 175m and 250m) increased slowly from pre-flood tide levels towards ~200NTU as turbid water moved upstream. Notably, turbidity measured at 50m, 309 minutes into the survey, was higher than recorded at 0m (225NTU).

Turbidity at 0m declined from a peak of 450NTU at ~200 minutes to 175NTU at 309 minutes before sharply climbing to 390NTU at ~397 minutes. This peak was not observed in the spring-open data and is attributed to the response of the Retarder. At this time the flap valve was observed to open up despite the level in the River Trent being higher than that in the drain. This is attributed to the tension of the Retarder spring forcing the flap valve open. This allowed the inflow of turbid water from the River Trent, consequently increasing turbidity at 0m and also accounting for the peak in turbidity at 50m recorded at 462 minutes. As this was only noted during the neap-open period it is likely that the higher water levels in the River Trent during the spring-open survey prevented premature opening of the flap valve. At ~424 minutes the flap valve opened fully as levels between the River Trent and the drain equilibrated. Turbidity at 0m declined towards pre-flood levels thereafter.

After the flap valve was noted to have opened (~424 minutes), turbidity at the upper sites, 50m to 250m, increased slightly due to outflow of the turbid water which had previously travelled upstream, before decreasing towards pre-flood levels as turbid water flowed out of the system and sediments settled out of the water column.

Analysis of spring-closed and neap-closed data

Figures 5.31 and 5.32 display the trends in turbidity measured in Laughton Highland Drain during the spring and neap tides respectively, when the Retarder fish access device was deactivated.

Turbidity levels measured during the spring-closed survey (Figure 5.31) and neap-closed survey (Figure 5.32) are in distinct contrast to those measured during the spring-open survey (Figure 5.29) and neap-open survey (Figure 5.30), with turbidity reduced by a significant amount. However, the graphs still possess the same general trend, albeit very subdued, namely a rise in turbidity during the flood tide, peaking around the start of flood slack and then decreasing during ebb slack. Generally turbidity levels in the drain during the spring-closed survey exceed 200NTU only once, while they do not exceed 70NTU at all during the neap-closed survey.

Figure 5.31 Turbidity measured in Laughton Highland Drain during the spring-closed survey

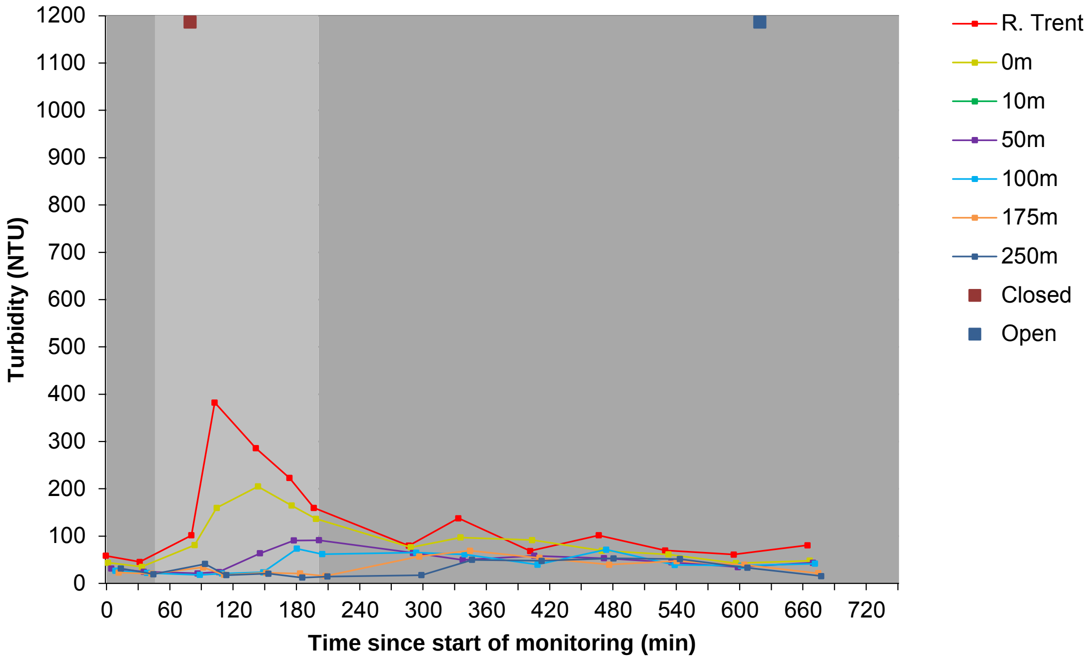
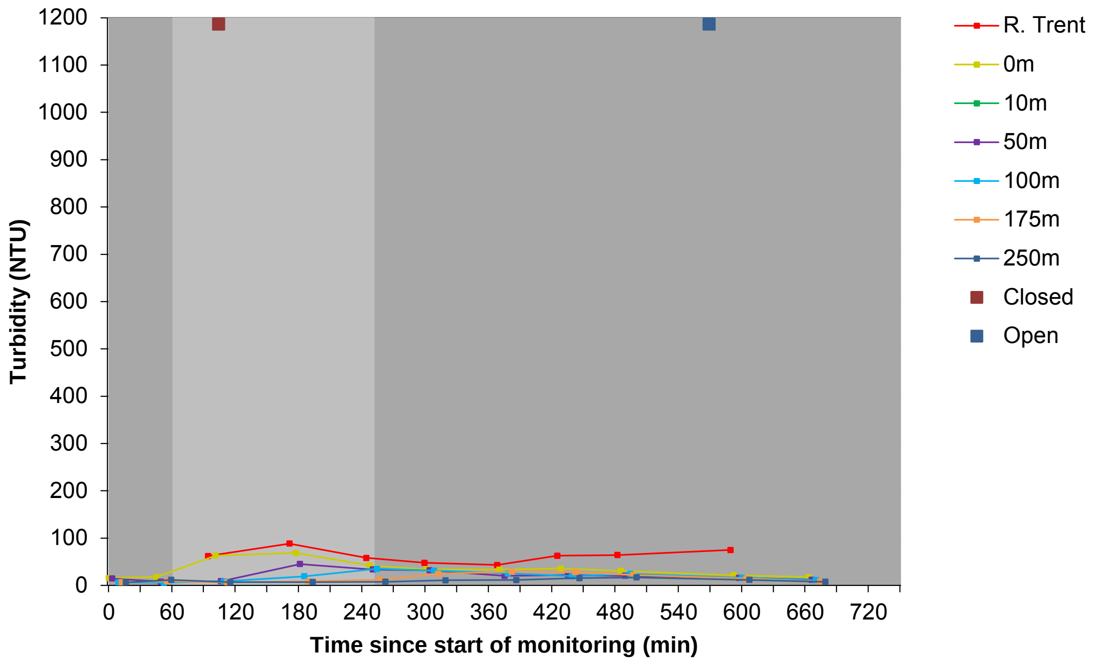


Figure 5.32 Turbidity measured in Laughton Highland Drain during the neap-closed survey



Spring-closed

Turbidity measured within Laughton Highland Drain during the spring-closed survey (Figure 5.31) displays a general trend of a steep rise in turbidity during the flood tide, from around 45NTU to a peak of ~205NTU at the start of flood slack and then a decrease in turbidity values during the ebb tide to pre-flood levels.

Prior to the commencement of the flood tide at ~40 minutes, turbidity values are ~45NTU throughout the drain (from 0m to 250m). Turbidity begins to increase at 0m at the start of the flood tide to a maximum of 205NTU at 144 minutes. A maximum of 382NTU was recorded in the River Trent at 103 minutes. This suggests that most of the sediment entering the drain is derived from the River Trent. At ~90 minutes the flap valve closed and the rate of increase of turbidity slowed markedly. At ~110 minutes, measurements at sites at 50m and 100m began to slowly increase from pre-flood tide levels as turbid water moved upstream, while at ~200 minutes, turbidity began to increase at 175m and 250m.

Turbidity at 0m began to decline from a peak of 205NTU at 103 minutes towards pre-flood baseline levels, with levels at the upstream measurement sites beginning to decline shortly thereafter. At ~620 minutes the flap valve opened and slight increases in turbidity were measured at 0m, 50m and 100m. These increases were related to downstream movement of turbid water and scour as the drain began to flow out into the River Trent.

As observed for the spring-open and neap-open surveys, there were small but noticeable peaks in turbidity at 175m and 250m of ~41NTU (compared to ~18NTU for 50m and 100m upstream). The potential source of these peaks, contribution from a drain upstream of the survey section, is postulated to remain unchanged from that suggested earlier.

Neap-closed

Turbidity measured within Laughton Highland Drain during the neap-closed survey (Figure 5.32) displays significantly lower turbidity measurements than those from the spring-closed survey. Only a slight rise in turbidity is noted during the flood tide, from around 10NTU to a peak of 63NTU around the start of flood slack, then decreasing during the ebb tide to around 8NTU. This trend is apparent at all measurement sites in the reach.

Prior to the commencement of the flood tide at ~100 minutes, turbidity values were very low at ~10NTU throughout the drain. Upon commencement of the flood tide, water flowed into the drain, causing a slight increase in turbidity at 0m up to a maximum of 63NTU at ~103 minutes. This was slightly lower than the turbidity measured it the River Trent, suggesting that sediment was predominantly derived from the River Trent. The flap valve closed at ~105 minutes, although turbidity at measurement sites further upstream (50m, 100m, 175m and 250m) increased slowly from pre-flood tide levels towards ~20–30NTU as turbid water moved upstream. Turbidity at all sites fell to pre-flood levels after peaking. No impact on turbidity was observed when the flap valve opened at ~570 minutes.

