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Factors affecting Atlantic salmon (*Salmo salar* L.) in the Mersey catchment, North West England, and the potential for a recolonisation

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CONTENTS

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ABSTRACT

Factors affecting Atlantic salmon (*Salmo salar* L.) in the Mersey catchment, North West England, and the potential for a recolonisation

Salmon became locally extinct from the River Mersey, northwest England, during the 1950s – 1970s due to deterioration in water quality and man-made barriers. Stray salmon began entering the River Mersey in the 1990s but a self sustaining population has yet to become established. The aim of the study was to review and investigate the recent history of the Mersey catchment, the current status of and factors effecting the salmon population and the potential for a natural recolonisation of River Mersey.

The requirements of adult and juvenile salmon and homing and staying in salmon were reviewed. The physiochemical requirements of salmon are highly specific with connectivity of fundamental importance to upstream migration. In reviewing the status of the Mersey catchment flow manipulation, obstructions to migration, poor water quality and river modifications were common in all rivers. Adult and juvenile salmon have been captured in the Mersey catchment since 2000 but have consistently been caught in low numbers and smolts have not been captured.

Genetic analysis was used to assign salmon entering the Mersey to their region of origin. The Mersey is dependent on stray salmon with the majority from rivers in the Solway and Northwest England areas. A tracking study was used to determine salmon behaviour and route choice in the Mersey catchment and salmon were found to be prevented from moving freely within or upstream of the lower Mersey catchment. Habitat surveys undertaken throughout the catchment revealed a general trend of key habitats existing upstream of barriers and inaccessible to adult salmon. Salmon are unable to recolonise the Mersey catchment in its current state. There are a range of management and restoration options available to restore salmon to the Mersey catchment but a coordinated and concerted effort is required to be successful.

1 GENERAL INTRODUCTION

Atlantic salmon (*Salmo salar* L.) (Figure 1.1) is listed in Annexes II and V of the European Union's Habitats Directive (Anon, 1992) as a species of European conservation importance. Historically, Atlantic salmon (here within referred to as salmon) has been widely distributed throughout northern Atlantic river systems, both in Europe and North America (MacCrimmon & Gots, 1979; Verspoor, 2005; Makhrov *et al*., 2005). However, global catches have been in steep decline since the 1970s (Parish *et al.*, 1998; Lacroix, 2008; Anon, 2011) (Figure 1.2). The reasons for the decline appears to be multi-faceted and include; overfishing, marine mortality, the effects of stocking, degradation of habitat, reduced access to key freshwater habitats, man-made barriers and deterioration in water quality (Verspoor *et al.*, 2007; Jonsson & Jonsson, 2011). As a result salmon populations have been made locally extinct in a number of catchments and rivers throughout the species range (Ugedal *et al*., 2008; Ikediashi *et al.*, 2012) and many river stretches, rivers, and catchments within the current native range of salmon do not support self sustaining populations (Quinn, 2005).

Figure 1.1 An Atlantic salmon (*Salmo salar*) caught from the River Mersey.

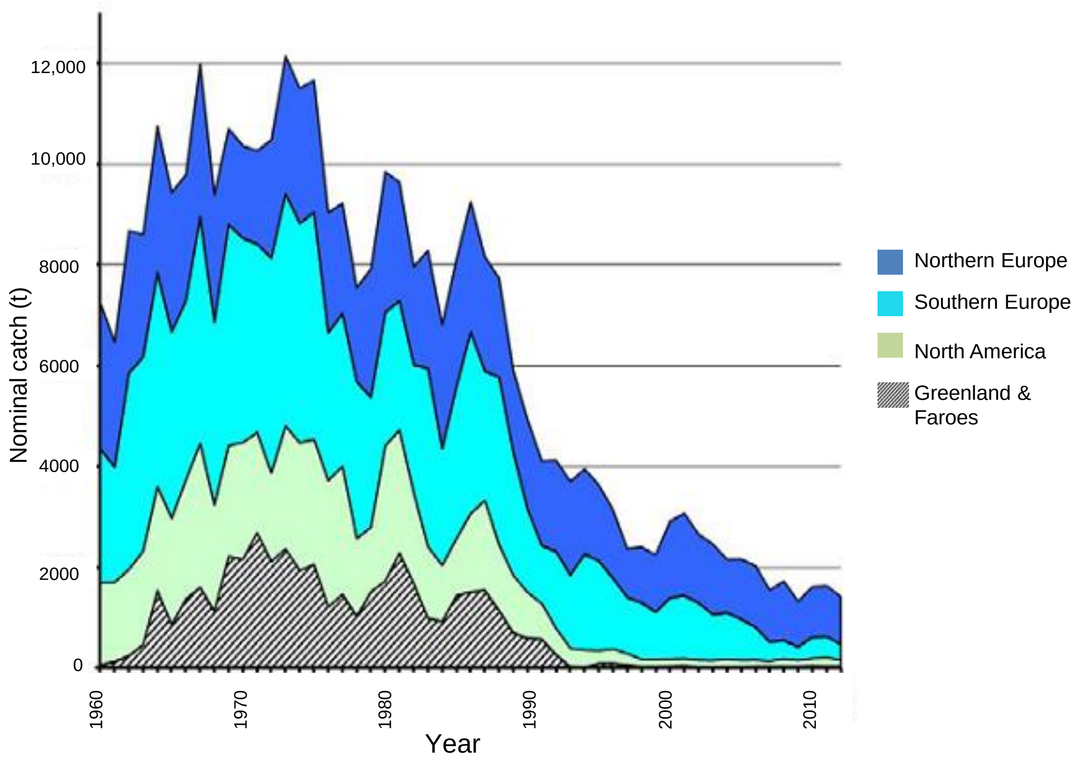


Figure 1.2 Reported total nominal catch of salmon (tonnes round fresh weight) in four North Atlantic regions, 1960 to 2012 (taken from NASCO 2013 report) (Anon, 2013a).

Salmon have considerable sporting and commercial value throughout their range and remain an important keystone species in freshwater habitats, providing a valuable indicator of good water quality (Schtickzelle & Quinn, 2007; Griffiths *et al*., 2011). Mawle & Peirson (2009) estimated a severe decline of salmon stocks would result in an overall economic loss to society in England and Wales of £350 million annually, based on angling expenditure and job losses associated with angling and salmon production. As a result there is considerable interest from commercial and recreational fisheries, local government and as well as conservation and interest groups in supporting the recovery of extirpated populations of salmon.

In rivers with extirpated or critically endangered populations, recovery or recolonisation can take place naturally through straying (Vasemagi *et al.*, 2001; Perrier *et al.*, 2010) and/or stocking using hatchery-reared fish (Myers *et al*., 2004) - where straying is defined as a salmon entering a non-natal river or tributary during its freshwater migration phase. Stocking is costly (Peirson *et al.*, 2001) and has been documented as highly variable in its success (Fraser, 2008; Griffiths *et al.*, 2011), a complete failure (Griffiths *et al.*, 2001; Finnegan & Stevens, 2008) and at times even being detrimental to native stocks (Einum & Fleming, 2001; Ayllon *et al.,* 2006; Hasegawa *et al.*, 2014). However, some fisheries managers continue to see stocking as a viable and effective management tool (Fraser, 2008). Although rare, some studies have documented natural recolonisation through straying as an effective means of restoring salmon populations, for example the River Tyne, England (Milner *et al.*, 2004), River Thames, England (Griffiths *et al.*, 2011), River Seine, France (Perrier *et al.*, 2010), Glacier Bay, Alaska (Milner *et al.*, 1989) and the Baltic Sea, Finland (Vasemagi *et al.,* 2001), largely because the environmental bottleneck constraining natural recovery has been ameliorated. Therefore improvements in the suitability or accessibility of river habitats, stretches, or catchments within the current natural range of salmon may provide the opportunity to increase the distribution of salmon populations through natural processes (Griffiths *et al.*, 2011; Ikediashi *et al.*, 2012). As such, improving understanding of the processes and potential for natural recolonisation is crucial for the effective management and conservation of salmon. There is limited knowledge of and recent studies suggest some ambiguity in the current understanding of:

- potential origins of colonising salmon and the role of meta-population dynamics in recolonisation;
- the effects of long term stocking in regions in which colonisation of newly available catchment may occur;
- the behaviour and success of straying salmon in a highly altered and controlled river system; and
- factors limiting successful natural recolonisation of catchments that have been improved to allow recolonisation.

The River Mersey is situated in northwest England and historically supported a range of locally important fisheries, including salmon (Wilson *et al*., 1988; Burton, 2003; Jones 2006). Due to significant deterioration in water quality and the effects of man-made barriers, salmon became locally extinct sometime during the 1950s – 1970s (Wilson *et al*, 1988; Jones, 2006). Through improved water quality and the opening up of barriers to migration, salmon began re-entering the Mersey estuary in the 1980s (Wilson *et al*., 1988) and the freshwater River Mersey in the 1990s (Burton, 2003; Jones, 2006; Environment Agency (EA), unpublished data). There has been no stocking of salmon in the River Mersey (personal communication, EA) and there is currently thought to be no self sustaining salmon population in the Mersey catchment (EA, unpublished data; Ikediashi *et al*., 2012). As such, salmon entering the Mersey catchment are non-native straying fish (Ikediashi *et al*., 2012). Therefore, the River Mersey presents an opportunity to study natural recolonisation by salmon in the absence of stocking and before a self-sustaining population has yet to be established. This is the subject of this study. The Mersey catchment also presents an opportunity to investigate the natural recolonisation by salmon of a newly accessible river system which is both highly altered and in some of which the flow is controlled.

Recent advances in genotyping (Griffiths *et al.*, 2009; Ikediashi *et al.*, 2012) and telemetry (Lucas & Baras, 2000; Heupel *et al*., 2006) allow for a fully comprehensive investigation into the process of recolonisation in the Mersey catchment. The overall aim of the study was to: review the recent history of the Mersey catchment and current status of the salmon population; to investigate the origins, success, and factors effecting straying fish entering the Mersey and the potential for a natural recolonisation; and to suggest key management and conservation measures to support a natural colonisation. To these ends, the study was divided into key topics that are addressed in Chapters 2 to 7.

Chapter 2 reviews the current literature documenting freshwater physiochemical requirements of adult and juvenile salmon and homing, straying and recolonisation by migrating adult salmon.

Chapter 3 reviews the history of the Mersey catchment (1700 – 2000), the factors that led to the absence of salmon and the current physiochemical conditions and the status of the salmon population in the Mersey catchment.

Chapter 4 investigates the patterns and process of straying in the Irish Sea and the origins of salmon entering the River Mersey and three other rivers discharging into the Irish Sea.

Chapter 5 investigates the behaviour and route choice of stray salmon in the Mersey catchment and factors limiting their upstream migration.

Chapter 6 investigates the availability and accessibility of salmon spawning and juvenile habitat in the Mersey catchment.

Chapter 7 summarises the information gained from Chapters 3 to 6 in the context of the literature reviewed in Chapter 2 and discusses the likelihood of a successful recolonisation and recommends management actions.

Specific objectives and hypothesis are provided at the start of each chapter.

The information in this report is intended to inform and guide management of salmon rivers, particularly those with recently established populations or that are undergoing natural recolonisation. Specifically, the outputs will inform future management decisions and conservation efforts in the Mersey catchment.

2 ECOLOGICAL CHARACTERISTICS OF ATLANTIC SALMON

2.1 INTRODUCTION TO ATLANTIC SALMON

Most salmon populations are anadromous and undertake large-scale transitional migrations between marine and fresh water habitats to spawn (Klemstsen *et al.,* 2003). Anadromy involves major habitat changes by a sequence of directional movements or migrations which salmon must successfully complete to reproduce (Webb *et al.*, 2007). The reproduction and nursery phases occur in fresh water and are followed by a period of feeding in the marine environment characterised by rapid growth and the early stages of sexual maturation (Webb *et al.*, 2007). After spending 1 to 5 years at sea, salmon migrate back into natal rivers, typically entering coastal home waters and rivers several months prior to spawning and moving upstream to spawning grounds during autumn and winter (Quinn *et al.*, 1999; Candy & Beacham, 2000). Spawning mainly takes place between October and December and may be confined to a period of 2 or 3 weeks (Fleming, 1996; Armstrong *et al.*, 2003). The timing of return migrations, referred to as runs, is highly variable within and between populations (Fleming *et al.*, 1996, Klemstsen *et al.,* 2003).