In contrast to the spring-open, neap-open and spring-closed surveys, no peaks in turbidity were noted at 175m or 250m (Figure 5.32).

The significantly lower turbidity recorded during the neap-closed survey reflects the low energy of the neap tide. However, the fact that the maximum turbidity values measured on the flood tide in the River Trent during the neap-closed survey were significantly lower than those measured in the neap-open survey (88NTU and 382NTU respectively) suggests that varying meteorological conditions, availability of sediment in the River Trent and wider Humber Estuary or variation in the energy of the tide may have contributed to the lower turbidity.

When the Retarder is activated, drains take much longer to empty and return to close to, or to, pre-flood turbidity levels. This is postulated to be due to the increased duration for which the flap valve is held open and the potential for the flap valve to open earlier than would be expected on the ebb tide (spring tension overcoming water pressure of the River Trent on the flap valve). The Retarder therefore allows an increased volume of turbid water to enter the drain, greater than what would be experienced when the Retarder is deactivated. Coupled with increased scour, this increases the level of water and sediment within the drain that has to flow out during a single tidal cycle. It is therefore possible that these drains may not fully drain out during a single tidal cycle.

Upstream influence of the Retarder fish access device

Both the spring-closed (Figure 5.31) and neap-closed (Figure 5.32) graphs show significantly different trends in turbidity compared with the spring-open (Figure 5.29) and neap-open (Figure 5.30) graphs. Although there are likely to differences due to the magnitude of the tides, the available sediment in the estuary and changes in flow in Laughton Highland Drain, it is highly unlikely that these variables can account for the differences measured. In this case it is very probable that the Retarder fish access device is responsible for the majority of the differences.

At 0m the peak turbidity measured during the spring-open survey was 799NTU compared with 205NTU during the spring-closed survey. Similarly, for the neap-open survey, a peak turbidity of 446NTU was measured at 0m compared with the 63NTU measured during the neap-closed survey. This suggests that ~75% of the turbidity levels recorded in Laughton Highland Drain during the surveys when the Retarder was activated are directly related to the action of the Retarder.

During the neap-open and neap-closed surveys the upstream limits of observed turbidity increases were >250m and 175m from the penstock respectively. This suggests that an additional 75m of reach could potentially be impacted by the Retarder. During the spring-open and spring-closed surveys the whole 250m survey section of the drain was found to be impacted by elevated turbidity levels. During the spring-open survey, however, turbidity levels were found to be higher at the 250m site (60NTU) than they were at the same site during the spring-closed survey (15NTU). These elevated levels suggest that the Retarder exerts an impact further upstream when activated than when it is deactivated.

5.5 Fish access structure activation periods

During the surveys, attempts were made to note the timing of closure of the flap valve and fish access structures. However, this was exceptionally difficult and only specific estimates can only be provided for the flap valves (although this actually includes the action of the Retarder fitted at Laughton Highland Drain as it exerts control directly on the flap valve). Difficulties in observations were due to a combination of:

- rapid tidal rise
- inundation of the flap valve and/or fish access structure (particularly during spring tides)
- the need to balance data collection with waiting for a fish access structure or flap valve to shut (the flood tide was the period of most significant change at all sites)

Although it was very difficult to quantify the times when fish access structures were open or closed, observations made at all sites seemed to suggest that these structures were generally open for up to 15 minutes on the flood tide and about 30–60 minutes before the actual flap valve opened on the ebb tide.

The estimates for the closure and opening of the flap valve at each site are given in Table 5.1, which includes a column detailing the duration of closure of a flap valve over a single tidal cycle – taken as 745 minutes or 12 hours 25 minutes (section 3.3.1). These latter data are represented graphically in Figure 5.33.

Rows highlighted in grey in Table 5.1 indicate that the fish access structure was active at the time the measurement was taken. Those rows not highlighted indicate that either the fish access structure was inactive or was not installed.

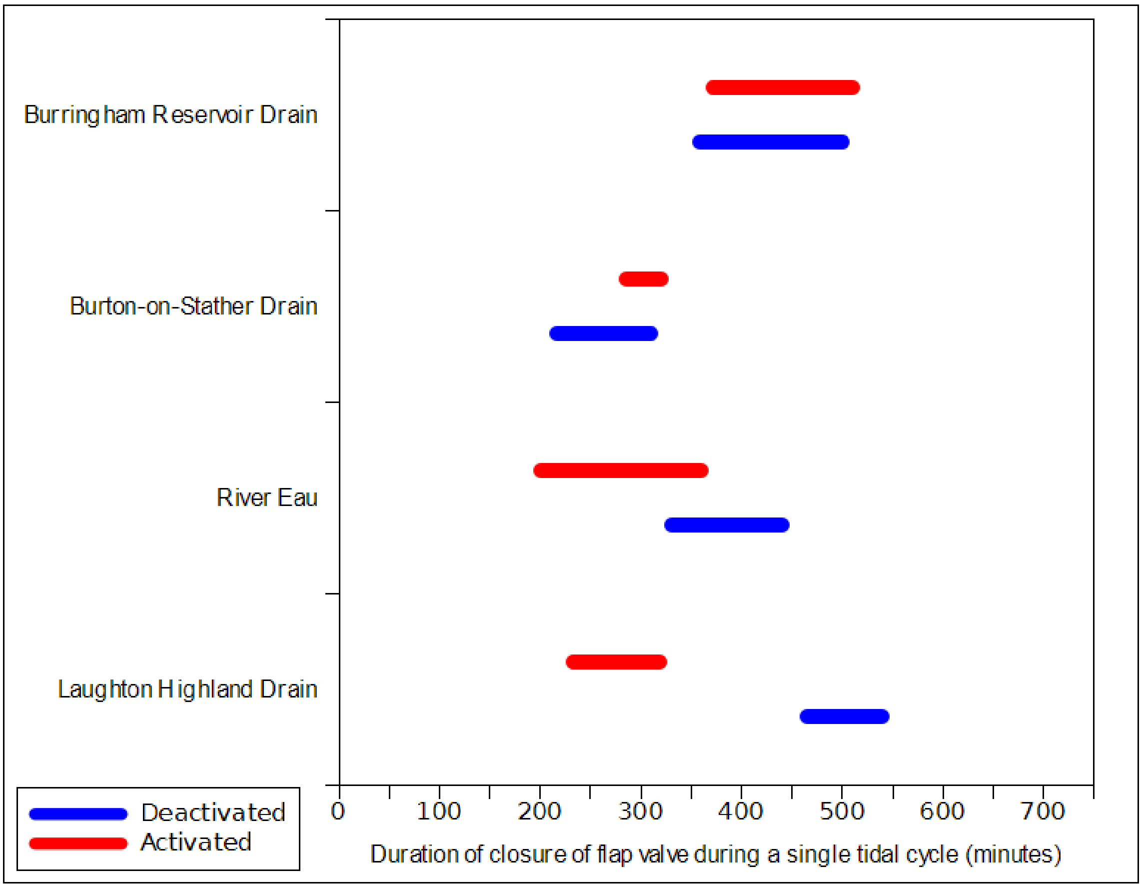
Table 5.1 highlights a wide variation in the length of time when the flap valve at each site is opened or closed. It is apparent that Burringham Reservoir Drain is generally closed for the longest period, with much lower variation in the periods of closure than the other drains (Table 5.1 and Figure 5.33). During neap tides, flap valves appear to be closed for the shortest times (Table 5.1). This is expected due to the lower level of neap tides compared with spring tides.

Table 5.1 Estimated times of closure and opening of flap valves at each site

Site	Survey	Approximate time of flap closure	Approximate time of flap opening	Approximate duration of closure per tidal cycle	Duration of closure as percentage of 12h 25min tidal cycle
		(minutes from start of survey)		(minutes)	
Burringham Reservoir Drain	Spring-open	50	560	510	68
	Neap-open	48	420	372	50
	Spring-closed	150	508	358	48
	Neap-closed	30	530	500	67
Burton-on-Stather Drain	Spring-open	142	462	320	43
	Neap-open	147	432	285	38
	Spring-closed	143	359	216	29
	Neap-closed	150	460	310	42
River Eau	Spring-open	240	600	360	48
	Neap-open	200	400	200	27
	Spring-closed	100	540	440	59
	Neap-closed	130	460	330	44
Laughton Highland Drain	Spring-open	258	490	232	31
	Neap-open	105	424	319	43
	Spring-closed	80	620	540	72
	Neap-closed	105	570	465	62

Figure 5.33 displays the time period in minutes for which a flap valve was closed over a single tidal cycle (~745 minutes) at each drain during the open survey period (when fish access structures were activated, red line) and the closed survey period (when the fish access structures were deactivated, blue line). Each line on Figure 5.33 represents the range of time (between the minimum period of closure to the maximum period of closure) over which flap valves were closed. The blue lines on Figure 5.33 essentially represent the operation of a normal flap valve.

Figure 5.33 Graphical representation of the duration of closure of flap valves over a single tidal cycle per site



It is apparent that Burringham Reservoir Drain was generally closed for the longest time (between 358 and 510 minutes over the 745-minute tidal cycle), with little variation in the period of closure. This is attributed to the absence of a fish access structure.

Burton-on-Stather Drain was closed for much shorter periods than the other drains during a single 745-minute tidal cycle (Table 5.1 and Figure 5.33) (285–320 minutes during the open surveys when fish access structures were activated and 216–310 minutes during the closed surveys when fish access structures were deactivated). This is partly due to the level of the drain on the bank of the River Trent, allowing it to be above the range of tidal influence for much longer than the other drains surveyed.

The River Eau shows a wide range of variation in the period of closure. However, the data show that when the Stoneman fish access structure was activated, the period of closure over a tidal cycle was lower (200–360 minutes) than when the Stoneman fish access structure was deactivated (330–440 minutes) (Figure 5.33). This increases the amount of time aquatic life can access a drain as well as also increasing the amount of water and sediment that can enter a drain.

Laughton Highland Drain (Figure 5.33) shows a distinct contrast to other sites with a significantly wider range of variation in the period of closure when the Retarder fish access structure was activated (232–319 minutes) than when the Retarder was deactivated (465–540 minutes). These data show a significant increase in the period of time aquatic life can access a drain when the Retarder is activated compared to when it is deactivated. This will also extend the period of time water and sediment can enter a drain.

The duration of closure of a flap valve when fish access structures are deactivated increases with distance upstream in the River Trent (Figure 5.33). This is attributed to the rate at which the tide rises and falls, which increases towards the mouth of the River Trent.

The values shown in Figure 5.33 appear to suggest that, when fish access structures are installed on a flap valve and are activated, the flap valve remains shut for less time than if the fish access structure was deactivated. This leads to an extension in the window of opportunity when aquatic life can access a watercourse. The data in Figure 5.33 also illustrate a clear upstream trend in the length of time a flap valve is closed. When a fish access structure is installed on a flap valve and is deactivated the duration of closure is shown to increase with upstream distance. On the same flap valves, durations of closure are much lower and relatively invariant with upstream distance when the fish access structure is activated.

Although there are variations between sites with respect to tidal energy, morphology of the drains and flow within drains it is probable that this difference in duration of closure of flap valves is related to the action of the fish access structure which allows flow of water into and out of a drain for a much longer period when activated. The lack of variation in duration of closure at the control site, Burringham Reservoir Drain, lends support to this hypothesis.

5.6 Flow velocity measurements

As described in section 4.1.3, flow measurements were taken at the penstock on the landward side of all drains (except the River Eau) when the fish access structure were open and activated to attempt to understand the velocity at which flow passed through the flap valve and fish access structure. Table 5.2 details the results of these measurements.

Velocity measurements highlighted in grey in Table 5.2 indicate that the measurement was taken during inflow of estuarine water into the drain. Those not highlighted were taken during outflow of water from the drain.

Table 5.2 Flow velocity measurements taken when fish access structures were activated

Site	Date	Tide	Fish access structure	Distance of measurement upstream from flap valve (m)	Min. velocity (m/s)	Max. velocity (m/s)
Burringham Reservoir Drain	24 November 2011	Spring	None	40	0.001	0.012
Burton-on-Stather Drain	24 November 2011	Spring	ACE	40	0.156	0.299
					0.185	0.296
	2 December 2011	Neap			0.119	0.268
					0.072	0.327
River Eau	23 November 2011	Spring	Stoneman	30		~0.6
Laughton Highland Drain	23 November 2011	Spring	Retarder	5	0.185	0.481

During the survey most measurements were taken at Burton-on-Stather Drain due to the greater ease and safety of access to the penstock compared with the other drains. The penstock behind the Stoneman fish access structure on the River Eau could not be accessed safely and therefore no flow velocity measurements could be taken. The flow velocity detailed in Table 5.2 for the River Eau is therefore an estimate made by timing debris in the flow over a known distance. It is highly probable that this flow velocity is underestimated.

The data in Table 5.2 show that, apart from the River Eau, the greatest flow velocity measured was at Laughton Highland Drain with a maximum of 0.481m/s. The minimum velocities measured at Burton-on-Stather Drain (ACE) and Laughton Highland Drain (Retarder) were generally similar, although velocities near to and below 0.1m/s were observed at Burton-on-Stather Drain. As can be seen in Table 5.2, flows at all sites with a fish access structure were several orders of magnitude higher than for Burringham Reservoir Drain, which did not have a fish access structure installed.

Although flow velocity through the Stoneman fish access structure could not be measured directly, the estimate and visual assessment of the flows within the field suggest that flow velocity through the Stoneman is the greatest out of the three fish access structures monitored. Additional work would be required to confirm this.

The measured flow velocities are likely not to be wholly representative of flow through either the flap valve and/or fish access structure since the velocity measurements were taken at varying distances upstream of the flap valve (as indicated in Table 5.2, column 'Distance of measurement upstream from flap valve (m)'). Over such distances it is likely that losses due to friction, turbulence and energy loss as flow moves upstream and upslope will reduce velocities. Velocities through the fish access structures, particularly the circular orifices of the ACE and Stoneman fish access structures, are likely to be much greater than in the drain due to acceleration of flow to maintain discharge through the fish access structure itself.

Despite these issues the velocities do provide an approximation of what velocities can be expected at each structure.

5.7 Inter-site variability

Figures 5.34 and 5.35 display the variability in salinity and turbidity measured at 0m upstream at each site over the four monitoring periods: spring-open, neap-open, spring-closed and neap-closed. Shortened names are used for each site.

Salinity measured at 0m in each drain throughout the survey period falls within a narrow band between 0.39 and 0.94ppt (Figure 5.34). Generally, Burton-on-Stather Drain varies the most, probably due to its location near to the mouth of the River Trent and the range in salinity values measured in the River Trent at this point. Burringham Reservoir Drain and the River Eau show very little variation. The widest variation in salinity is observed at Laughton Highland Drain during the spring-closed and neap-closed surveys, although this variability falls within the range of that measured at the other sites during the various survey periods.

The plot in Figure 5.34 shows:

- There are no significant differences in salinity between sites.
- There are no controls on salinity due to the presence or absence of a fish access structure.