Freshwater migratory behaviour of adult salmonids from self-sustaining healthy populations in unmodified rivers is well defined. There is broad agreement of a three phase migration model in UK rivers of: (1) immediate post entry comprising of rapid upstream movement; (2) river passage comprising of gradual upstream passage, including both up and downstream movement, with holding behaviours of up to several months, which is thought to reflect the search for natal spawning grounds; and (3) rapid migration to the spawning tributary or main river spawning site (Hawkins & Smith, 1986; Milner, 1990; Laughton, 1991; Solomon *et al.*, 1995; Milner *et al.*, 2012). During spawning migrations salmon do not feed and can lose up to 60% of energy reserves fuelling body maintenance, gonad growth and migration (Jonsson *et al.*, 1997), and as a result mortality is high and most salmon only return to fresh water and spawn once or twice (Klemstsen *et al.,* 2003). Females deposit eggs as discrete groups in one or more nests called redds constructed in stable gravel (Webb *et al.*, 2007). Males do not participate in nest acquisition or construction but rather seek out and compete for access to females (Fleming, 1996).

Habitat and water quality requirements of spawning salmon, and ultimately their eggs and juveniles, are highly specific and include a well oxygenated gravel substrate

(Jonsson & Jonsson, 2011). Spawning takes place when both the female and male press their bodies into the nest where eddying currents help retain the eggs (Fleming, 1996). Some male salmon reach sexual maturation as parr whilst in fresh water and are able to spawn with returning females (Figure 2.1) (Fleming, 1996). Salmonids release a small quantity of large eggs: 1600 – 1800 per kg female on average (Armstrong *et al.*, 2003). The fertilized eggs are embedded in the bed substratum and hatch in spring (Jonsson & Jonsson, 2011). After hatching the alevins emerge (Figure 2.1) and find shelter among crevices and interstitial holes on the stream bed, undercut banks and stream vegetation and begin feeding (Jonsson & Jonsson, 2011). After about 2 weeks, most alevins have moved off the nest and established territories, typically 0.1-0.2 m^2 in size, usually located within 1–5 m of the redd (Jonsson & Jonsson, 2011). With increasing age and size, the juveniles, now parr, typically move from the nursery area and start feeding in a range of habitats; from small streams to large rivers (Crisp, 1996; Jonsson & Jonsson, 2011).

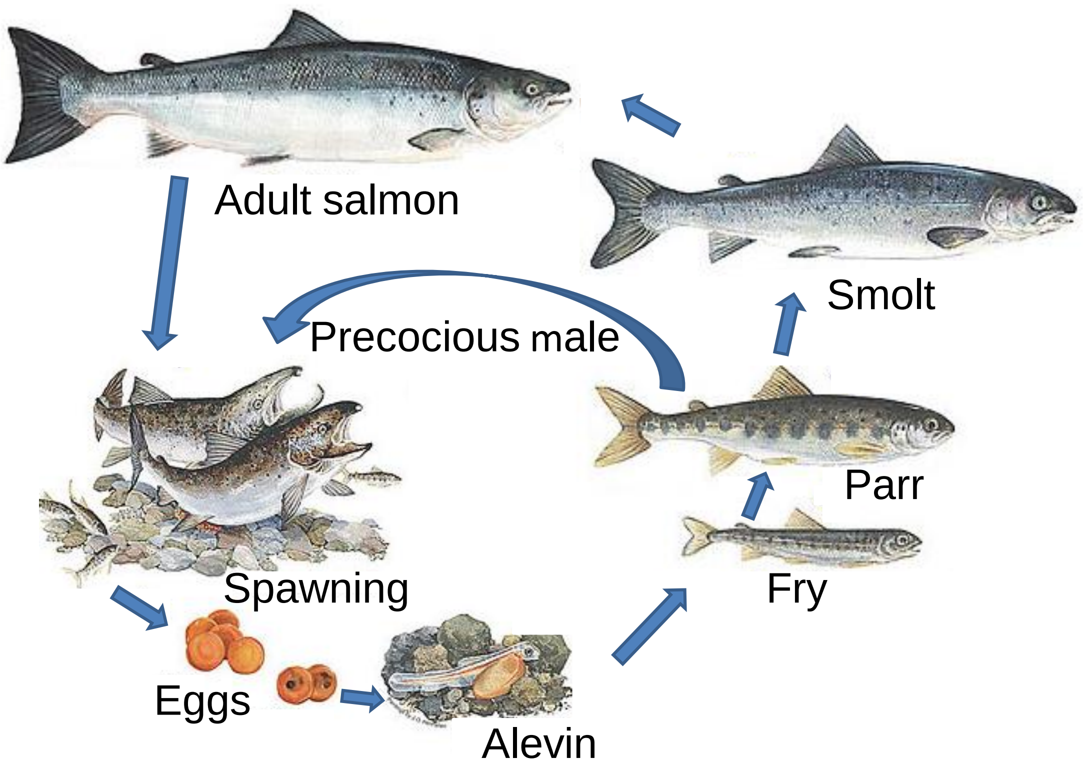


Figure 2.1 Simplified Atlantic salmon life cycle.

Juveniles remain in fresh water for a variable number of years but up to a maximum of 8 years (Klemstsen *et al.,* 2003) after which they undergo physiological, morphological and behavioural changes (smolting) that make them ready for seaward migration and life at sea (Webb *et al.*, 2007; Jonsson & Jonsson, 2011). Smolting involves alterations to vision, buoyancy and ionoregulation mechanisms (Jonsson & Jonsson, 2011) and behaviour (Zydlewski *et al*., 2005). Smolts typically move downstream and migrate to sea in spring (Webb *et al.*, 2007; Jonsson & Jonsson, 2011). Adult salmon remain at sea for 1–5 years after which they return to fresh water for spawning (Klemstsen *et al.,* 2003) typically returning to natal rivers and even to specific spawning grounds (Stabell, 1984; Quinn *et al.*, 1999; Candy & Beacham, 2000).

2.2 PHYSIO-CHEMICAL REQUIREMENTS OF ATLANTIC SALMON IN FRESH WATER

Salmon have specific physicochemical requirements that must be met for them to survive and thrive (Erkinaro *et al*., 1999; Crisp, 2000). Environmental stressors will have a negative impact on salmon and their spawning success; either directly by impacting on physiology or indirectly by causing increased energy consumption through increased avoidance behaviour in response to unfavourable conditions (Thorstad *et al.,* 2008).

The European Union Freshwater Fish Directive (1978) (FFD) (78/659/EC) (Anon, 1978) sets out parameters that all European fresh waters should ensure water quality is sufficient to sustain fish species through all life stages (Table 2.1). The EC FFD sets an upper temperature limit of 21.5° C, a minimum of 9 mg l^{-1} of dissolved oxygen (DO) for at least 50% of the time, and a pH range of 6.0 to 9.0 for salmonids. The physicochemical requirements of salmon are difficult to assess and quantify, vary between life cycle stages and many are covariates to one another (Banks, 1969; Thorstad *et al.,* 2008) and species do not respond linearly to environmental gradients (Armstrong *et al.,* 2003).

Factors likely to affect salmon moving into fresh water include discharge volume and current velocity (flow), water temperature, habitat degradation, physical barriers, and water quality/pollution (Bendall *et al*., 2012). Some are considered fundamental and have been described as master variables such as flow (Milner *et al*., 2012), temperature (Milner *et al*., 2012), dissolved oxygen (Alabaster *et al*., 1991) and river connectivity (Lucas *et al*., 2009). Crisp (2000) identified four stimuli responsible for triggering upstream migration and considered them major factors affecting salmon whilst in fresh water, *viz*.: physiological readiness of fish to spawn, temperature and dissolved oxygen concentration, water discoloration and time of day (i.e. levels of light) and river flow velocity.

Table 2.1 EC Freshwater Fish Directive (1978) for salmonids (Anon, 1978). Target criteria are divided into Imperative and Guideline values, where imperative values must be met for the fishery to achieve compliance and guideline values are desirable quality standards that should be achieved where possible. Note, the EC FFD does not set standards for physical habitat.

Parameter	Standards	
	Imperative	Guideline
Temperature	1.5°C increase due to thermal discharge 21.5°C maximum at monitoring site* 10.9°C maximum for breeding season**	
Dissolved oxygen	50% >9 mg l^{-1}	50%>9 mg l^{-1}
Suspended solids		<25 mg l^{-1}
BOD		<3 mg l^{-1}
pH	6.0 to 9.0	
Phenols	No odour	
Hydrocarbon oil	Non visible	
Nitrites		<0.01 mg l^{-1}
Nonionised ammonia	<0.025 mg l^{-1}	<0.005 mg l^{-1}
Total ammonium	<1 mg l^{-1}	<0.04 mg l^{-1}
Total residual chlorine	<0.005 mg l^{-1}	
Total zinc	<0.5 mg l^{-1}	
Dissolved copper	<0.112 mg l^{-1}	

*where monitoring site is the location where the parameter is measured and **breeding season limit applies only to breeding periods and only in waters which may contain such species.

Solomon & Lightfoot (2008) identified that the presence and well-being of populations of salmonids depends on more subtle factors than the simple absence of directly lethal conditions. Solomon & Lightfoot (2008) suggested permissible conditions may be acting as a control rather than a lethal limit. Studies have documented the absence of salmonids in areas where conditions are below upper or lower lethal limits (Brett, 1956; Huet, 1962; Alabaster & Lloyd, 1982; Hari *et al.,* 2006).

This section will review the physico-chemical requirements and factors affecting all freshwater life stages of salmon. Although not reviewed in this chapter, climate change will influence almost all factors impacting on salmon and is increasingly implicated in the declines of salmon stocks and is a significant factor affecting both adult and juvenile salmon (Seo *et al.,* 2006; Clews *et al.,* 2010).

2.2.1 Water temperature

The influence of water temperature on upstream salmon migration has been studied in detail (reviewed by Banks, 1969; Jonsson, 1991; Solomon & Lightfoot, 2008; Elliott & Elliott, 2010). Moore *et al.* (2012) suggested temperature plays a fundamental role in salmon biology regulating distribution, migration, survival, physiology, feeding, growth, reproduction, ecology and general behaviour, and described it as a master variable. Studies have documented the effect of temperature on fecundity (Jonsson & Jonsson, 1999), time of spawning (Webb & McLay, 1996), passage of barriers (Thorstad *et al*., 2008) and temperature dependent metabolic costs (Moore *et al.*, 2012). There are well defined physiological thermal tolerances of salmonids determined through laboratory studies (Solomon & Lightfoot, 2008). However, these findings may not be applicable to the distribution and behaviour of fish in many UK rivers and there is little information on the thermal requirements of adult salmon in fresh water (Moore *et al.*, 2012) (Table 2.2). Although both the upper and lower limits for fish activity depend on acclimatisation (Beamish, 1978), the EC FFD gives a target criteria of a maximum of 21.5° C at a monitoring site and 10.9° C during the breeding season. Elliott (1994) described the upper and lower critical temperature thresholds for salmon as 22–23° C and 0–7° C, respectively, and the upper incipient lethal temperatures as 27.8° C. The thermal requirements for feeding are at or close to the critical limits for survival, whereas the limits for growth are narrower (Jonsson & Jonsson, 2009).

Swimming capability is reduced at lower temperatures (Beamish, 1978) and reduces the ability of salmon to negotiate physically demanding obstacles, even smaller ones (Jensen *et al.*, 1986). Gerlier & Roche (1998) found temperature to be the main factor affecting the result of attempts to pass obstacles by salmon, by swimming or jumping. Higher water temperatures (>20° C) may also reduce upstream migration activity (Alabaster, 1990). Karppinen *et al.* (2004) found migration speeds were higher at lower temperatures and similarly Erkinaro *et al.* (1999) found migration speed tended to increase with decreasing air temperatures (both studies were conducted within 8.5–17.0° C, so reduced activity was not the result of high water temperatures).

Lower temperatures also impact on migrating salmon with burst swimming limited by low temperatures (Solomon and Lightfoot, 2008). Salmon have been documented unwilling or unable to ascend fish passes or obstacles at low temperatures (Pyefinch, 1995; Mills & Graesser, 1981).

Table 2.2 The effects of temperature on Atlantic salmon whilst in freshwater cited in the literature.