Figure 5.34 Inter-site variations in salinity measured at 0m site

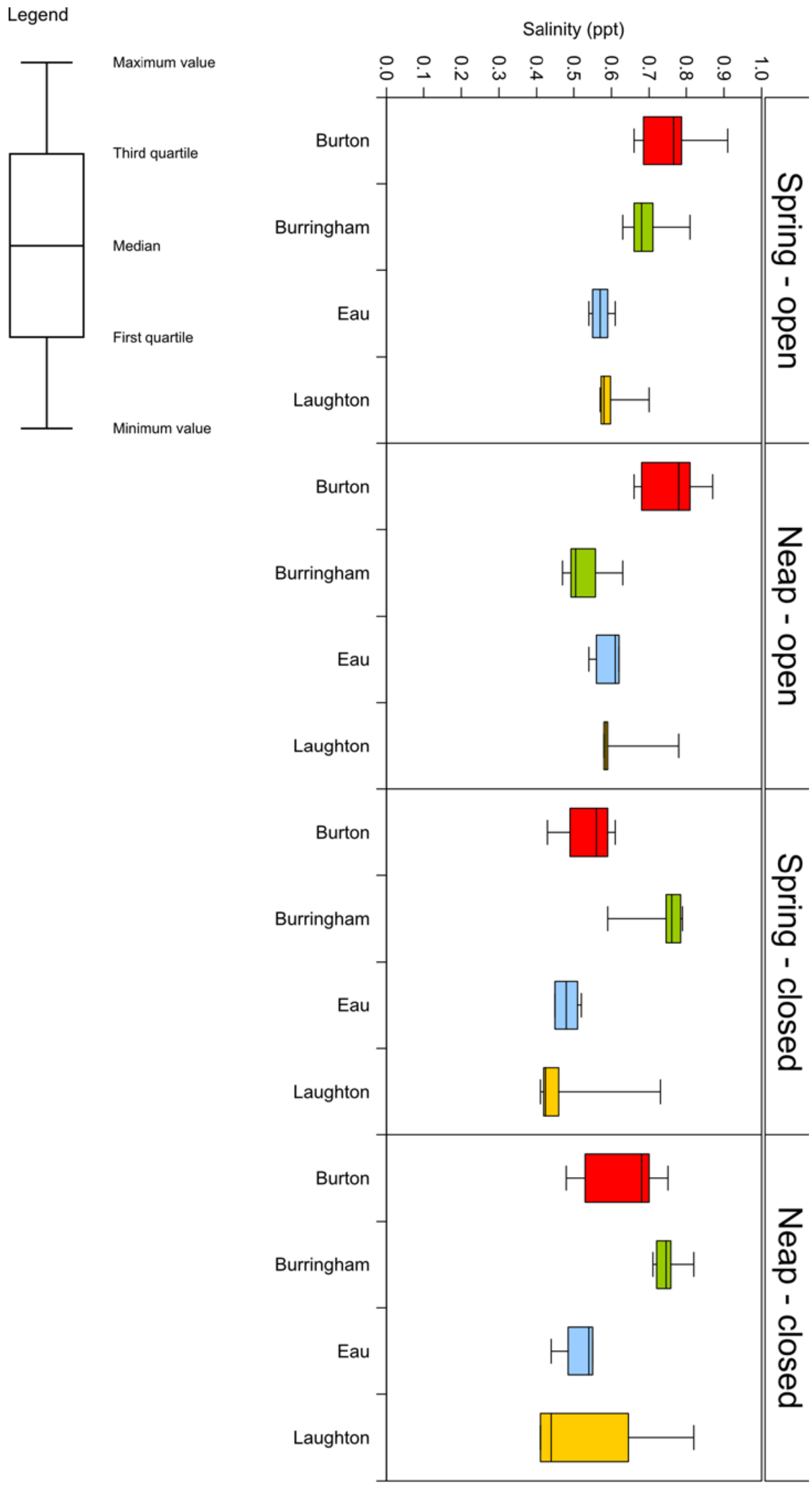
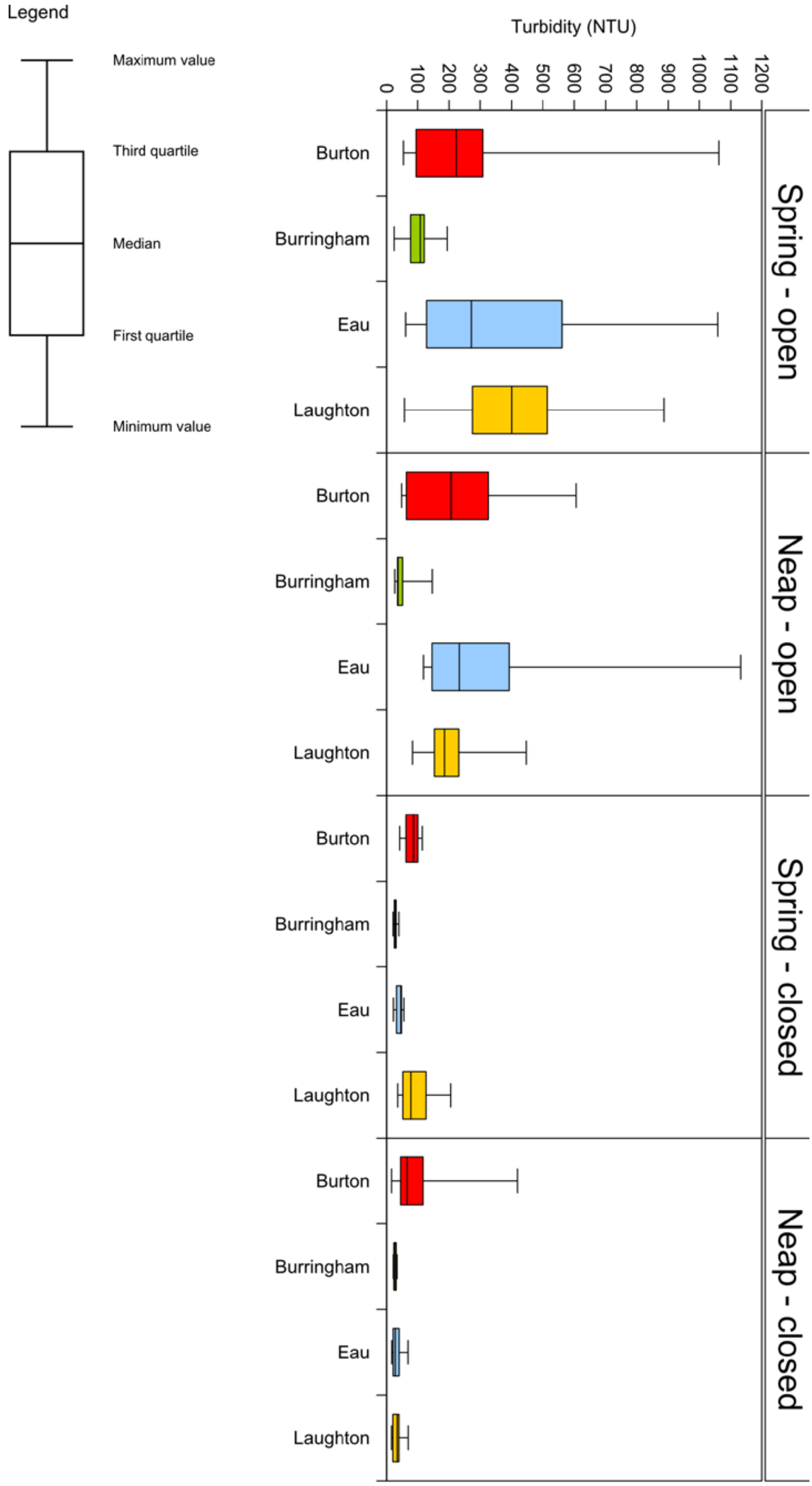


Figure 5.35 Inter-site variations in turbidity measured at 0m site



Turbidity measured at 0m in each drain throughout the survey period falls within a very wide range (Figure 5.35). During the open surveys, turbidity ranged from 24 to 1,131NTU. During the closed surveys, this range decreased significantly to between 15 and 418NTU.

During the spring-open and neap-open surveys, variation in turbidity was significant compared with the control site at Burringham Reservoir Drain. Median turbidity calculated at Burton-on-Stather Drain, the River Eau and Laughton Highland Drain exceeded the maximum turbidity measured within Burringham Reservoir Drain during the open survey period. The largest ranges in turbidity were noted at the River Eau, particularly during the spring-open survey; this was related to the flow velocity through the Stoneman fish access structure and the bed scour created by the flow. The range in turbidity measured in the River Eau remained essentially constant for both the spring-open and neap-open surveys. This suggests that the turbidity within the River Trent, the energy and tide level differences between the spring and neap tides, and the configuration and operation of the individual fish access structures are all exerting control on turbidity in the River Eau.

There was also a noticeable reduction in the range of turbidity values measured at Burton-on-Stather Drain and Laughton Highland Drain during the neap-open survey compared with the spring-open survey. This is likely to reflect the varying tidal conditions and their interaction with the activated fish access structures on these drains.

Figure 5.35 also highlights a trend between the median turbidity measured at three sites with active fish access structures during the spring-open and neap-open surveys. At Burton-on-Stather Drain, median values between 222NTU and 206NTU were calculated for the spring-open and neap-open surveys respectively, while 271NTU and 233NTU were calculated at the River Eau for the spring-open and neap-open surveys respectively. In contrast, a median turbidity of 400NTU was calculated at Laughton Highland Drain during the spring-open survey, declining to 185NTU during the neap-open survey.

This difference is hypothesised to be related to the configuration of the fish access structure itself. The ACE at Burton-on-Stather Drain and the Stoneman at the River Eau both have circular orifices, while the Retarder at Laughton Highland Drain is essentially an elongated rectangular slot formed by the gap between the flap valve and flap valve mounting when the flap itself is open. Velocity through the ACE and Stoneman are likely to be similar during either a spring or a neap tide, but the velocity through the Retarder slot will vary due to the tidal level and interaction between the changing force exerted by the varying tidal level and the constant force applied to the flap valve from the Retarder spring. During a spring tide the flap valve slot is likely to be narrower, promoting increased flow velocities through the slot, while during a neap tide the flap valve slot is likely to be wider, promoting lower flow velocities through the slot and resulting in lower levels of scour inside the drain around the penstock. This hypothesis is partially supported (given the limitations in the velocity measurements detailed in section 5.6) by the constant velocity measured at the ACE on Burton-on-Stather Drain over both spring and neap tides when the fish access structure was operational and the higher velocity recorded at the Retarder at Laughton Highland Drain during a spring tide (Table 5.2).

Turbidity measured within each drain during the spring-closed and neap-closed surveys was significantly less than that measured during the spring-open and neap-open surveys, with turbidity mostly below 200NTU (the exceptions being Laughton Highland Drain during the spring-closed survey and Burton-on-Stather Drain during the neap-closed survey). As the fish access structures were deactivated during these surveys, variability in turbidity is due to conditions in the drain or variability in the estuary and tidal regime.

The plot shown in Figure 5.35 clearly highlights the impact of fish access structures on controlling turbidity within a drain.

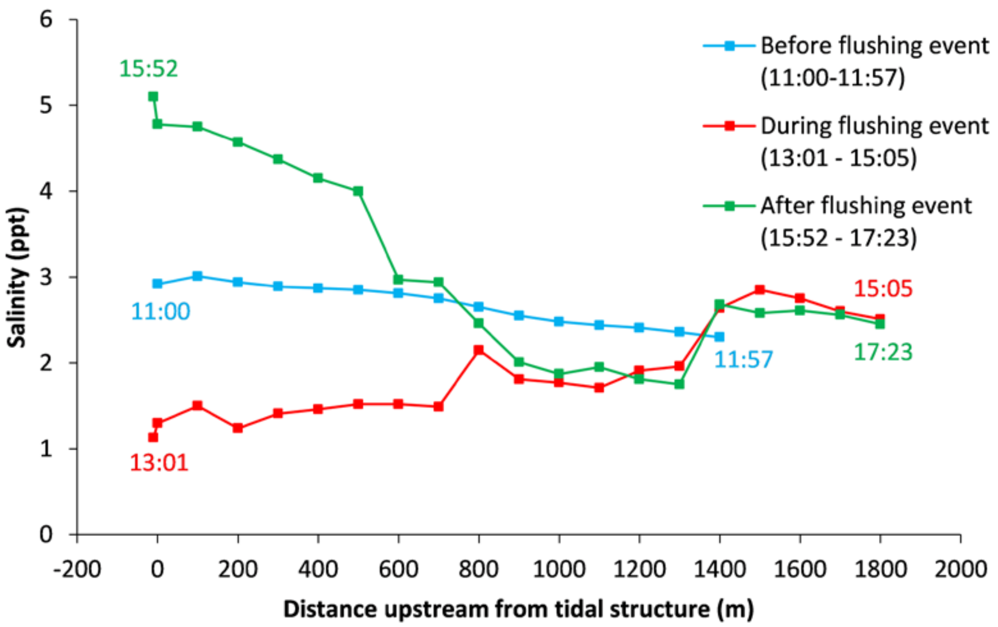
5.8 Adlingfleet Drain

As discussed in section 4.2, monitoring of salinity and turbidity within Adlingfleet Drain was undertaken during the inflow of tidal water in the inflow stage of the tidal flushing event. The changes in salinity and turbidity before the tidal flushing event, during the tidal flushing event and after the tidal flushing event are discussed in sections 5.8.1 and 5.8.2 respectively. As detailed in section 4.2 this survey only covers the inflow stage of the tidal flushing event and does not record changes during the outflow stage of the tidal flushing event.

5.8.1 Salinity

Figure 5.36 displays the trends in salinity measured in Adlingfleet Drain before, during and after the inflow of water from the inflow stage of the tidal flushing survey.

Figure 5.36 Salinity measured in Adlingfleet Drain



Notes: Times on the graph represent the time of first and last measurement of each survey undertaken.

Prior to the start of the tidal flushing event at 13:01, salinity upstream in the drain showed a gradual decline from 2.92ppt at the penstock on the tidal structure to 2.30ppt at the end of the survey reach – a decrease of 0.62ppt (Figure 5.36). Salinity in the River Trent could not be measured as the estuary-side creek was not in water (section 3.3.6 and Figure 3.24).

At 13:01 tidal water began to flow into the drain through the open flap valve and penstock. Salinity was measured up the drain during the flushing event between 13:01

and 15:05. Due to the changes noted during the survey, the total upstream survey section length was extended past Hoggard Lane Bridge, which is located ~1,400m upstream (Figure 3.24), to 1,800m. Salinity rose markedly in the drain from 1.3ppt at 0m to 1.96ppt at 1,300m, although a significant reduction compared with the values recorded prior to the tidal flushing event of 2.92ppt at 0m and 2.36ppt at 1,300m.

The reduction in salinity prior to 1,300m is due to the dilution effect of significant volumes of water entering and moving upstream in the drain on the rising tide. This is supported by the salinity measurement taken in the estuary-side creek at the very start of the inflow of tidal waters of 1.13ppt. However, after Hoggard Lane Bridge, located at 1,400m upstream, salinity increased slightly above the pre-tidal flushing values of 2.68ppt at 1,400m and 2.45ppt at 1,800m. This suggests that Hoggard Lane Bridge acts as a barrier to the upstream movement of the incoming tidal waters, preventing wholesale mixing between the water below and above the bridge. Observations of stagnant water and very slow circulation in the field taken at the downstream side of the bridge water suggest there could be a blockage beneath the bridge itself.

After 15:52 a third survey section up the drain was made to measure the salinity after the flushing event had ceased (~30 minutes earlier). Salinity measurements taken prior to 1,300m were found to be near the opposite of those taken during the flushing event (Figure 5.36), with 4.78ppt measured at 0m at the penstock of the tidal structure, declining rapidly to 1.75ppt at 1,300m. After Hoggard Lane Bridge, salinity measured between 1,400m and 1,800m upstream was found to be essentially the same as that measured during the tidal flushing event of between 2.68ppt at 1,400m and 2.45ppt at 1,800m. This further highlights the controlling influence of Hoggard Lane Bridge on the upstream movement of incoming tidal flow.

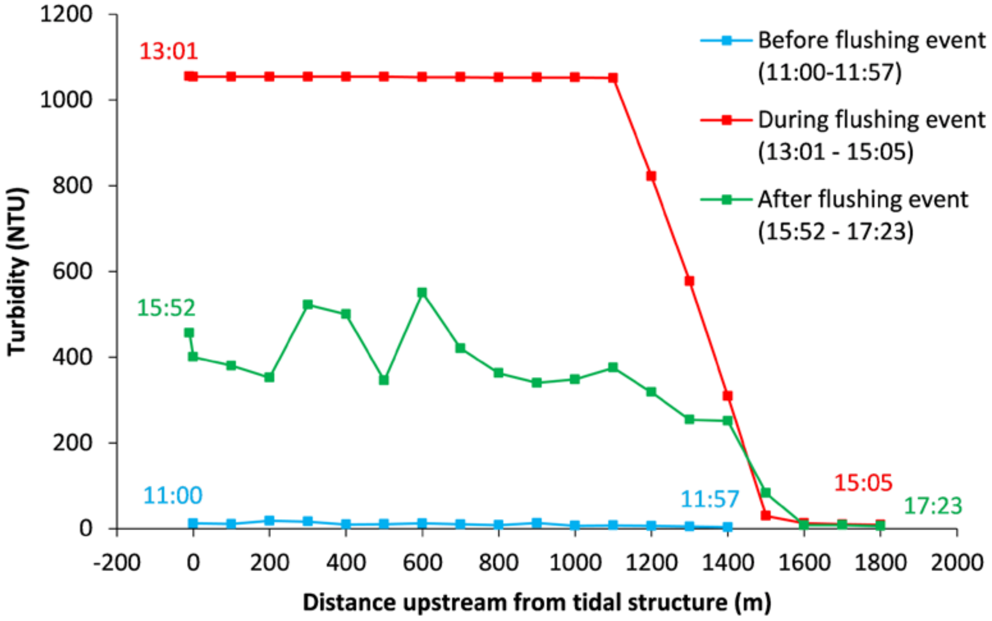
The reason for the significant increase in salinity measured after the end of the tidal flushing event, particularly between 0m and 900m, is not fully understood. Due to the impacts of Hoggard Lane Bridge there is unlikely to be any significant upstream influence on salinity in the drain. It is hypothesised that the increase is due to the inflow of significantly more saline water from the estuary after an initial inflow of lower salinity water. Salinity in the estuary-side creek was measured at 5.1ppt immediately after the flap valve and penstock of the tidal structure was shut to prevent inflow of the estuarine water. This measurement lends some support to the reasoning behind the elevated salinities measured in the drain after the flushing event had ceased.

5.8.2 Turbidity

Figure 5.37 displays the trends in turbidity measured in Adlingfleet Drain before, during and after the inflow of water from the inflow stage of the tidal flushing survey. Times on the graph represent the time of first and last measurement of each survey undertaken.

Prior to the start of the tidal flushing event at 13:01, turbidity throughout the surveyed length of the drain was very low (12NTU measured at 0m at the penstock, 3NTU at 1,400m and a maximum of 18NTU at 200m upstream), indicating essentially no suspended sediment in the water column. Turbidity in the River Trent could not be measured as the estuary-side creek was not in water (section 3.3.6 and Figure 3.24).

Figure 5.37 Turbidity measured in Adlingfleet Drain



At 13:01 tidal water began to flow into the drain through the open flap valve and penstock. Turbidity was measured up the drain during the flushing event between 13:01 and 15:05. Like the salinity survey and due to the changes in turbidity noted in the drain, the total upstream survey section length was extended past Hoggard Lane Bridge, located ~1,400m upstream (Figure 3.24), to 1,800m. Turbidity climbed significantly in the drain by several orders of magnitude over that recorded before the start of the tidal flushing event, with 1,055NTU recorded within the estuary-side creek and from 0m to 1,100m upstream of the penstock.

Given the extremely high and uniform turbidity readings it is likely that the sonde used actually over-ranged during these measurements, that is, the water was so turbid it was beyond the measurement range of the sonde turbidity sensor. These measurements suggest that most of the suspended sediment would have been derived from the estuary. However, field observations seemed to suggest that bed scour was a significant contributor to the increased suspended sediment load and turbidity. Beyond 1,100m upstream, turbidity dropped rapidly to 309NTU at 1,400m at Hoggard Lane Bridge and continued to decrease to 29NTU at 1,500m and 6NTU at 1,800m upstream of the bridge. The rapid decrease in turbidity at 1,100m suggests that either the upstream moving sediment plume had not traversed the entire survey section or the rate of upstream movement of the plume was decreasing. The rapid decline after 1,300m again highlights the influence which Hoggard Lane Bridge exerts on upstream movement of the flow in the drain.

From 15:52 a third survey of the drain was undertaken to measure the turbidity after the tidal flushing event had ceased (~30 minutes earlier). Turbidity measurements taken between 0m and 1,300m were found to be rapidly declining from their peaks during the tidal flushing event, mostly decreasing by ~600NTU. A slight decrease was noted with upstream distance, with turbidity measuring 251NTU at 1,300m upstream. Given the cessation of inflow to the drain from the estuary it was concluded that the reduction in turbidity was related to settling of suspended particles transported into the drain from the estuary and the cessation of bed scour. Given the change in turbidity noted after the cessation of tidal flushing, it is likely that turbidity would take at least four hours to return to the pre-flushing levels. After Hoggard Lane Bridge, turbidity dropped rapidly towards levels measured before the start of the tidal flushing (6NTU at 1,800m).

6 Conclusions

This section presents the key findings from the study and the potential impacts on management of drains and watercourses where fish access structures are installed. It also provides an overview of the recommendations for future work designed to build on the knowledge acquired during the project.

6.1 Key findings

The key findings summarised below are based on the results of the long-term tidal cycle surveys and the tidal flushing survey.

6.1.1 Salinity

Salinity measured at each of the four main survey sites was found to be very low, never falling outside the range 0.4–0.9ppt. This indicates that salinities measured during the surveys were either freshwater (defined as ≤0.5ppt) or brackish (defined as >0.5 to ≤30ppt).

Within the River Trent measured salinity very rarely exceeded 1.0ppt, indicating that the River Trent was essentially brackish during the survey. Salinity maxima of over 5.0ppt were noted during the spring-open and neap-open surveys at Burton-on-Stather Drain on 24 November 2011 and 2 December 2011 but were not recorded at any of the upstream sites. These maxima did not affect the drain as they occurred after the flap valve and fish access structures were shut. However, it is possible that had such saline waters entered a drain, either via leakage or through input from an upstream source, significant increases in salinity could occur within the drain.