Temperature affect	Literature cited
Adult salmon	
Movement inhibited at >22° C and probably ceased between 22 - 25° C	Alabaster *et al*. (1991)
Upstream movement inhibited at <5° C	Pyefinch (1995)
Lower critical range 0-6° C, optimum range 6-20° C, Upper critical range 20-34° C	Elliott (1981)
Lower critical range 0 -7° C, Upper critical range 22-33° C, Upper Incipient lethal temperature 27.8° C	Taken from Jonsson & Jonsson (2009)
Reduction in migrating salmon at >16° C and <8° C	Brayshaw (1966)
Fish began using thermal refuges at 19° C (Southwest Miramichi, Canada)	Pero (1994)
Movement inhibited at <5° C and >22° C	Crisp (2000)
Juvenile salmon	
Optimum of 15.9° C, lower and upper limit of 6 - 22.5° C for growth, and lower lethal limit of 0° C in two rivers in northwest England	Elliott & Hurley (1997)
Optimum temperature for growth in Baltic salmon fry of 16.6° C	Siginevich (1967)
Preferendum of salmon parr presented with a range of temperatures of 17° C	Javid & Anderson (1967)
Optimum temperature for growth of salmon parr of 16 - 19° C	Wankowski & Thorpe (1979), Dwyer & Piper (1987) and Peterson & Martin-Robichaud (1989)
Parr growth is negligible in the River Eden, north west England <7° C	Allen (1969)
Ceased growing and feeding activity in a Scottish stream <6 - 7° C	Gardiner & Geddes (1980) and Cunjak (1988)
Winter inactivity occurs at <9° C	Gibson (1978) and Rimmer *et al*. (1983)
The lower threshold for growth of juveniles in the field	
7° C	Symons (1979) and Evans *et al*. (1985)
6° C	Power (1969)
5.6° C	Lee & Power (1976)
6.3 - 7.4° C	Jensen & Jensen (1986) and Jensen *et al.* (1989)
6° C	Elliott & Hurley (1997)

The impact of temperature on upstream migration will be site specific and work in combination with other factors, for example: Thorstad *et al.* (2008) suggested low temperatures coinciding with high water discharge in spring may work in combination to delay fish at obstacles; Jensen *et al.* (1998) found salmon did not ascend a fishway in a 10 m high waterfall in spring until both the water temperature had reached 8° C and the water discharge 300 m^3 s^{-1}. The ability of juvenile salmon to swim against strong currents decreases rapidly as the water temperature falls below 6-8° C (Jonsson & Jonsson, 2009). Salmon parr have been documented leaving riffled areas at low temperatures as their ability to retain their position is reduced (Graham *et al.*, 1996).

A likely strategy for salmon to reduce the negative impact of undesirable temperatures is behavioural thermoregulation, moving to areas of a more suitable temperature (Broadmeadow *et al.*, 2010; Moore *et al.*, 2012). Moore *et al.* (2012) found adult salmon were able to locate areas and use cool water refugia at various levels during the holding phases in their spawning migration. Breau *et al.* (2007) found that 1- and 2-year-old salmon parr congregated in cool water sites when the water temperature exceeded 23° C, although age 0+ fish did not increase in abundance in the cool water. Jonsson & Jonsson (2009) suggested this behaviour may be linked to the size of the fish and previous experience from the habitat. If this is the case, it is the youngest fish which are most susceptible to high temperatures.

The growing season of salmon is defined as the number of days during which air temperature reaches a minimum of 5.6° C or water temperature reaches a minimum of 7° C (Armstrong *et al*., 2003). In England, the growing season for salmon is about 315 days/year (Solomon & Lightfoot, 2008). There is also a relationship between degree-days and the growth of juvenile salmon (Solberg *et al.*, 2015). Gibson & Myers (1988) found a positive relationship between temperature and survival of salmon aged <1 year whilst some studies have demonstrated a negative correlation between temperature and the survival of juveniles, as an effect of high water temperature is to lower oxygen content in the water (Jonsson & Jonsson, 2009). There is generally a correlation in size in the early life stages and survival (Einum & Fleming, 2000) and mortality in juveniles is generally considered to be size selective with larger individuals being more resistant to starvation, less prone to size-limited predators and probably able to exploit larger food items (Jensen *et al.,* 2008). Hence early development and growth are critical for survival, both of which are highly affected by temperature (Einum & Fleming, 2000). At temperatures below 7° C salmon parr do not feed well (Gardiner & Geddes, 1980; Crisp, 1995) and show little growth (Solomon & Lightfoot, 2008). Crisp (1995) suggested it is reasonable to assume a lower critical range of 0-7° C for juveniles at which growth is inhibited. However, juvenile salmon are able to acclimatize and Elliott

(1991) documented juvenile salmon feeding as low as 4° C after 2 weeks acclimatization at 5° C. Elliott and Hurley (1997) undertook growth experiments with salmon parr from Rivers Lune and Leven, northwest England and found optimal temperature for growth was 15.9° C and growth occurred in the temperature range of 6–22.5° C. Dwyer & Piper (1987) found juvenile salmon growth rate increased from a temperature of 4° C to a maximum of 16-17° C.

The temperature experienced by females in the months prior to spawning can have a significant effect upon egg quality and survival (Solomon & Lightfoot, 2008). King *et al.* (2003) found eggs derived from females experiencing warmer waters (22° C) were smaller, exhibited reduced fertility, and experienced reduced survival to the eyed stage compared with those from cooler waters. Taranger and Hansen (1993) studied the effects of temperature on ovulation in salmon and found that in females from warmer water groups (gradually falling from 10° C from 1 November – 19 December) ovulation faltered after a week compared with those in the control (ambient) and cool-water groups.

The timing of spawning in different salmonid stocks may be genetically determined by the winter temperature of the environment so that fry start to feed at the optimum time in spring (Shields *et al*., 2004). There are examples of spawning occurring earlier in areas of catchments that see the lowest winter temperatures, for example Webb and McLay (1996) concluded variations in spawning time was a genetic adaptation to allow hatching at the most opportune time in spring.

2.2.2 Dissolved oxygen (DO) concentrations

Hypoxia has been identified as an important environmental stressor affecting many physiological processes of fish (Jonsson & Jonsson, 2011). However, the effects of DO on the passage of salmon in estuaries and fresh water are difficult to elucidate and distinguish from temperature (Alabaster, 1990; Alabaster *et al*., 1991), DO is correlated with temperature (Jonsson & Jonsson, 2009) and the level of oxygen consumption per body weight increases with temperature and activity (Crisp, 2000; Armstrong *et al.*, 2003). Studies have concluded a minimum annual 5-percentile of 5 mg l^{-1} would allow passage of migratory salmonids in most estuaries (Hugman *et al.,* 1984) and the EC FFD set out a minimum for DO of 9 mg l^{-1} for 50% of the time in salmonid rivers (Table 2.1.). Alabaster *et al*. (1991) found the effect on migration of a reduction in DO of 1 mg l^{-1} can be equated with that of an increase in temperature of 4° C. Some laboratory studies have suggested minimum levels of DO are required to maintain some physiological process, such as Beamish (1978) who concluded a critical limit of 5 mg l^{-1}

is required to maintain swimming speeds. Indeed, the high swimming speed or burst activity needed to move upstream of a fish pass (Katopdis, 1994; Colavecchia, 1998) is known to carry a large metabolic cost and the fall in arterial oxygen content can take up to 2 hours to recover from (Tufts *et al.*, 1990).

Some studies have documented the impacts of DO in combination with other factors on salmon, for example Svobodova *et al*. (1993) concluded a reduction in DO in association with increases in temperature and other toxicants had serious effects including depressed immune systems and increased susceptibility to infections, parasites, and pathogens in salmon. Others have suggested fish are able to survive elevated levels of ammonia as long as DO levels are maintained (Alabaster, 1959; 1972; White & Williams, 1978).

As seen with thermal stress, salmonids will deploy behavioural responses to short term or episodic events and to avoid asphyxiation (Crisp, 1996). Spoor (1990) demonstrated brook trout (*Salvelinus fontinalis* Mitchill) actively select zones of preferred levels of DO in the laboratory. Elliott & Elliott (2010) reviewed the temperature requirements of salmonids and cited studies of salmon showing similar behavioural responses to thermal and oxygen stress, but concluded salmon always chose lower temperatures in preference to higher oxygen concentrations.

2.2.3 Water discoloration and temporal variation

Excluding some individual variation, within river migration in UK rivers by salmon is considered to take place during night usually starting at dusk and ending at dawn (Hawkins and Smith, 1986; Webb, 1990; Laughton, 1991). Increased daytime activity may occur during spate conditions and turbid water (Laughton, 1991; Rivinoja, 2001); however, Thorstad *et al*. (2008) suggested excessive turbulence may disorient salmon or prevent passage of obstacles especially at high flows. The diel pattern in the passage of fish counters in weirs and fishways seems site specific and there are conflicting results among studies (Thorstad *et al.*, 2008). Thorstad *et al*. (2008) suggested the difference may thus be a result of different requirements associated with visual orientation in passing different obstacles. Banks (1969) suggested there is a conflict between the need for light to ascend obstacles and a preference for darkness or turbid water as an antipredator device.

2.2.4 River flow

River flow is the factor most frequently reported to control upstream migration of salmon, and effects on upstream migration are complex and confounded with other factors (Jonsson, 1991; Jonsson & Jonsson, 2011; Milner *et al*., 2012). It is widely accepted that the detailed flow requirements of salmon are difficult to quantify and that major inconsistencies in the movement response to flow exist within rivers, between rivers, seasons, and fish run groups (Banks, 1969; Thorstad *et al*., 2008; Milner *et al*., 2012). Studies have shown that increases in water discharge stimulate salmon to enter rivers from the sea and other studies have found the effect of flow to be non-existent (Thorstad *et al*., 1998; Milner *et al*., 2012). As a result common flow standards are inapplicable, although some broad preferenda of depth and velocities exist (Milner *et al*., 2012) (Table 2.3).

Table 2.3 Reported habitats used by spawning salmon (taken from Armstrong *et al.,* 2003).

Habitat variable	Measure	Values	Authors
Water velocity	Mean	40 cm s^{-1}	Heggberget (1991)
		53 cm s^{-1}	Moir *et al*. (1998), Beland *et al*. (1982)
	Range	35–80 cm s^{-1}	Beland *et al*. (1982)
	Minimum	>15–20 cm s^{-1}	Crisp and Carling (1989)
Water depth	Mean	50 cm	Heggberget (1991)
		25 cm	Moir *et al*. (1998)
		38 cm	Beland *et al*. (1982)
	Range	17–76 cm	Beland *et al*. (1982)
Substrate size	Median grain size	22 mm	Kondolf and Wolman (1993)
		5.4–78 mm	Kondolf and Wolman (1993)
		20–30 mm	Crisp and Carling (1989)
	Mean particle size	20.7 mm	Moir *et al*. (1998)
		100 mm	Heggberget (1991)
Depth in gravel of egg burial	Mean	15–25 cm	Bardonnet and Bagliniere (2000)
Percentage fines	Material <1mm	5.40%	Moir *et al*. (1998)
	Range	2.3–8.0 %	Moir *et al*. (1998)

Baxter (1961) defined flows as percentages of the average daily flow (ADF) and suggested adult salmonids require certain thresholds to be exceeded before initiating upstream migration; the minimum percentage required to initiate upstream migrations in salmon is 30-50% ADF in the lower and middle reaches and 50-70% ADF in the upper reaches. Broad agreement now exists that salmon passage through larger rivers is often independent of normal flow variations or flow exceeding some critical threshold level and passage in main stem rivers with more stable, deeper and lower energy channels will be easier than upstream sections (Gee, 1980; Hawkins & Smith, 1986; Laughton, 1991; Smith *et al.*, 1994; Solomon *et al*., 1999; Milner *et al*., 2012).

Thorstad *et al*. (2008) concluded there is a stronger influence of water discharge on river entry from the sea than on upstream migration and suggested salmon moving in the main river stem appear little affected by water discharge, both in exceptionally wet years and during dry summers. Webb and Hawkins (1989) and Thorstad *et al*. (2008) suggested the timing of river entry may depend on a range of factors including the flow patterns of the previous summer and the acclimatisation of the fish to earlier rates of discharge. Webb & Hawkins (1989) and Thorstad *et al*. (2008) suggested there is unlikely to be an annual consistent threshold level of flow triggering entry into tributaries.

Webb (1990) found the movements of salmon in middle reaches of rivers were correlated to mean daily water discharge. Flow increases are important for restarting the movement of holding fish if they have to migrate further upstream (Solomon *et al*., 1999; Milner *et al*., 2012). Laughton (1991) and Solomon *et al*. (1999) suggested discharge is important in stimulating the last stages of upstream migration where salmon were leaving holding pools heading for spawning grounds. Flows are thought to be more important in more upstream areas in smaller river sections (Laughton, 1991; Solomon *et al*., 1999; Webb *et al*., 2001) and increased water discharge towards the spawning period was highly important in allowing fish to access shallower spawning tributaries (Webb, 1989). Flow can significantly influence spawning distributions with increased flow allowing salmon to access steeper, narrower channels, and negotiate physical obstructions (Webb & Hawkins, 1989; Webb *et al.*, 2001). Moir *et al.* (1998) demonstrated fish tend to penetrate further upstream in years with higher median discharge during the spawning period.

The response to flow is relative to the ambient and to the antecedent flow conditions (Smith *et al*., 1994) and Erkinaro (1999) found increasing discharge was generally associated with increased migration speed once salmon were moving. However, Solomon *et al*. (1999) documented a strong tendency for salmon to become quiescent after <20 days in the river and thus less likely to be stimulated by any set of flow conditions. Milner *et al*. (2012) suggested a distinction may be necessary between the flows required to initiate movement of holding fish, those needed to sustain movement and those to enable passage through partial barriers.