Salinity variation measured at the four sites was generally very limited, being between 0.10ppt and 0.20ppt. The greatest changes in salinity were found to occur during the flood tide. In most drains, the salinity measured in a drain prior to the inflow of estuarine water on the flood tide was commonly higher than that measured in the River Trent (by ~0.10ppt). The inflow of water from the River Trent to a drain was found to reduce the salinity within that drain due to dilution. These reductions in salinity were found to be transient, lasting only until water flowed out of a drain when the tide level dropped. Salinity in a drain then commonly returned to levels measured prior to the inflow of water on the flood tide. The findings suggest that, when not influenced by inflowing tidal water, salinity levels within the drains themselves are generally higher than within the River Trent, although this difference is only marginal.

Given the very low levels of flow within the drains and the River Trent it is possible that the measured salinities could be lower if freshwater contributions from upstream areas were higher. In addition, it cannot be assumed that the impact of fish access structures on salinity observed in this study will be directly applicable to fish access structures situated in other estuarine environments. This is mainly due to the similarity in salinities within the River Trent and the drains surveyed which may not be the case in other estuaries.

6.1.2 Turbidity and sediment dynamics

With the exception of Burringham Reservoir Drain (the control site), turbidity was shown to vary significantly at each site, although a general trend in turbidity was detected within a drain during each survey. This trend was characterised by a rapid increase in turbidity on the flood tide followed by a decrease in turbidity during the ebb tide with slight increases in turbidity (particularly between 0m and 50m upstream from the penstock) after flap valves and fish access structures had opened. This trend was greatly subdued in Burringham Reservoir Drain and at the three other drains when fish access structures were not operational.

The highest values and the greatest ranges in measured turbidity were found to occur in drains when the fish access structures were activated, while the lowest values were found when the fish access structures were deactivated. When fish access structures were deactivated turbidity levels at all sites (Burton-on-Stather Drain, the River Eau and Laughton Highland Drain) approached that of Burringham Reservoir Drain (the control site).

Data and field observations highlighted that the increased suspended sediment in the drains was derived from several sources. During inflow on the flood tide, sediment was primarily derived from the River Trent along with scour of the channel bed in the drain by the high velocity flows, particularly between 0m and 10m upstream from the penstock. During outflow, when flap valve and fish access structures had opened, scour of the channel bed by downstream moving flows was the dominant source of sediment. It was also concluded that settling of either input or entrained sediment particles out of the water column was the main cause of reductions in turbidity measured in a drain between the inflow of the flood tide and outflow on the ebb tide from the drain.

At Burton-on-Stather Drain, increases in turbidity were measured at around 175m and 250m upstream when no inflow from the estuary was occurring or measured turbidity downstream of these sites was low. The increases in turbidity were attributed to the variable impact of discharge from Burton Stather STW located ~500m upstream. Although insignificant compared with turbidity changes caused by the inflow from the River Trent, this observation highlights the potential impact within a drain on sediment contributed by upstream sources.

Field observations highlighted that there was significant variability in the bed sediment distribution within Burton-on-Stather Drain, the River Eau and Laughton Highland Drain between the survey dates, particularly after the first spring tide at the end of November 2011. Bed sediment moved around in the drains and marginal deposits was observed to accrete or erode between surveys. This was particularly notable in the River Eau between 50m and 100m upstream from the penstock and also within Burton-on-Stather Drain in the lower reaches between 0m and 50m upstream from the penstock.

The muddy sediments within Burton-on-Stather Drain have only been deposited in the drain since the ACE fish access structure was installed.[7] This is in contrast to observations at Burringham Reservoir Drain where the sediments within the drain are a much darker brown than those in the River Trent and at the other drains surveyed. These sediments were more akin to the colour of the soil surrounding the drain. This further suggests that the fish access structures do exert control on the sediment deposited within a drain, although further quantitative work would be required to determine the impact more precisely.

Greater upstream variability in turbidity, and hence upstream movement of a sediment plume or disturbance of bed sediments as flow moves upstream, was observed during

[7] Neil Goulding, Environment Agency, personal communication (2011)

spring tides. Although spring tides possess higher energy, have a more rapid increase in tidal level and a larger tidal range (compared with neap tides) which cause flap valves and fish access structures to shut more rapidly, the initial volume of inflow and its momentum caused sediment to move much further upstream. This was observed during all surveys on a spring tide, though significantly greater upstream movement of sediment was noted when fish access structures were activated compared to when they were deactivated.

The data showed that the presence of an active fish access structure impacted on the turbidity measured within a drain. At Burton-on-Stather Drain, the data show a ~25% and ~90% increase in measured turbidity levels recorded during the spring-open and neap-open surveys respectively (when the fish access structure was activated) compared to the spring-closed and neap-closed surveys (when the fish access structure was deactivated). At the River Eau, the data show a ~95% increase in measured turbidity in the river during the spring-open and neap-open surveys compared with the spring-closed and neap-closed surveys. Finally, in Laughton Highland Drain, the data show a ~75% increase in measured turbidity in the drain during the spring-open and neap-open surveys compared with the spring-closed and neap-closed surveys.

The data also showed that, when a fish access structure was active, higher levels of turbidity were measured further upstream from the penstock than when the fish access structure was deactivated. At Burton-on-Stather Drain, the data show that up to an additional 200m or reach was impacted by elevated turbidity levels during the spring-open and neap-open surveys compared with the spring-closed and neap-closed surveys. At the River Eau, an additional 200–550m of reach was found to be impacted during the spring-open and neap-open surveys. Finally, at Laughton Highland Drain, an additional 75–250m of reach was found to be impacted during the spring-open and neap-open surveys.

The increases in turbidity within a drain and the elevated turbidity levels measured with increasing upstream distance in a drain are concluded to be caused by the presence of an active fish access structure. The presence of the structure allows both an increased exchange of water with a high suspended sediment load from the River Trent and the drain, and increased scour within the drain due to the greater volume of water exchanged between the River Trent and the drain.

Significant variation in turbidity was observed both within a single tidal cycle and between tidal cycles in the River Trent. For example, turbidity values measured outside Burringham Reservoir Drain during the first spring tide (23–24 November 2011) were between 800 and 1,100NTU, although these decreased to 200–900NTU during the next spring tide (12–13 December 2011). This variability was related to wider scale changes throughout the estuary and North Sea, but reflects the wide variability in turbidity and the variability in responses within drains that can be expected over several tidal cycles.

Despite the observations on the input of suspended sediment from the River Trent and entrainment via scour during inflow and outflow, the study cannot quantify the relative proportion of sediment supplied by each of these processes or the ultimate fate of the sediment, that is, how much sediment entering the drain during inflow is deposited and remains within the drain and how much is entrained and transported during outflow. Quantification of these processes would greatly assist in future management of drains where fish access structures are installed.

The surveys were conducted during a period of very low rainfall where levels within the surveyed drains and the River Trent were unseasonally low. This particularly affected the River Eau where levels where additionally impacted by increased abstractions upstream for the purposes of turf cultivation. This suggests that the findings of this study and the operation of the fish access structures may not be wholly representative of 'normal' conditions.

At each of the three sites where fish access structures have been installed there are significant differences between turbidity measured during the spring-open and neap-open surveys and that measured during the spring-closed and neap-closed surveys. Although changes in turbidity and suspended sediment levels within the River Trent have been measured during these surveys, it is highly unlikely that these alone can account for the differences in turbidity (and hence suspended sediment) measured in the drains. In this case it is highly probable that the fish access structures are responsible for the majority of the observed differences in turbidity and suspended sediment.

6.1.3 Impacts of leakage

Leakage through the flap valve and tidal structure when the flap valve and fish access structure (where present) had shut was found to be a significant problem during the study at all the drains but particularly at Burringham Reservoir Drain and the River Eau.

Leakage was found to cause variations in both salinity and turbidity. Salinity was impacted by dilution due to the incoming leakage. Turbidity and suspended sediment concentrations were increased by a combination of the action of flow upstream from the source of leakage and increases in turbulence from disturbance of the water surface. The latter was particularly common where flow depths were low. Within the River Eau, erosion of sediment by flow (from the south penstock group) over marginal sediment deposits was a key cause of increased suspended sediment loads between 0m and 10m upstream.

The impacts of leakage were observed to occur only at the very start of drains at 0m and 10m upstream. Sites further upstream were not affected. Furthermore, field observations identified that the rate of leakage was reduced during neap tides when tidal levels were lower and pressures on the flap valves and external tidal structure were less than from spring tides. This highlights that leakage is only a localised and transient disturbance, even when very significant such as was the case at the River Eau.

There was no evidence from the collected data or field observations that leakage impacted on the times of opening of flap valves or fish access structures by increasing the volume of flow in a drain and increasing the hydraulic head on the upstream side of the tidal structure.

6.1.4 Flow velocity measurements

The fastest flow velocity measured during the surveys was at the Retarder enabled flap valve at Laughton Highland Drain at 0.481m/s. A peak velocity of 0.327m/s was noted at Burton-on-Stather Drain (ACE fish access structures), while at the River Eau a crudely estimated velocity of ~0.6m/s was recorded. Minimum flow velocities at Laughton Highland Drain and Burton-on-Stather Drain were 0.185m/s and 0.072m/s respectively. In contrast, measured flow velocity at Burringham Reservoir Drain was between 0.001 and 0.012m/s.

These values highlight the significantly higher flow velocities recorded when fish access structures were operational. However, these velocities are not likely to be wholly representative of flow through the flap valve and/or fish access structure because velocity measurements could not be collected at the fish access structure or flap valve (section 5.6). It is therefore expected that significantly higher velocities are likely at and adjacent to the fish access structure and flap valve.

6.1.5 Observations specific to the three fish access structures

During the surveys it was noted that the Stoneman fish access structure installed at the River Eau concentrated the incoming flow into an upstream directed jet. This jet of water was observed to create significant amounts of turbulence and bed scour between 0m and 10m upstream. Its impact was observed to be particularly high during a spring tide due to the rapid rise in the tide. This impact was also observed during a neap tide, although the amount of turbulence and the action of the jet in scouring the bed and entraining sediment had reduced somewhat. This action of the Stoneman is caused by channelling of the incoming flow through the cylindrical orifice of the valve itself.

At Laughton Highland Drain, an unusual response of the Retarder fish access structure was recorded. Experience at the other sites showed that the flap valve on the estuary side of the tidal structure began to open when water levels within the drain and the River Trent were in equilibrium. However, it was observed that the Retarder caused the flap valve to open even though levels in the River Trent were higher than in the drain. This allowed ingress of turbid water from the River Trent, increasing the suspended sediment concentration in the drain between 0m and 50m upstream. This response was attributed to the tension of the Retarder spring forcing the flap valve open but was only observed during the neap tide. This is likely to be because the pressure exerted by the higher level of the spring tide counteracts the additional tension of the Retarder spring, which is trying to force the flap valve open.

Although this response is of importance to enhancing fish and eel passage into the drain it may have additional management implications. It was observed that with the Stoneman operational at the River Eau and the Retarder operational at Laughton Highland Drain, the drains took significantly longer to return to pre-flood tide levels of salinity and turbidity. It is therefore possible that these drains may not fully drain out during a single tidal cycle, particularly during neap tides when the variation in tidal level is limited compared to spring tides. In addition to the potential for greater volumes of suspended sediment to be input to the drain, this sediment could remain in the drain for longer periods before flushing, increasing the chances of settling from suspension and deposition on the bed of the drain.

Differences in the response of each fish access structure were noted by comparing median turbidity values calculated for the 0m site in each drain. Median turbidity calculated at Burton-on-Stather Drain and the River Eau during the spring-open and neap-open surveys were similar, but those calculated at Laughton Highland Drain varied. This was hypothesised to be due to the configuration of each fish access structure. The circular orifices of the ACE and Stoneman access structures are likely to cause the velocity through the access structure to remain relatively similar in spite of varying tidal conditions, while the varying width of the slot around the Retarder controlled flap valve exerts control on the velocities of inflowing water. Velocities through the Retarder flap valve are likely to be further reduced during neap tides compared with spring tides due to the lower tidal level and force exerted on the flap, valve which results in a larger slot. This suggests that the Retarder may be a more appropriate choice where the flap valve of a drain is located in parts of the estuary subjected to more extreme tidal conditions. In addition, the Retarder itself may allow a more ‘natural’ response to varying tides (that is, higher velocities passing through during spring tides and lower velocities passing through during neap tides) rather than the constant velocities of the ACE and Stoneman access structures. Furthermore, the varying flow conditions may also allow a wider range of aquatic species to utilise the access provided by the flap valve while also allowing a much wider range of flow velocities within the lower reaches of the drain than might be expected if other types of flap valve were utilised.

As discussed in section 3.2 the Stoneman fish access structure operates in a different manner to the ACE and Retarder fish access structures. During the surveys it was noted that sediment was being deposited on many of the flat surfaces of the Stoneman, particularly the rigid metal arm and float. It was hypothesised that deposition on these surfaces may adversely affect the operation of the Stoneman due to the addition of extra weight on the float and metal arm. However, during both the spring-open and neap-open surveys, it was observed that the sediment had no discernable impact on the operation of the fish access structure. Furthermore, variation in the distribution of sediment deposits on the Stoneman between all surveys was noted to change, showing that any sediment deposited on the Stoneman would be rapidly removed.

6.1.6 Fish access structure activation periods

Although very difficult to time with any accuracy, observations made of all fish access structures suggested that these structures generally remained open for ~15 minutes on the flood tide and opened up about 30–60 minutes before the flap valve opened on the ebb tide. It is therefore likely that the most significant gains in fish access will occur during the ebb tide.

Analysis of the estimated times of closing and opening of flap valves showed that Burringham Reservoir Drain was closed for the longest time during a tidal cycle, with very little variation in the duration of closure between spring and neap tides. Burton-on-Stather Drain was closed for much shorter durations than the other drains In the River Eau and Laughton Highland Drain; their respective fish access structures reduce the duration of closure of the flap valves on these drains, thus extending the period over which fish and eel passage can occur. Given the data presented for the sites with active fish access structures, the differences in the time of closure compared with Burringham Reservoir Drain are entirely due to the presence of the fish access structure.

6.2 Impacts of tidal flushing on drains

Measurements of the inflow stage of a single tidal flushing event at Adlingfleet Drain suggested that salinity declined markedly during inflow of water from the estuary compared with that measured before the flushing event due to dilution by the large volume of inflowing tidal water. After the flushing event ended, salinity was found to have increased near to the penstock and tidal structure of the drain but to have declined to near pre-tidal flushing levels towards the end of the measured survey section.

Measurements of turbidity showed that pre-tidal flushing event turbidity levels were very low, the water in the drain being essentially clear. During tidal flushing, turbidity increased by several orders of magnitude in response to the input of large volumes of turbid water into the drain. The plume of turbid water was noted to travel up to 1,100m upstream before rapidly declining thereafter. After the tidal flushing event had ceased, turbidity was found to have decreased significantly and was trending towards pre-tidal flushing event levels. This reduction was attributed to a cessation of bed scour by incoming flow from the estuary as well as settling of suspended sediment through the water column.

This study also highlighted the significance of upstream features on controlling the upstream transmission of saline or turbid waters. Hoggard Lane Bridge, located ~1,300m upstream, was found to effectively stop the upstream transmission of saline and turbid waters both during and after the tidal flushing event.

These findings suggest that tidal flushing of a drain could be a useful management technique, particularly since increases in salinity are limited, although consideration must be given to the increased suspended sediment loads entering the drain during such events (as these may be beneficial or detrimental based on the need for the tidal flushing technique). However, the applicability of this technique to other estuaries would need to be validated as the response in salinity and turbidity noted at Adlingfleet Drain is unlikely to be similar around the country.

6.3 Implications for drain management

Given the findings noted above, it is clear that the presence of a fish access structure impacts directly on the amount of sediment entering a drain and the upstream distance over which turbid water and suspended sediment can be transmitted. However, the data collected during this study cannot quantify:

- how much of the sediment that enters a drain is derived from the estuary
- how much of this sediment is deposited within a drain
- how temporal changes in the spring and neap tide over the course of several months or years control sediment dynamics in the drain

These unknowns are crucial in quantifying any changes in drain management.

Before installing a fish access structure, consideration should be given to the catchment area of a watercourse and the presence of any upstream impacts on flow or sediment. If, for example, there are significant sediment sources entering the river upstream (for example, as an industrial discharge from a quarry, fine sediment contributions from cultivated farmland or a large tributary), then this could add to the sediment being stored in a drain behind a tidal structure in addition to the elevated levels being input during the inflow of estuarine waters. Also, specific fish access structures may be more applicable where more precise management of flow within a watercourse is required, such as in the River Eau.

Fish access structures are very likely to require additional management, particularly with respect to sediment. Without further study of sediment dynamics and interactions between the estuary and a drain, however, it is difficult to quantify the level of additional management required.

6.4 Recommendations for future work

During the course of the study and analysis of the results it became apparent that additional studies could be undertaken in the future to build on the findings from this project. These recommendations are detailed below.

The last two recommendations (see sections 6.4.5 and 6.4.6) are considered key to:

- achieving a full and wide understanding of the operation of fish access structures
- quantifying their contribution to fish and eel passage

- adding directly to our understanding of the impact of the fish access structures on drain management

6.4.1 Consideration of a wider range of fish access structures

A more detailed understanding of the impact of fish access structures on water quality and sediment loads within a drain could be gained by undertaking similar studies on other types of fish access structure. In addition, the current work could be expanded by considering the same types of fish access structures but installed on watercourses or drains with significantly different catchment, flow, geomorphological and tidal conditions to those encountered in the current survey.

6.4.2 Repeat study under 'normal' flow conditions

Although not considered critical, it would be advantageous to gather additional results for all the drains surveyed, using the same methodology, to understand how the very low incipient flow conditions and lack of rainfall may have impacted on the results collected. This would additionally lead to the production of a dataset which considers the operation of the types of fish access structures considered in this project over a wide range of flow conditions, including extreme flow conditions.

6.4.3 Upstream impact

Significant upstream impacts on turbidity were noted for the drains in this survey. It would add to the knowledge of the impacts of fish access structures to undertake surveys that focused on understanding the distance and magnitude of their upstream impact under different tidal and operational conditions. This could be reliably undertaken on all the drains monitored, although Burton-on-Stather Drain would be potentially very challenging due to land use and tree cover.

6.4.4 Tidal flushing events

The impacts of tidal flushing could be better understood by monitoring over a full tidal flushing event, both the inflow stage and outflow stage. It would also be beneficial to measure the response of a drain where there are no structures that could potentially act as a barrier to upstream passage of saline and turbid waters. In addition, it would be useful to understand how such tidal flushing events would impact on a drain which was much smaller than for example Adlingfleet Drain or Burton-on-Stather Drain. This could be pertinent in that tidal flushing could be useful in such drains to remove sediment that accumulates over time.