Flow is likely to play an influential role in the upstream movement past physical barriers, even in larger rivers when movement would otherwise be independent of flow (Milner *et al*., 2012) and especially during low flows (Hawkins & Smith, 1986; Solomon *et al*., 1999). Erkinaro *et al*. (1999) found increases in water discharge stimulated the passage of riffles. Several studies have documented migrating salmon stopping for extended periods of time below natural features such as riffles (Okland *et al*., 2001), areas of high flow (Rivinoja *et al.,* 2001) and seemingly passable waterfalls (Thorstad *et al*., 2008). The specific flow criteria that either allow or limit the passage of salmon at any site will be unique due to the unique combinations of physical and hydraulic conditions (Solomon *et al*., 1999; Thorstad *et al*., 2008; Milner *et al*., 2012).

Reduced river discharge can lead to some individuals migrating downstream after entering a section of river with reduced flow (Thorstad *et al.,* 2003, 2005). Thorstad *et al*. (2008) suggested the cause was not reduced discharge physically hindering migration but the response to moving into a section of river with a reduced discharge compared with the natural discharge in the river downstream. Salmon have been observed undertaking repeated excursion into tributaries and returning to confluences under low flow conditions believed to be a delay in entry until flow conditions have become favourable (Webb, 1989; Laughton, 1991). There are several reasons why delaying migration in response to low flows may be adaptive; subsequent upstream migration is likely to be impeded, increased exposure to predators, susceptibility to disease also tends to be higher at low flows resulting from crowding of fish, extremes of temperature and reduced DO (Smith *et al.*, 1994).

Fluctuations in discharge influence stream depth and width, water velocity, the hydraulics of intragravel flow, the transport and deposition of fine silt and movements in stream-bed gravel and therefore is a critical factor in juvenile survival (Crisp, 2000) (Tables 2.3 - 2.5). Flows that allow access to and suitable hydraulic conditions over, spawning gravels are key to determining access of spawners and so the distribution of juveniles (Gibbins *et al.* 2002). This could play a significant factor in mortality amongst juveniles as a wide distribution of spawning will reduce density dependent mortality, which is known to be an important control in juveniles (Elliott, 1989). Variations in stream discharges can cause changes in the wetted area in the long term and cause modifications on the stream bed reducing habitat available to salmonids (Gibbins & Acornley, 2000; Malcolm *et al.*, 2012). Fluctuations in wetted area can also lead to the stranding of juvenile salmonids (Crisp, 2000). Drought can have serious repercussions on the survival and growth rates of juvenile salmonids (Elliott, 1986; Crisp, 2000). Studies by Riley *et al*. (2009) and Clews *et al*. (2010) documented increased mortality in salmon under low summer flow conditions, possibly a result of a reduction in habitat.

Huntingford *et al*. (2001) found parr tended to find shelter in an upstream direction at low and decreasing water flows. Gibson & Myers (1988) found a positive relationship between water discharge and the survival of 0+ salmon. Some studies have documented the effect of flow manipulation such as Skaala *et al*. (2014) who reported hydroelectric power generation has considerably changed annual patterns of discharge in some rivers in western Norway and has reduced available juvenile habitat and Nagrodski *et al*. (2012) who reported redds becoming isolated and mass egg moralities as a result of reduced winter discharges in the same rivers. Tetzlaff *et al*. (2008) stressed the minimum discharge should not be viewed as static, particularly given that channel geometry may change and affect depths and velocities produced by a given discharge. Ugedal *et al.* (2008) found juvenile salmon densities reduced by 80% in the River Alta, Norway, upstream of a hydropower development and suggested one primary factor for this was stranding mortality due to sudden drops in water.

The range of water velocities that can be tolerated by juvenile salmon increases with size (Tables 2.4 and 2.5). Salmon can tolerate high water velocities >60 cm s^{-1} but normally avoid velocities >120 cm s^{-1} and prefer habitats with water velocities <20 cm s^{-1} (Armstrong *et al*., 2003).

Table 2.4 Reported rearing habitats used by salmon (taken from Armstrong *et al.,* 2003).

Habitat variable	Measure	Values	Authors
Snout water velocity	Range	5–35 cm s^{-1}	Morantz *et al.* (1987)
	Range	0–20 cm s^{-1}	Heggenes *et al*. (1999)
	Range	10–50 cm s^{-1}	Rimmer *et al*. (1984)
Mean column velocity	Maximum	>60 cm s^{-1}	Heggenes *et al*. (1999)
	Maximum	<120 cm s^{-1}	Morantz *et al.* (1987)
	Minimum	<20 cm s^{-1}	Heggenes *et al*. (1999)
	Utilised preference	50–65 cm s^{-1}	Symons and Heland (1978)
	Utilised preference	10–65 cm s^{-1}	Heggenes (1990)
Water depth	Range	25–60 cm	Symons and Heland (1978), Rimmer *et al.* (1984), Morantz *et al*. (1987), Heggenes (1990)
	Range	20–70 cm	Heggenes (1990)
Substrate size	Range	64–512 mm	Symons and Heland (1978), Heggenes (1990), Heggenes *et al.* (1999)

Table 2.5 Reported nursery habitats used by salmon (taken from Armstrong *et al.,* 2003).

Habitat variable	Measure	Values	Authors
Snout water velocity	Range	5–15 cm s^{-1}	Morantz *et al*. (1987)
	Range	10–30 cm s^{-1}	Rimmer *et al.* (1984)
Mean column velocity	Range	20–40 cm s^{-1}	Crisp (1993, 1996)
	Minimum	>5–15 cm s^{-1}	Heggenes *et al*. (1999)
	Maximum	<100 cm s^{-1}	Heggenes (1990)
	Range	10–30 cm s^{-1}	DeGraaf and Bain (1986)
Water depth	Maximum (for fry)	<10 cm	Heggenes *et al*. (1999)
	Range (for fry)	20–40 cm	Morantz *et al*. (1987)
	Preference (for 0+)	<25 cm	Symons and Heland (1978) Kennedy and Strange (1982) Morantz *et al*. (1987) Heggenes (1990) Crisp (1993)
	Range	5–65 cm	Heggenes (1990)
	Maximum	<100 cm	Morantz *et al*. (1987) Heggenes (1990) Heggenes *et al*. (1999)
Substrate size	Range	16–256 mm	Symons and Heland (1978)

Juveniles prefer shallower and faster flowing waters, preferring velocities of 50-60 cm s^{-1} (Crisp, 2000). Water velocity has a significant role in adjusting population density on newly emerged fish in juvenile salmonids (Crisp, 2000). Too much flow can be detrimental causing downstream displacement and prevent adequate feeding (Tetzlaff *et al.,* 2008). Increased flow can also cause mortality through scour and mechanical shock (Malcolm *et al.*, 2012), a concern of regulated rivers where discharges can increase due to overtopping of reservoirs for example (Gibbins & Acornley, 2000).

2.2.5 Water Quality

There are numerous studies describing the effects of toxins on salmonids (see, for example, Moore & Waring, 1996; 1998; Waring & Moore, 1997; Koltes, 1985; Scholz *et al*., 2000; Ytrestoyl *et al.,* 2001; Lower & Moore, 2007; Tierney *et al.* 2010; Moore *et al*., 2012). Poor water quality can have either lethal or sub-lethal effects and exposure can lead to mortality (McWilliam, 1982) or salmon becoming less able to perform essential functions, such as feeding or swimming (Ytrestoyl *et al.,* 2001; Moore *et al*., 2012). A wide range of toxins have been documented as impacting on salmonids (Table 2.6), for example; wooden fibres, wood pulp and suspended solids (Thorstad *et al.*, 2005); labile aluminium (Skogheim *et al.,* 1984; Velstad & Leivestad, 1984); copper and zinc pollution (Saunders & Sprague, 1967); manure releases (Skaala *et al.*, 2014); acid and aluminium exposure (Monette & McCormick, 2008); mercury entering the diet (Berntssen *et al.*, 2003.); cadmium (Berntssen & Lundebye, 2001); and insecticides (Hatfield & Anderson, 1972).

Most chemical contaminants can disrupt olfactory based responses. Contaminants can act as signals, modify odorant perception, and/or act on the nervous system and/or other physiological responses (i.e. not directly through olfaction) and so compromise the migratory behaviour and ultimately the reproductive success of salmon (Lower & Moore, 2007; Tierney *et al.*, 2010; Moore *et al*., 2012). The impact of metals on homing and other behaviours is well documented (Florea & Busselberg, 2006; Tierney *et al.*, 2010). Baldwin *et al*. (2003) documented a decline in homing success in coho salmon (*Oncorhynchus kisutch* Walbaum) from copper exposure and Tierney *et al.* (2010) found exposure to aluminium reduced olfaction in salmonids. Other contaminants such as pesticides (Tierney *et al.*, 2010); fungicide and insecticides (Jarrard *et al*., 2004), herbicides (Tierney *et al*., 2007) and hydrocarbons (Klaprat *et al*., 1988) have also been documented impacting olfaction in salmonids.

Acid rain, mining wastes and industrial discharges are among some of the factors that can alter the pH of an aquatic environment, and extremes of pH, both acidity and alkalinity also alter fish olfactory responses in salmon (Tierney *et al.*, 2010). Increased acidity and inorganic aluminium (Al) is known to cause declines in salmonid populations (Jonsson & Jonsson, 2011) and salmon are extinct from rivers having an annual mean pH <5.2 and a concentration of aluminium (labile Al) of >50 µg l^{-1} (Kroglund *et al.*, 2007). pH values >9 affect the growth of most salmon by interfering with normal ionic regulation (Jonsson & Jonsson, 2011). Changes in pH are also known to modify the toxicity a variety of pollutants (e.g. many trace metals) (Sadler & Lynam, 1987; Everall *et al.*, 1989). Ytrestoyl *et al.* (2001) found swimming performance of salmon was reduced after exposure to reduced pH and acid river conditions. Elevated levels of pH increase the toxicity of ammonia to fish, by increasing the proportion of un-ionised ammonia which is highly toxic to salmonids and can result in stress or direct mortalities (Train, 1979). Salmon eggs are vulnerable to low pH levels and water reaching pH <3.5 is fatal to eggs and pH of <4.5 inhibits the action of the hatching enzyme (chorionase) in salmon (Mills, 1989).

Table 2.6 Summary information regarding the toxins affecting salmonid fish together with their limits and guidelines (EC Freshwater Fish Directive (1978) for salmonids (Anon, 1978)).

Determinants	Limits/guidelines
Finely divided inert solids	25-80 mg l^{-1} acceptable, <15 mg l^{-1} preferable
pH	Harmful at <5.0 and >9.0, lethal at <4.0 and >9.5-10
Ammonia	Toxicity is due to the unionized form (NH_3). The guideline value for NH_3 is 5 µgl^{-1} with a maximum permissible of 25 µgl^{-1}
Chlorine	The toxic species is hydrochloric acid (HOCl) which is most abundant at low pH. Maximum permissible is 5 mg l^{-1} as HOCl
Cyanides	The toxic species is the unionized molecule (HCN). Lethal at about 4 µg l^{-1}
Nitrates	Toxic when reduced to <0.01 mg l^{-1} nitrite (NO_2^-)
Nitrites	Highly toxic as the nitrite ion NO_2^- with an EU directive guideline of < 10 µg l^{-1} and 3 µg l^{-1} as NO_2^{-N}
Phosphates	Not toxic but contribute to eutrophication. Limit is <0.2 mgl^{-1} as PO_4
Aluminium	Only toxic as the monomeric form Al^{+++} which occurs only in soft, low pH waters and is toxic at concentrations <3 µg l^{-1})
Chromium	Toxic as CrO_7. Recommended mean concentration <25µgl^{-1} and the 95 percentile ahould be <100 µgl^{-1}
Copper	Toxic as the cupric ion (Cu^{2+}). Guideline values ranging from 5 mg$l^{-1}$for soft waters (<10 mg l^{-1} as $CaCO_3$) to 112 mgl^{-1} for hard waters (>300 mg l^{-1}as $CaCO_3$)
Iron	Only normally toxic in waters already dangerously acidic for fish
Lead	Damaging to salmonids at levels of about 1 mg l^{-1} in waters of medium softness (50 mg l^{-1} of $CaCO_3$)
Mercury	Exceptionally toxic in certain compounds
Nickel	Average concentration should be 10 µg l^{-1} and 95 percentile 30 µg l^{-1} in soft water (20 mg l^{-1} as $CaCO_3$) and the average and 95 percentile should be 40 mg l^{-1} and 120 mg l^{-1} respectively, in hard water (320 mg l^{-1} as $CaCO_3$)
Zinc	Mandatory levels from 30-500 µg l^{-1} for water with hardness values from 10-500 mg l^{-1} as $CaCO_3$

Juvenile salmonids are affected by pH fluctuations in the same manner as they are during the intragravel stage. pH levels of >9.2 and <4.5 can be harmful and in some cases lethal to both juveniles and adults (Bandt, 1936; McWilliam, 1982).