6.4.5 Quantification of fish access structure periods of operation

An understanding of the exact times that fish access structures and flap valves open and close is fundamental to understanding their effectiveness for fish and eel passage and for within-drain management. Such a study could be undertaken by the use of fixed tilt sensors attached to both the fish access structure and flap valve to note when these structures open and close.

Water level sensors could also be attached on the tidal structure on the estuary and landward side of the drains to measure the changes in water level around the tidal structure for the purposes of understanding the critical depths when fish access structures and flap valve open and close. Vented level sensors are likely be most appropriate and robust for use in a tidal environment.

In addition, the provision of two in-situ flow meters at the orifice of the fish access structure and at the lower edge of the flap valve would allow precise determination of the range of flow velocities through each structure during inflow and outflow. This is important for understanding accessibility for fish and eel.

Monitoring of turbidity on the estuary and landward side of the tidal structure would also aid understanding of the suspended sediment entering and leaving the drain. This could be bolstered by autosampling of sediment at the flap valve to allow detailed correlation between turbidity and suspended sediment concentration.

The monitoring equipment would be used remotely, with data ideally being measured and logged over very short time periods, preferably one-minute intervals, with the monitoring lasting over at least one month in order to measure a range of different spring and neap tides. This would allow an exceptionally detailed dataset to be collected, necessary for accurate quantification of the periods when fish access structures open and close. It is expected that data would be downloaded from the monitoring equipment on average every two weeks. Manual, rather than telemetered, data collection would be envisaged as this allows regular inspection of the equipment and tidal structure. Such a study could be undertaken at any of the sites surveyed in the current project (Burton-on-Stather Drain, the River Eau or Laughton Highland Drain) which had active fish access structures.

Monitoring of more than one type of fish access structure is recommended to allow a range of information to be collected. Like the current study, a control site is recommended to allow the operation of a standard flap valve to be compared with those with fish access structures installed.

6.4.6 Bed topographical surveys

In order to understand the long-term changes in sediment accretion and erosion within a drain it would be advantageous to undertake repeat surveys of bed topography and sediment size within a drain over several tidal cycles. Such a study would be best undertaken on a drain largely unimpacted by anthropogenic flow and sediment controls and which was fitted with a normal tidal flap valve (no fish access structure installed). Such a survey would involve measurement of the bed topography, using either graduated stage boards or surveying, and particle size measurements.

When these surveys were complete, a fish access structure could be installed and subsequent re-surveys of bed topography carried out over several tidal cycles. This survey could be coupled with long-term monitoring of turbidity (and sampling of suspended sediment to calibrate turbidity), which would help quantify the proportions of sediment that enter the drain from the River Trent and which is then deposited within it.

References

BLACK AND VEATCH, 2011. *Lower Trent outfalls refurbishment: Provision for eel passage.* Bristol: Environment Agency.

BGS, 2012. *OpenGeoscience – Geology of Britain* [online]. Keyworth, Nottingham: British Geological Survey. Available from: http://www.bgs.ac.uk/opengeoscience/ [Accessed October 2012].

CEH, 2012. *National Rivers Flow Archive* [online]. Wallingford: Centre for Ecology and Hydrology. Available from: http://www.ceh.ac.uk/data/nrfa/ [Accessed October 2012].

CHARLAND, J.W., 1998. *Tide gate modifications for fish passage and water quality enhancement.* Garibaldi, OR: Tillamook Bay National Estuary Project.

CHARLAND, J.W., 2001. *Alternative tide gate designs for habitat enhancement and water quality improvement.* Presented to Marine Environment Engineering Technology Symposium, Alexandria, Virginia.

ENVIRONMENT AGENCY, 2003. *Regulated tidal exchange: an inter-tidal habitat creation technique*. Peterborough: Environment Agency.

ENVIRONMENT AGENCY, 2009. *River Basin Management Plan: Humber River Basin District.* Main document. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011. *Elver and eel passes: a guide to the design and implementation of passage solutions at weirs, tidal gates and sluices. The Eel Manual*. Bristol: Environment Agency.

GIANNICO, R. AND SOUDER, J.A. 2004. *The effects of tide gates on estuarine habitats and migratory fish*. Corvalis, OR: Oregon State University.

INSTITUTE OF HYDROLOGY, 1999. *Flood Estimation Handbook*, v1.0. Wallingford: Institute of Hydrology.

JNCC, 2012. *Special Areas of Conservation (SAC): Humber Estuary* [online]. Peterborough: Joint Nature Conservation Committee. Available from: http://jncc.defra.gov.uk/protectedsites/sacselection/sac.asp?eucode=uk0030170 [Accessed October 2012].

NSRI, 2012. *Soilscapes* [online]. Cranfield: National Soil Resources Institute. Available from: http://www.landis.org.uk/soilscapes/ [Accessed October 2012].

PATRIK, P., VERZHBITSKIY, L., MARIS, T., STEVENS, M. AND VIAENE, P. 2009. *On-site evaluation of a fish-friendlier tide gate design*. In 33rd IAHR Congress: Water Engineering for a Sustainable Environment, pp. 1071-1077.

PETHICK, J., 1993. *An Introduction to Coastal Geomorphology*. London: Edward Arnold.

SOLOMON, D.J., 2010. *Eel passage at tidal structures and pumping stations.* Reading: Environment Agency, Thames Region.

SOLOMON, D.J. AND BEACH, M.H. 2004. *Fish pass design for Eel and Elver (*Anguilla anguilla*).* R&D Technical Report W2-070/TR. Bristol: Environment Agency.

List of abbreviations

AOD	above Ordnance Datum
BGS	British Geological Survey
CEH	Centre for Ecology and Hydrology
JNCC	Joint National Conservation Committee
NSRI	National Soil Resources Institute
NTU	nephelometic turbidity units
ppt	parts per thousand
SAC	Special Area of Conservation
SPA	Special Protected Area
SSSI	Site of Special Scientific Interest
STW	sewage treatment works
WFD	Water Framework Directive

Appendix: Water quality sonde calibration certificates

YSI SONDE CALIBRATION CERTIFICATE

SONDE S/N: 6600 V2-4 06H1900 AB
Date: 16/11/11
Customer: CASCADE CONSULTING
Contact :

CALIBRATION STANDARDS

CONDUCTIVITY	1000µS/CM	**N/A**	1413µS/CM	**N/A**	12.880µS/CM	**12880**
ODO	100%	**N/A**	mmHg	**N/A**	-ve Polarisation	**N/A**
pH	7.00	**N/A**	4.00	**N/A**	10.00	**N/A**
ph mv	7.00	**N/A**	4.00	**N/A**	10.00	**N/A**
SLOPE CHECK	+162 to +180→	**N/A**	-	**N/A**	+162 to +180	**N/A**
ORP mv CHECK	TEMP	**N/A**	mv	**N/A**	Within ysi spec	**N/A**
DEPTH	0.0M	**0.0**	Press Offset		-14.6945	
TURBIDITY	0.0 NTU	**0.0**	100NTU	**N/A**	126 NTU	**126.0**
TURBIDITY Offset	6.10537					
CHLOROPHYLL	RFU ZERO	**N/A**	OFFSET	**N/A**		
BGA-PC / PA	ZERO	**N/A**	OFFSET	**N/A**		

CALIBRATION CONSTANTS - DIAGNOSTICS

CONDUCTIVITY	(0.92-1.08)	**1.028044**	
DO GAIN	(0.7 TO 1.7)	**N/A**	
DO CHARGE	(25-75)	**N/A**	

ALL SENSORS ARE CALIBRATED TO YSI ACCURACY SPECIFICATIONS.

Calibration Technician: J HULL Date: 16/11/11

YSI SONDE CALIBRATION CERTIFICATE

SONDE S/N: 6600 V2-4 06H2574 AD
Date: 16/11/11
Customer: CASCADE CONSULTING
Contact :

CALIBRATION STANDARDS

CONDUCTIVITY	1000µS/CM	**N/A**	1413µS/CM	**N/A**	12.880µS/CM	**12880**
ODO	100%	**N/A**	mmHg	**N/A**	-ve Polarisation	**N/A**
pH	7.00	**N/A**	4.00	**N/A**	10.00	**N/A**
ph mv	7.00	**N/A**	4.00	**N/A**	10.00	**N/A**
SLOPE CHECK	+162 to +180→	**N/A**	-	**N/A**	+162 to +180	**N/A**
ORP mv CHECK	TEMP	**N/A**	mv	**N/A**	Within ysi spec	**N/A**
DEPTH	0.0M	**0.0**	Press Offset		-14.6258	
TURBIDITY	0.0 NTU	**0.0**	100NTU	**N/A**	126 NTU	**126.0**
TURBIDITY Offset	5.42198					
CHLOROPHYLL	RFU ZERO	**N/A**	OFFSET	**N/A**		
BGA-PC / PA	ZERO	**N/A**	OFFSET	**N/A**		

CALIBRATION CONSTANTS - DIAGNOSTICS

CONDUCTIVITY	(0.92-1.08)	**1.027564**	
DO GAIN	(0.7 TO 1.7)	**N/A**	
DO CHARGE	(25-75)	**N/A**	

ALL SENSORS ARE CALIBRATED TO YSI ACCURACY SPECIFICATIONS.

Calibration Technician: J HULL Date: 16/11/11

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