Excessive levels of ammonia can cause direct damage to the gill epithelium causing asphyxiation, increased acidosis and reduction in blood oxygen-carrying capacity, the inhibition of cell metabolic functions, disruption of osmoregulation, disruption of blood vessels, repression of the immune system and an increased susceptibility to bacterial and parasitic diseases in salmonids (Camargo & Alonso, 2006). Unionized ammonia (NH_3) is very toxic to fish, whereas ionised ammonia (NH_4^+) is less toxic and sometimes non-toxic (Camargo & Alonso, 2006). The EC FFD sets an imperative maximum value of 0.025 mg l^{-1} of unionised ammonia and 1 mg l^{-1} for total ammonium for compliance. However, where aquatic systems are under excessive stress from hypoxic conditions these standard values may not be sufficient to prevent damage and therefore the EC FFD suggests guideline standard of 0.005 mg l^{-1} for NH_3 and 0.04 mg l^{-1} for total ammonium for salmonids (Table 2.1). In laboratory studies, Herbert & Shurben (1965) found salmon fry to have a LC_{50} (median lethal dose; the concentration which is fatal to 50% of the test group) of 0.23 mg l^{-1} of NH_3 after exposure for 24 hr and Rice & Bailey (1980) found pink salmon (*Oncorhynchus gorbuscha* Walbaum) fry to have a LC_{50} of 0.08 mg l^{-1} of NH_3 after exposure for 96 hr. Increases in pH and temperature tend to increase the relative proportions of unionized ammonia, and decreases in DO concentrations increase the susceptibility of fish to ammonia toxicity (Camargo & Alonso, 2006). Svobodova *et al*. (1993) documented the combined sub-lethal, but chronic toxicity, of ammonia and low DO depressed immune systems and increased susceptibility to infections, parasites and pathogens in salmon.

Both nitrate and nitrite are toxic with the main effect on salmon being the conversion of oxygen carrying pigments to a form incapable of carrying oxygen (Cheng *et al*., 2002). Nitrite (NO_2) is more toxic owing to the low branchial permeability to nitrate ions in fish (Camargo *et al.,* 2005) and the EC FFD sets a guideline standard of <0.01 mg l^{-1} NO_2.

The toxic effects of aquatic contaminants can result in inappropriate behavioural responses and can have severe implications for survival of salmon (Weber & Spieler, 1994). Juvenile Chinook salmon exposed to 1 and 10 µg l^{-1} of pesticides for only two hours lost their behavioural responses to alarm substances from a predation threat (Scholz *et al*., 2000). Organophosphates reduce the numbers of salmon holding territories and altering the social structuring within an artificial stream for up to 7 days after exposure (Symons, 1973). Koltes (1985) documented a 5 h pulse of 100 µg l^{-1} of copper disrupted schooling behaviours in adult salmon. Laboratory studies showed salmonids are able to detect and avoid chemical components (Gray, 1983; Atland, 1998), and avoidance and refuge seeking behaviour in salmon in response to unfavourable environmental conditions is well documented (Spoor, 1990; Ytrestoyl *et al.,* 2001; Thorstad *et al.*, 2008; Elliott & Elliott, 2010; Broadmeadow, *et al*., 2010; Moore *et al*., 2012).

Poor water quality can have indirect effects such as those of synthetic pyrethroid (SP) sheep dips, which is of major concern (Hendry *et al.*, 2003). The Environment Agency in England and Wales suggested that inadequate disposal of SP has seriously affected several thousand kilometres of upland streams in England, sometimes wiping out invertebrate populations resulting in little or no food for juvenile salmon (Millbrand, 1997)

2.2.6 Barriers and river connectivity

River connectivity is fundamental to the upstream migration of salmon (Thorstad *et al.,* 2008) and anything acting to prevent upstream migration will lead to a population decline (Lucas *et al.*, 2009). The dendritic structure of streams and rivers make them vulnerable to fragmentation by anthrpogenic barriers (Yeakel *et al.*, 2014) and a single barrier can sever connectivity in an entire stream, tributary or river (Favaro & Moore, 2014). Anthropogenic barriers dramatically reduce river connectivity and access to habitats and their effect can be detrimental to salmon populations (Lucas & Baras, 2001; Gowans *et al.*, 2003; Lucas *et al.*, 2009; Favaro & Moore, 2014). Barriers can form impassable obstacles to salmon and prevent upstream migration and access to key habitats preventing salmon from spawning (Gowans *et al.*, 2003; Thorstad *et al.*, 2008). Barriers are responsible for declines and extirpation of many salmon populations (Netboy, 1968; Mills, 1989; Fraser *et al.*, 2007; Gephard, 2008; Saura *et al*., 2008; Wolter, 2015).

Barriers to migration reduce motivation to migrate (Thorstad *et al*., 2003); there are examples of salmon leaving rivers systems and entering neighbouring rivers after encountering barriers to migration (Croze, 2005), including those that are not absolute barriers to upstream migration (Thorstad *et al.*, 2003; 2005). Significant riverine obstacles have been documented causing erratic movement patterns downstream of the obstacle (Thorstad *et al*., 2005; Kennedy *et al*., 2013) and can increase stress in fish (Mathers *et al*., 2002); both of which have been documented reducing fitness and success and causing immunosuppresion in salmonids (Jacobson *et* al., 2003; Quigley & Hinch, 2006; Cooke *et al*., 2006; McConnachie *et al*., 2012).

Fish passage success is determined by the physical parameters and hydraulic conditions of the barrier and the darting and jumping abilities of the fish during migration (Meixler *et al.*, 2009). Some barriers may be passable under a limited range of environmental conditions (Hawkins & Smith, 1986; Lucas & Frear, 1997; Solomon *et al*., 1999; Moore *et al.*, 2012). There are studies documenting the cumulative effect of multiple partial barriers on the upstream migration and motivation of salmon (Gowans *et al.,* 2003; Thorstad *et al*., 2005) and in other of species, for example, the river lamprey (*Lampetra fluviatilis* (L.)) (Lucas *et al.*, 2009). Partial barriers can lead to prolonged delays in salmon reaching suitable spawning sites (Ovidio & Philippart, 2002; Thorstad *et al*., 2005), increasing exposure to environmental stressors, the over-ripening of gonads, salmon entering unsuitable areas to spawn and reaching spawning grounds too late for spawning (Thorstad *et al.*, 2008). Thorstad *et al.* (2008) identified the magnitude of delay is often not predictable and examples exist of salmon stopping below natural barriers that may not appear to present a barrier to migration (Okland *et al.*, 2001; Thorstad *et al.,* 2008).

The depth of a plunge pool below a barrier can affect the ability of migratory fish to pass that barrier and a pool depth at least twice as deep as the fish is long is required to achieve maximum leaping ability (Powers & Orsborn, 1985; Ovidio & Philippart, 2002). In shallow plunge pools, falling water can create turbulence affecting leaping orientation (Powers & Orsborn, 1985), and Meixler *et al.* (2009) suggested even large salmon may be blocked from passing barriers if the plunge pool is shallow. Ovidio & Philippart (2002) documented a 0.45 m vertical sill as being insurmountable for salmonids if the water depth is not sufficient, and radio-tracking studies revealed weirs with a head losses of only 0.5 m and of 1.2 m can delay and be impassable to salmon, respectively (de Leaniz, 2006).

Flow is likely to play an influential role in the upstream movement past physical barriers (Milner *et al.,* 2012). Karppinen *et al.* (2002) concluded water current is the main factor guiding ascending fish below obstacles such as dams and minor changes in flow regimes may alter fish behaviour and orientation. Jensen *et al.* (1998) suggested fish attempting to overcome obstacles during high flows may be doing so at an energetic disadvantage compared with those waiting for more optimal conditions. High speed swimming or burst activity needed to move upstream of a fish pass or obstacle (Katopdis, 1994; Colavecchia, 1998) carries a large metabolic cost and a fall in arterial oxygen content can take up to 2 hours to recover from (Tufts *et al.*1990). Gowans *et al.* (2003) identified rates of metabolisms in salmon remained high for prolonged periods of time after passing through a fish ladder and suggested this would reduce the amount of energy available for further migration, spawning activity and gonad production.

Some barriers are associated with facilities to generate hydropower. Although mortality resulting from turbines is highly site specific, major issues exist for any migrating fish such as elevated stress and injury to and mortality of eggs, larvae, juveniles and adult fish that pass through turbines (Cada *et al*., 2006; Larinier, 2008). Webb (1990) associated the loss of tagged salmon migrating upstream with entry into unscreened turbine draft tubes. Larinier (2008) documented cumulative mortality rates of 64% of juvenile salmon moving downstream as a result of 23 small-scale hydroelectric plants in France.

Fish pass construction is frequently used and considered one of the most effective means to mitigate barriers and hydropower schemes (Robson *et al.*, 2011). Fish pass efficiency has been suggested to depend on the topography, location and hydraulic conditions near the entrance (Guiny *et al.,* 2003) and construction must be both site and species specific (Robson *et al.*, 2011). However, problems have been documented such as flows though the pass being ineffective to attract and ensure upstream migration (Bjorn & Perry, 1992); ineffective location of fish pass entrance (Clay, 1995); colour of the pass channel (Lindmark & Gustavsson, 2008); and poor admission of light into the pass (Turnpenny *et al.* 1998) putting salmonids off entering the pass. Gowans *et al.* (2003) found salmon stranded in rocks alongside a fish ladder and highlighted the importance of constructing fish passage facilities so they are as easy to pass through as possible.

2.2.7 Habitat and spawning site

Habitat use is a central aspect in the ecology of a species and those individuals exploiting richer habitats can grow larger, compete better and produce more offspring than conspecifics exploiting poorer habitats (Jonsson & Jonsson, 2011). Armstrong *et al*. (2003) concluded that the habitat features most important to the distribution and abundance of salmonids are depth, current, substrate and cover. There is also genetic adaption to local habitats in salmon, and salmonids are phenotypically highly plastic in their response to environmental factors. They have evolved a range life history strategies enabling them to thrive in a range of conditions, provided that the key habitat of useable spawning gravels is available (Armstrong *et al.*, 2003; Malcolm *et al.*, 2012; Dunbar *et al.*, 2012).

The total area and distribution of suitable spawning gravel is of fundamental importance in determining the productivity of a river and may limit productivity in many streams (Kondolf & Wolman, 1993; Armstrong *et al.*, 2003). Spawning habitat preference is well documented in salmon (Table 2.7). Adults select sites for spawning where depths and velocities can ease the process of redd cutting (Moir *et al.,* 2012), the latter of which typically ranges from 15 – 80 cm s^{-1} (Armstrong *et al*., 2003). Moir *et al*. (2002) found site-specific upper limits to depth utilization in that the deepest water tended to be avoided when spawning and suggested that, for deep water to be suitable for spawning, it must be associated with proportionally higher flow velocities.

Cover, in the form of boulders, overhanging banks and deep pools is required by adult salmon migrating upstream both as protection from predators and to enable them to avoid bright sunlight (Crisp, 1996). Habitat heterogeneity is known to play a role in salmon population density with a variable habitat more likely to support larger population densities of salmonids (Crisp, 2000; Dolinsek *et al*., 2007). Finstad *et al.* (2007) demonstrated that increased availability of shelters significantly improves juvenile salmon performance, which is most likely as a result of a reduction in metabolic costs associated with high-shelter environments. In the same study, Finstad *et al.* (2007) described habitat structure as an integral part of predator avoidance and the availability of shelters having a direct influence on mortality. In addition, increased habitat heterogeneity increases visual isolation, which will reduce competitiveness and allow more individuals to coexist, increasing the productivity of the stream (Stradmeyer & Thorpe, 1987; Armstrong *et al.*, 2003). Visual isolation along with available cover, water velocity and the irregularity of the stream bed determines the size of the territory occupied by salmon (Kalleberg, 1958; Armstrong *et al.*, 2003).

There are individual differences in substrate and habitat preference in juveniles (Johnsson *et al*., 2000), and the preferred particle sizes increase with increasing size of the fish (Heggenes *et al.,* 1999). Nursery habitats used by fry and parr are well documented (Tables 2.5 and 2.7). Most small parr (<7 cm) appear to prefer substrate particle sizes of >1.5 cm in diameter and individuals >7 cm prefer substrate stone diameters of 10–50 cm, or more (Jonsson & Jonsson, 2011). Juveniles tend to prefer a water depth 20-60 cm and stream velocities of 50–65 cm s^{-1} (Armstrong *et al*., 2003).

Overhead cover is an important feature of salmon parr habitats (Heggenes & Traaen 1988; Mäki-Petäys *et al*., 1997; Johansen *et al*., 2005). Milner (1982) suggested that cover is possibly the most important single attribute determining salmonid abundance. Gibson (1978) and Heggenes *et al.* (1999) found shade and overhead cover attracts salmon, and the absence of cover causes chronic stress in salmon and reduced growth in cultured salmon (Pickering *et al*., 1987).

Table 2.7 Substrate quality for spawning salmon and parr (Semple, 1991). Semple (1991) defined silt (<0.1 cm diameter, i.e. fine particles of earth and sand); sand (0.1-0.6 cm diameter); gravel (0.6-6.4 cm diameter); cobble (6.4-25.0 cm); boulder (>25.0 cm) and bedrock (ledges/sheets of rock).

Habitat Quality	Composition
Spawning	
Good	40-80% gravel 10-40% cobble <20% boulder <20% combined silt and sand
Marginal	40% gravel 50-90% combined gravel and cobble <20% combined silt and sand
Poor	>8% fine sand (0.03-0.05) >15% fines
Salmon parr nursey	
Good	>50% combined cobble and boluder >20% cobble >18cm deep
Fair	10-49% combined cobble and boulder <50% gravel <18cm deep
Marginal	<10% combined cobble and boulder <18 cm deep

Shade cast by riparian vegetation can substantially modify the thermal regime of a watercourse (Caissie, 2006; Broadmeadow *et al.*, 2010) and therefore can strongly influence the potential survival of juvenile salmon. Broadmeadow *et al.* (2010) found riparian shade affected both the timing and the magnitude of stream water temperature change, and substantially moderated the thermal regime of woodland rivers in particular. Broadmeadow *et al.* (2010) suggested streams that are surface run-off water dominated, i.e. not ground water fed, are very responsive to changes in air temperature and solar insolation, displaying marked diel and seasonal variation in water temperature, which is in sharp contrast to streams dominated by ground water (Webb and Zhang, 1999). Reduced water temperature can have a marked effect and can reduce the growth of salmonids, but overhead cover might be preferred as it provides protection from predation (Armstrong *et al.*, 2003). Broadmeadow *et al.*

(2010) suggested riparian shade is likely to become increasingly important to salmon in reducing the impact of thermal stress due to climate change.

Increased mortality resulting from a reduction in habitat during low summer flow conditions has been documented in regulated rivers (Riley *et al.,* 2009; Clews *et al.,* 2010). Geomorphologists have provided evidence of the impacts of impoundments and physical processes in rivers, including changes in sediment transport (Williams & Wolman, 1984) and the establishment, break-up and re-establishment of the armoured layers of compacted sediment on the river bed (Vericat *et al*., 2006); each of which has important implications for salmon, such introducing harmful fine material and impeeding redd construction (Malcolm *et al.*, 2012).

2.2.8 Interspecies and intraspecies specific competition

Salmonid populations are often regulated by density-dependent mortality, typically during the early life stage after fry emerge from spawning gravel (Milner *et al*., 2003). Jonsson *et al*. (1998) found the number of smolts leaving the River Imsa in Norway to be density dependent and suggested there must be a carrying capacity limiting the population size in fresh water. Juvenile salmon are known to protect their territory and compete for shelters during winter; newly emerged fry occupying a reach of up to 0.02-0.03 m^2, parr a reach of >1.0 m^2 and juvenile salmon of 10 cm occupying territories of 0.2-5.0 m^2 (Kalleberg, 1958; Jonsson & Jonsson, 2011). Harwood *et al*. (2002) and Finstad *et al*. (2007) suggested the increase in aggressive behaviour and energy expenditure associated with defending territories may be detrimental to survival. Mortality in juvenile salmon is generally considered to be size selective with larger individuals being more resistant to starvation, less prone to size-limited predators and probably able to exploit larger food items (Jensen *et al*., 2008). After dividing emergence times in salmon into three groups, accelerated, normal and decelerated, Skoglund *et al*. (2010) found the performance of those that emerged the earliest was the strongest and suggested offspring success in salmon is highly affected by intraspecific competitive interactions.

Due to the similar habitat requirements of juvenile salmon and brown trout (*Salmo trutta* L.) (herein referred to as trout), inter-species competition plays a role in salmon survival (Armstrong *et al*., 2003). Several studies concluded that there is spatial segregation between juvenile salmon and trout; Kennedy & Strange (1982, 1986) found 0+ and 1+ aged trout tended to use deeper water than salmon of the equivalent age group, and salmon were found in higher stream bed gradients. Jones (1975) recorded species segregation of the two species in different habitat types, reporting age 0+

salmon are found predominantly in riffles, 0+ trout and age 1+ salmon in riffles and runs, 1+ trout in runs and pools and 2+ and older trout in pools. Bagliniere *et al*. (1994) found juvenile salmon were predominately found in shallow and fast moving water of the main river whereas trout are found in tributaries in the upstream section of the river. Trout are known to be more aggressive and dominant than salmon parr of similar size and have advantages in deep and slow moving water, and salmon parr are more dominant than trout of similar size in fast flowing shallow areas (Armstrong *et al*., 2003; Jonsson & Jonsson, 2011).

2.2.9 Factors affecting the incubation and emergence of eggs

Egg burial depth is correlated with female fish length (Ottaway *et al.*, 1981; Crisp & Carling, 1989) and can vary between 5 and 30 cm (Crisp & Carling, 1989; Crisp, 2000). Burial depth is likely to affect both development and survival, influencing the temperature experienced by the egg, potential loss by washout, asphyxiation and exposure during low flows (Crisp, 1996). There is a high heritability in time of alevin emergence in salmonids (Jonsson & Jonsson, 2011).

Salmon embryos hatch when a specific number of degree-days have been accumulated (Jonsson & Jonsson, 2011). Crisp (1981) maintained that salmon require an average of 63 days from fertilisation to 50% hatching at 8.0° C (504 degree-days) and 37.8 days at 12.0° C (454 degree-days). However, some authors caution against simple concepts such as degree days (Gunnes,1979; Solomon & Lightfoot, 2008). The optimal temperature for egg incubation is 6° C and mortality begins to increase above 12° C (Peterson *et al.*, 1977) (Table 2.8). King *et al.* (2007) suggested spikes of high temperature might be as damaging to eggs as prolonged exposure. Hatched alevins of salmonids are able to survive significantly higher temperatures than pre-hatching stages: Ojanguren *et al*. (1999) reported hatched larvae surviving at 22° C.

High temperature can cause low oxygen content in the water and accompanied by pollutants can cause egg mortality (Jonsson & Jonsson, 2009). Lack of oxygen can also delay egg development time (Solbé 1997). Water reaching pH <3.5 is lethal and pH <4.5 or lower inhibits the action of the hatching enzyme (chorionase) in salmon (Bandt, 1936; McWilliam, 1982). pH values of <4.5 can have a lethal effect if in association with other toxicants, such as high levels of aluminium and other heavy metals (Sadler & Lynam, 1987; Everall *et al.*, 1989).

Table 2.8 The effects of temperature on salmon egg cited in the literature.

Temperature affect	Literature cited
>50% survival to hatch of salmonid eggs when inclubated between 0° C and 12° C	Gunnes (1979), Humpesch (1985), and Crisp (2000)
Upper thermal limit of eggs of 16° C	Ojanguren *et al*. (1999)
Poor survival (66.1% mortality) was recorded by at 12° C	Gunnes (1979)
Increased mortality of salmon eggs at temperatures of 12° C	Peterson *et al.* (1977)
Optimal incubation temperature of eggs of 6° C	Peterson *et al.* (1977)

Reductions in flow can have a direct effect on egg and embryo survival through dewatering and scour during the incubation period (Malcolm *et al.*, 2012). A good supply of oxygen in water within redds is essential for the survival of alevins to emergence (Chapman, 1988). Alevins are especially vulnerable to dewatering and high mortalities have been recorded even over short (1 hour) periods of dewatering (Malcolm *et al.*, 2012). Concerns apply to regulated rivers where redds constructed during higher discharges will be dewatered as flows return to compensatory flow (Gibbins & Acornley, 2000), and to non-regulated rivers related to implications of climate change (Jonsson & Jonsson, 2011). Large spates can cause movements of gravel beds, the wash out of juvenile salmon and eggs, the destruction and death of salmonid eggs and alevins by physical damage and predation during drifting (Crisp, 2000). Mechanical shock can cause high mortality rates with sensitivity developing soon after fertilisation (Jensen & Alderdice, 1983; Roberts and White, 1992; Crisp, 1996). If eggs are mechanically disturbed or stressed through lack of oxygen they can hatch sooner (Naesje & Jonsson, 1988), which is of significance as fry survival will be low if emergence is too early (Einum & Fleming, 2000).

There is a positive relationship between water discharge and the survival of eggs (Gibson & Myers, 1988). With low flow, gravel interstices can be clogged by fine sediment, which reduces intra-gravel oxygen supply to eggs and alevins, thus, low flow and high temperature in synergy with low oxygen supply can restrict salmonid recruitment (Jonsson & Jonsson, 2009).

Gravel composition is of extreme importance in the intra-gravel life of salmonids. Chapman (1988) suggested that survival rates declined sharply above approximately 10% fines (<0.85 mm). A high content of fines (particles of 0.0-2.0 mm diameter (Crisp, 1996)) can adversely affect the development of embryos by preventing sufficient permeation of oxygenated water into the interstitial spaces within the gravel

(O'Connor & Andrew, 1998; Armstrong *et al.*, 2003; Jonsson & Jonsson, 2011) and efficient removal of metabolic waste, particularly ammonia (Crisp 1996; Payne & Lapointe, 1997). Gravel composition also influences the success of emergence from the gravel and the time of swim-up (Jonsson & Jonsson, 2011).

Density-dependent mortality is a key regulatory factor of salmonids (Jonsson *et al.*, 1998) and several studies have attempted to describe an optimal egg deposition for maximum survival to smolting. Elson (1975) estimated that an egg deposition of 2.4 eggs m^2 gave optimal smolt production on the Rivers Miramichi and Pollett in Canada and Buck & Hay (1984) estimated an optimal egg density of 3.4 eggs m^2 in the Girnock Burn, Scotland. Six eggs m^2 is widely regarded as the egg density at which recruitment curves begin to level off (Kennedy & Crozier, 1993, 1995; Jonsson *et al.*, 1998). However, Jonsson *et al.* (1998) noted several exceptions where alternative density dependent curves better describe freshwater survival than the stock recruitment curve described by Cushing (1973), on which the maximum optima of 6 eggs m^2 is based.

2.2.10 Factors affecting smolts

Salmon respond to the challenges of moving into sea water by physiological alterations of vision, buoyancy and ionoregulation mechanisms, which in the UK typically begins in March - April and can last until June (Jonsson & Jonsson, 2011). The chief factors controlling the smoltification process and seaward migration are water temperature, water flow and photoperiod (Jonsson & Jonsson, 2009; 2011).

Jonsson & Jonsson (2009; 2011) suggested smolt migration is not triggered by a specific water temperature or a specific number of degree days but is controlled by a combination of the actual temperature and temperature increase in the water during spring. Correlation between annual variation in the timing of the river descent of smolts and variation in water temperature patterns in spring suggest temperature may play a significant role in initiating smolt migration (Jonsson & Jonsson, 2009). Jonsson and Ruud-Hansen (1985) concluded water temperature was the only factor significantly influencing smolt migration, accounting for 89 – 95% of the variance in the River Imsa, Norway. McCormick *et al.* (1998) suggested temperature may strongly influence the migration of smolts and reviewed numerous field studies of smolt migration and concluded that a temperature of around 10° C triggered smolt migration. Zydlewski *et al.* (2005) showed that the temperature experienced over time determines the behavioural and physiological changes associated with smolting as well as the onset of the smolt migration. McCormick *et al.* (1996; 2002) suggested temperature affects the rate of development and found increasing the mean daily rearing temperatures from 2°

C to 10° C can advance smolting by up to a month and temperatures below 3° C restrict smolt development.

Wotton (1998) suggested day length and changes in photoperiod are proximate factors indicating the season and represent important cues in the smolting process. McCormick *et al.* (1998) suggested photoperiod appears to be the main stimulus for the development of smolt characteristics. There is likely to be a complex relationship between factors, for example low water temperatures (2° C) limits the response of salmon parr to increased day length (McCormick *et al.,* 2002), and time series data from a study on the River Imsa (1976 to 2000) suggested confounding factors act to affect growth rate such as fish density and feeding opportunities and hence smolting (Jonsson & Jonsson, 2009; 2011).

In several rivers increased water flow has been documented as initiating downstream migration of smolts (Jonsson & Jonsson, 2009; 2011). Several studies of hatchery reared salmon post-smolts have suggested water current is the major transport factor in the seaward migration (Lacroix & McCurdy, 1996; Moore, *et al.,* 2000). However, Thorstad *et al.* (2004) and Okland *et al.* (2006) found no relationship between direction of observed movement and direction of water current in wild salmon post-smolts and hatchery-reared post-smolts, respectively, and suggested neither passively drifted with the current, but actively swam.

2.2.11 Summary

1. Salmon species have complex life cycles with a general pattern of spending their juvenile stage in fresh water, moving to sea after a physiological transformation called smolting and returning to fresh water as adults to spawn.

2. The upstream movement of salmon in a river is fundamental in allowing salmon to complete their life cycle and can be affected by a range of factors. Connectivity is of fundamental importance in upstream migration in freshwater.

3. The habitat and water quality requirements of adult salmon and their spawning requirements, their eggs and juveniles are highly specific. Temperature and dissolved oxygen are key abiotic factors regulating the survival, distribution, growth and feeding of salmon

4. Successful spawning requires gravel bottoms with high flows of well oxygenated water. Density dependent factors play a key role in the survival of juveniles.

2.3 HOMING AND STRAYING IN ADULT ATLANTIC SALMON

2.3.1 Homing

Philopatry to natal rivers and even to specific spawning grounds in salmon is well documented (Stabell, 1984; Dittman *et al.*, 1996; Quinn *et al.*, 1999; Candy & Beacham, 2000; Fraser *et al.*, 2011) and has resulted in the reproductive isolation of populations and the development of large numbers of genetically distinct populations (Verspoor, 2005; Spidle & Lubinski, 2001 Finnegan & Steven, 2008). This allows adaptation to local conditions and has resulted in substantial phenotypic, genetic and behavioural variation between populations (Taylor, 1991; Candy & Beacham, 2000; Verspoor, 2005, Finnegan & Stevens, 2008). Local adaption is important and known to enhance the survival or reproductive success of individuals (Taylor, 1991), and some studies have reported rapid local adaptation, within 6 - 30 generations (Quinn *et al.*, 2000; Fraser *et al.*, 2011).

The navigation of anadromous salmonids has traditionally been divided into two stages; navigation whilst at sea and navigation adjacent to or within the home river system (Hasler, 1960; Haslet *et al.*, 1978; Harden Jones, 1968; Stabell 1984). The literature contains several theories of how salmon are able to home so precisely and homing success is thought to depend upon both learned and innate behaviour (Candy & Beacham, 2000).

Chemical cues are known to play a crucial role in salmon migration and homing (Dittman *et al.*, 1996; Candy & Beacham, 2000). However, such cues cannot persist and extend over the thousands of kilometres of ocean and salmon migration in the open sea is thought to involve a different set of mechanisms (Lohmann *et al.*, 2008). Young salmon are capable of orientating themselves using the Earth's magnetic field (Quinn, 1980; Quinn & Brannon, 1982) and crystals of magnetite that might function as receptors for a magnetic sense have been discovered in salmon (Mann *et al.*, 1988). Lohmann *et al.* (2008) suggested salmon may be able to imprint on the magnetic signatures of coastal area and that geomagnetic imprinting occurs in tandem with olfactory imprinting and functions in guiding long distance movements that precede the more precise coastal homing.

Homing in coastal regions and locating natal rivers is thought to involve a combination of factors. Olfactory cues are widely considered to be amongst the most important (Bertmar & Toft, 1969; Troft, 1975; Candy & Beacham, 2000; Keefer *et al.*, 2008). Successful homing to natal rivers and within rivers involves the imprinting of olfactory cues of a natal stream as juveniles during the freshwater phase (Stabell, 1984; Candy & Beacham, 2000). Experimental evidence indicates that olfactory imprinting may start to occur even before hatching and continue until smoltification (Hasler & Scholz, 1983; Courtenay, 1989; Dittman *et al.*, 1994). Harden Jones (1968) and Brannon (1982) proposed a sequential imprinting hypothesis whereby salmon learn a series of olfactory waypoints as they migrate through fresh water and then retrace this odour sequence as adults. The chemical attractants that guide salmon into estuaries are as yet unknown (Webb *et al.*, 2007). Grandjean *et al.* (2008) found groups of salmon inhabiting different geologies evolved independently of each other and suggested water chemistry could act as an olfactory cue and allow salmon to distinguish their natal area. A number of studies have suggested and inferred freshwater and a reduction in salinity are key to attracting salmon into estuaries and work in conjunction with chemical cues (Alabaster *et al.*, 1991; Jonsson *et al.*, 2007).

Contrary to the imprinting hypothesis, salmon themselves may condition the water (Miller, 1954; Solomon, 1973). Nordeng (1971) proposed that population-specific scent from young conspecifics in the river could be the guiding cue for homing salmonids. The ability of salmon to recognise conspecifics is acute, with parr being able to discriminate scents from strains of their own species and even prefer the scent from their own genetic strain (Stabell *et al.*, 1982). Other mechanisms such as schooling behaviour may also play a part in coastal navigation and eventual choice of river (Stasko, 1971). Quinn & Fresh (1984) found that in the Cowlitz River (a tributary of the Columbia River in Washington State, USA) in years when more salmon returned the proportion that successfully homed was higher. Candy & Beacham (2000) suggested it may be possible that certain individuals have an inherently lower homing instinct and swim with conspecifics. It has been speculated that social factors strengthen the motivation to home because higher proportions of homing salmon have been associated with greater numbers of returning adults (Quinn & Fresh, 1984; Hard & Heard, 1999).

Visual sense has also been suggested as a mechanism of orientation and homing in migratory fish (Hasler *et al.*, 1958) and that fish are able to use the sun as a visual clue (Braemer, 1960; Hasler & Schwassmann, 1960; Schwassmann & Hasler, 1964). Quinn (1982) suggested celestial navigation coordinated by an endogenous clock may be one of a variety of geo-positioning mechanisms. However, Stabell (1984) stated that any ‘chronometer’ required for navigation would have to be capable of telling not only local time but comparing local time with ‘home’ time throughout changing seasons. Serious doubt exists that the sun is a primary navigation mechanism in salmon (Neave

1964; Stabell, 1984), with Royce *et al.* (1968) pointing out salmon migrate at night as well as through regions where the sun is often obscured.

There is also a suggestion that there is a genetic component to homing and that there appears to be a genetic predisposition to imprint at some particular stage in the life history (Candy & Beacham, 2000; Jonsson *et al.*, 2003). Candy & Beacham (1998) found hybrid Chinook salmon stocks three times more likely to stray than natal stocks released at the same time and location (6.2% compared to 2.4%), suggesting there is a genetic component to homing. Transplanted salmon, collected as gametes from their ancestral site that have not had opportunity to develop learned behaviour allowing them to home to their ancestral sites, home to their ancestral sites at a rate higher than expected from random straying, which has been suggested to result from an innate component (Candy & Beacham, 2000). This is consistent with McIsaac & Quinn (1988) who found after two generations removed from direct experience with their ancestral site, transplanted Chinook salmon stocks maintained their upstream homing migration tendency.

2.3.2 Straying and factors effecting straying

Not all salmon return to their natal river, with some individuals straying into and spawning in other rivers (Thorpe, 1994; Griffith, 1999; Jonsson, 2003; Pedersen, 2007; Saura, 2008). Some straying between populations is thought to be important for maintaining the genetic diversity of the stock, counteracting the possible effects of inbreeding, reducing dependence on a single breeding or nursery site and colonising new habitat (Milner & Bailey, 1989; Thorpe, 1994; Jonsson *et al.*, 2003; Perrier *et al.*, 2010). The offspring of stray salmon adopt the new river as their home river and return to the river they leave as smolts not the river of their genetic origin (Jonsson & Jonsson, 2011). As a result, stray salmon are able to establish new populations if they enter rivers not inhabited by the species (Milner & Bailey, 1989) or the population has been extirpated (Perrier *et al*., 2010). There are numerous factors cited in the literature as causing and influencing straying (Table 2.9).

Straying may be inheritable (Hard & Heard, 1999), and be an adaptation for fish spawning in small unpredictable streams (Unwin & Quinn, 1993; Jonsson *et al*., 2003) or unfavourable conditions (Pascual & Quinn, 1994). However, a high rate of immigration may negatively affect genetic adaptations of local populations (Jonsson *et al.*, 2003). Patterns of straying can vary greatly with age, sex, between rivers and by distance to home stream (Pascual & Quinn, 1994; Jonsson *et al.*, 2003; Palstra *et al.*, 2007; Baker *et al.*, 2008).

Table 2.9 Factors affecting and causing straying cited in the literature.

Cited factors influencing straying	Authors
Heritable behaviour	Hard & Heard (1999), Anderson & Quinn (2007)
Adaption for unpredictable streams and unfavourable conditions	Unwin & Quinn (1993), Pascual & Quinn (1994), Jonsson *et al*. (2003)
Failure in orientation whilst at sea and in coastal waters	Candy & Beacham (2000), Anderson & Quinn (2007)
A decision based behaviour	Quinn (1984), Thorpe (1994), Leider (1989), Anderson & Quinn (2007)
Directional nature of environmental factors	Hanfling & Weetman (2006), Palstra *et al.* (2007)
Population size of river being entered	Quinn (1984), Quinn *et al.* (1991), Hindar (1991), Jonsson (2003)
Age and time spent at sea	Quinn *et al*. (1991), Pascual *et al*. (1995), Jonsson (2003)
River flow	Quinn *et al.* (1991), Candy and Beacham (2000)
River temperature	Goniea *et al.* (2006)
Geology and associated chemical cues	Griffiths *et al.* (2011)
Unfavourable river conditions	Whitman *et al*. (1982), Quinn & Fresh (1984), Thorpe (1994), Pascual & Quinn (1994)
Hatchery rearing practices	Potter & Russell (1994), Potter & Russell (1994), Schroeder et al. (2001), Jonsson *et al.* (2003), Pedersen *et al*. (2007)

Straying may result from orientation failure (Candy & Beacham, 2000, Anderson & Quinn, 2007). Candy & Beacham (2000) suggested the transition from biocoordinate navigation to imprinted stream cues may be the cause of some straying.

It has been suggested straying may be decision based (Quinn, 1984; Leider, 1989 Thorpe, 1994; Anderson & Quinn, 2007), and Anderson & Quinn (2007) suggested exploration is an innate component of salmon breeding behaviour. Griffith *et al.* (1998) defined the terms homing and straying by the end points of migration, natal or non-natal sites, respectively. During migration some salmon are known to enter non-natal rivers (Ricker & Robertson, 1935; Anderson & Quinn, 2007). These fish might be 'exploring' (actively seeking different sites and comparing their attributes) or 'wandering' (searching in the absence of stimuli) (Griffith *et al.,* 1998).

There is a correlation between genetic and geographical distances found in wild salmon populations (Rousset, 1997; Koljonen *et al.*, 1999; Nielsen *et al.*, 1999; Grandjean *et al.*, 2008) and most stray recoveries occur within close proximity of the home river; Candy & Beacham (2000) recovered 48% of stray Chinook salmon migrants within 30 km of the release site, Hard & Heard (1999) recovered 64% within 25 km, and Labelle (1992) recovered 50% within 7 km of release sites. Candy & Beacham (2000) suggested the high recovery of straying fish close to their natal rivers results form an unsuccessful transition from bio-coordinate navigation to imprinted stream cues in coastal waters close to natal rivers. A breakdown in latter stages of homing has been reported in other species; Thorold *et al.* (2001) reported straying in weakfish (*Cynoscion regalis*) was largely confined to locations adjacent to natal estuaries, and was not due to a complete breakdown of homing behaviour.

Salmon are also capable of long distance straying. Perrier *et al.* (2010) showed two of seven salmon caught on the River Seine to be from foreign stocks rather than those nearby to the River Seine; Ikediashi *et al.* (2012) found salmon from French stocks entering the River Mersey in northwest England; Griffiths *et al.* (2011) found one of 16 salmon sampled from the River Thames in south east England to be from French populations; Hamann & Kennedy (2012) recorded wild Chinook salmon straying 80 – 200 km from their natal streams. Tucker *et al*. (1999) provided evidence that some Northern American salmon feed in the European sector of the North Atlantic, which indicated salmon are capable of moving large distances and may explain past straying of North American salmon into European rivers (Makhrov *et al*., 2005).

There is often a spatial pattern to straying. Hard & Heard (1999) found a northern bias in Chinook salmon strays and suggested this was a function of the routes used by adult salmon on the final phase of their return migration. Studies have suggested dispersal, and so straying, can be a function of the directional nature of environmental factors (Hanfling & Weetman, 2006; Palstra *et al.*, 2007). It is likely currents in coastal waters affect dispersal and therefore straying patterns (Ikediashi *et al*., 2012). Studies document salmon displaying negative rheotaxis in the absence of directional cues (Hard & Heard, 1999) and would therefore be influenced by the direction of currents (Palstra *et al.*, 2007).

It is unknown whether a relationship exists between population size and straying (Quinn, 1984; Quinn *et al.,* 1991; Hindar, 1991; Jonsson, 2003). Quinn *et al*. (1991) found that rivers with the fewest returning adult salmon attracted the fewest strays and vice versa. However, in the same study Quinn *et al.* (1991) found a river with a relatively large population attracted very few strays.

Quinn *et al.* (1991), Unwin & Quinn (1993) and Pascual *et al.* (1995) all documented older salmon having a greater tendency to stray than younger fish. Quinn *et al.* (1991)

and Jonsson (2003) suggested that the chance of making mistakes and so straying increases with time spent at sea. This may result from an increased turnover of sensory epithelial cells associated with odour recognition (Nevitt *et al*., 1994). Quinn *et al.* (1991) suggested that the chemical characteristics of river water undergo subtle changes over the years making them less recognisable to older fish. However, some studies have found no consistent trend of increased straying with age (Candy & Beacham, 2000). Hard & Heard (1999) found straying was higher in younger smaller fish. Quinn (1984) proposed an inverse relationship between age-structure complexity and straying in salmon, because multiple ages at maturity and straying both reduce the risk that all offspring of a set of parents will be killed by an environmental catastrophe.

Quinn *et al.* (1991) suggested river flow and temperature may be factors in attracting strays to non-natal rivers and provided evidence that straying salmon avoid rivers with lower flows. Unwin & Quinn (1993) documented an increase in Chinook salmon straying into New Zealand rivers with increased water discharge. However, Hindar (1992) found Atlantic salmon straying was not affected by flow in rivers in the United Kingdom. Goniea *et al.* (2006) demonstrated that straying of Chinook salmon in the Columbia river increased exponentially as water temperature in the main stem increased. River size or discharge may also determine the attractiveness of a river. For example, Candy & Beacham (2000) documented a small estuary producing six and half times more strays than a larger estuary just 15 km apart, suggesting the larger estuary makes an easier homing target. Odour is thought to play a part in the river choice of strays. Anderson & Quinn (2007) suggested stray coho salmon chose to spawn in areas where the odours were more similar to those of natal sites. Salmon are known to be able to distinguish different geologies through olfaction and the water chemistry (Grandjean *et al.*, 2008), and straying salmon may be attracted into rivers with similar geology and so water chemistry (Griffiths *et al.,* 2011).

Unfavourable conditions may cause straying (Pascual & Quinn, 1994). Returning adult coho salmon and Chinook salmon bypassed their natal River Toutle, a tributary of the Cowlitz River, northwest United States of America, following the eruption of Mt St Helen and were recorded 40 km further up the Cowlitz River (Whitman *et al.*, 1982, Quinn & Fresh, 1984; Thorpe 1994). Over the three years following the Mt St Helen eruption Leider (1989) and Thorpe (1994) found steelhead trout (*Oncorhynchus mykiss* Walbaum) belonging to affected Columbia river tributaries increased their straying into tributaries upstream that were unaffected by the eruption and resulting increased sedimentation from 16% before the eruption to 45% after it.

However, unfavourable conditions can also prevent straying into and colonisation of new habitats, for example, streams fed directly by glaciers are not attractive due to the high sediment loading (Milner & Bailey, 1989 Thorpe 1994). Hamann & Kennedy (2012) reported that extensive movements as juveniles potentially reduce the propensity of adult salmon to home accurately. A number of factors, including food availability, habitat quality and competition, contribute to whether juvenile salmon establish territories or explore multiple habitats during freshwater residency (Achord *et al*., 2003). Hamann & Kennedy (2012) suggested juvenile movements may act as a mechanism to regulate straying rates and the exploration of new habitats as adults. Stewart *et al.* (2004) suggested a trade-off between precise homing and spawning habitat selection is likely whereby salmon establish nests away from their natal site if local conditions elsewhere are better. Anderson & Quinn (2007) found coho salmon strayed into new habitat and suggested this was by choice as the reduced competition for breeding space would allow female colonists to devote their energy almost entirely to nest site selection and preparation.

Poor homing ability and increased straying in hatchery reared salmon has received much attention and is of fundamental concern for both ranching and stock enhancement exercises (Potter & Russell, 1994; Jonsson *et al.*, 2003). The difference in the homing behaviour of hatchery reared and wild fish is likely to be multi-factorial (Potter & Russell, 1994; Jonsson *et al.*, 2003; Pedersen *et al.*, 2007), with the origin of the brood stock and their genetic makeup (McIsaac & Quinn, 1988; Potter & Russell, 1994), the rearing regime or water sources in the hatchery (Quinn, 1993) and the times and locations of release (Hansen & Jonsson, 1991) all potentially effecting homing behaviour. Hatchery reared salmon released in the wild stray more than their wild conspecifics (Schroeder *et al.*, 2001; Jonsson *et al.*, 2003) and those of non-native origin more than those of native origin (Quinn, 1993). However, the effects of standard hatchery practices on straying are contradictory (Jonsson *et al.*, 2003). A lack of exposure to and opportunity to imprint on cues during outward migration at smolting of hatchery reared fish has been suggested to cause straying (Hansen *et al.*, 1993; Pedersen *et al.*, 2007; Fleming & Peterson, 2011). Gunnerod (1988) reported straying from sea release of salmon to be higher than from riverine releases, with Pedersen (2007) suggesting this could be caused by a deprivation of migratory cues during outward migration at smolting. Excessive straying of hatchery fish into adjacent populations is cause for concern as there is strong evidence that progeny from hybrid fish may be less viable than the local stock (Brannon, 1982; Bailey, 1987; Candy & Beacham, 2000).

Table 2.10 Straying rates in salmonids and their native rivers cited in the literature.

Salmon species	Straying rate (%)	Authors
Mean straying of Atlantic salmon in rivers on the west coast of Sweeden	3.8	Pedersen *et al.* (2007)
General straying rates of Atlantic salmon in the Baltic Sea	2	Carlin (1969)
Wild Atlantic salmon, Severn Estuary, England	8	Swain (1982)
Hatchery reared Atlantic salmon, River Imsa, Norway	15	Jonsson *et al*. (2003)
Wild Atlantic salmon, River Imsa, Norway	6	Jonsson *et al*. (2003)
Hatchery reared Atlantic salmon, River Tyne, North East England	3	Potter & Russell (1994)
Wild Atlantic salmon, River Tyne, North East England	2.2	Potter & Russell (1994)
General straying of wild Atlantic salmon in British and Irish rivers	3	Thorpe & Mitchell (1981)
Wild Atlantic salmon, River Magree, Nova Scotia	10	Stasko *et al*. (1973)
Wild Atlantic salmon, River Conon, Scotland	20	Mills & Shackley (1971)
Wild chum salmon, vancouver Island rivers	37.9	Tallman & Healy (1994)
Hatchery origin chinook salmon, Klamath River, California	94	Pascual & Quinn (1994)
Wild chinook salmon, Cowlitz River, Washington, USA	1.4	Quinn (1984)
Wild chinook salmon, Klamath River, California, USA	13	Snyder (1931)
Wild chinook salmon in Feather River, California, USA	10	Scholes & Hallock (1979)
Wild chinock salmon, Lewis River, Washington, USA	9.9	Quinn *et al.* (1991)
Wild chinook salmon, Cowlitz River, Washington, USA	1.6	Quinn & Fresh (1984)
Trasnlonated coho salmon, Creek Hatchery and hatchery on Issaquah Creek, Washington, USA	0	Donaldson & Allen (1958)
Wild coho salmon, Waddell Creek, California, USA	15 and 27	Shapovalov & Taft (1954)

2.3.3 Patterns and rates of straying

There is great variation in reported rates of straying in salmon (Table 2.10), but typically ranges between 1 and 10% (Stabell, 1984; Quinn 1993, Jonsson *et al.*, 2003; Palstra *et al.*, 2007; Baker *et al.*, 2008). However, Tallman & Healy (1994) found straying rates of 54% in a wild chum salmon (*Oncorhynchus keta* Walbaum) and Pascual & Quinn (1994) found straying rates as high as 94% in hatchery origin Chinook salmon. Potter & Russell (1994) noted the difficulty in comparing results obtained from different straying studies as the tendency of fish to stray may also be affected by other factors, such as the size and proximity of neighbouring rivers.

Straying usually occurs between proximal rivers (Vasemagi *et al.*, 2001; Griffiths *et al.*, 2011) and recolonisation by strays usually occurs from the geographically nearest population (Nielsen *et al.*, 1999; Vasemagi *et al.*, 2001), which is consistent with the correlation between genetic and geographical distances found in wild salmon populations (Rousset, 1997; Koljonen *et al.*, 1999; Nielsen *et al.*, 1999; Grandjean *et al.*, 2008). However, some studies have found no relationship between genetic and geographic distances (Fontaine *et al.*, 1997; Castric *et al.*, 2001). Nevertheless, straying can occur across much larger scales (Perrier *et al.*, 2010) and there is evidence of Northern American salmon straying into European and Arctic rivers (Makhrov *et al.*, 2005). A high genetic diversity resulting from long-distance straying has been suggested as being important during the early phase of the recolonisation of newly available river as a mechanism to buffer the impact of loss of genetic variability linked to the low number of migrants (Perrier *et al*., 2010).

Youngson *et al.* (2003) identified that many observations and empirical studies indicate that levels of gene flow between salmon populations is low and lower than would be assumed from observed straying rates. In investigating genetic migration, Stahl (1981) estimated numerical straying rate of 50–200 individuals per year between several Swedish stocks. However, Stahl (1981) concluded from isozyme analysis that the genetic migration rate was less than one individual per year and the contribution to spawning from strays was minimal. Tallman & Healey (1994) found straying rates of 37.5% in three populations of chum salmon on Vancouver Island but electrophoretic analysis suggested gene flow was substantially lower at only 5%. These results suggest that although salmon are able to stray into established populations they may not be reproductively successful. Several studies have suggested barriers to the reproductive success of stray salmon exist (Jonsson *et al*., 2003; Anderson & Quinn, 2007). Thorpe (1994) suggested a physical inability to reach spawning grounds, a behavioural inability to acquire or stimulate mates, reduced matching of genotype to specific habitat leading to the progeny of strays being relatively unsuccessful competitors or might possess developmental timing inappropriate to the habitat conditions, may all play a role in the reduced success of stays. Quinn *et al.* (1991) suggested assortative mating may take place, resulting in discrimination of strays. Keefer *et al.* (2008) demonstrated initial passage of natal tributaries and temporary use of non-natal tributaries may represent a temporary tributary use and not functional straying. Quinn *et al*. (1991) noted that the upstream migration of salmon often involves a certain amount of testing or movement up non natal streams.

Staying is seen as an adaptive population strategy (Palstra *et al.*, 2007) and plays a significant role in regional salmon systems, and as such regional metapopulation dynamics are likely to apply (Hanski 1991; Young, 1999; Palstra *et al.*, 2007). Hanski (1991) described a metapopulation as a group of populations inhabiting discrete patches of suitable habitat that are connected by the dispersal of individuals between habitat patches. The concept of 'source-sink' dynamics (Morris, 1991; Dias, 1996) have been applied to salmon populations (Palstra *et al.*, 2007) and studies have documented patterns of asymmetrical gene flow from large to small populations (Fraser *et al.*, 2004; Hansen *et al.*, 2007). Dispersal has been reported as a function of the directional nature of environmental factors (Hanfling & Weetman, 2006; Palstra *et al.*, 2007; Ikediashi *et al.*, 2012) and so independent of productivity and habitat quality of a 'source' population (Hanski & Gaggiotti, 2004). As such Palstra *et al.* (2007) concluded that in metapopulations large populations functioning as the main sources of gene flow cannot be taken for granted.

Straying and the resulting gene flow between populations, even at a low level, can cause outbreeding depression (Lynch, 1997; Candy & Beacham, 2000). Candy & Beacham (2000) suggested this could lead to a 'hybridization cascade', in that assuming hybrid stocks have higher straying rates and that stray fish can successfully mate in adjacent populations, excessive gene flow between populations from straying could trigger a cycle of more straying followed by increased hybridization.

2.3.4 Recolonisation and successful recoveries

Owing to the steep decline in the global catches of salmon, there has been considerable effort and money spent on attempting to return salmon to rivers from which they have been extirpated (Hendry *et al.*, 2003). For example, the Environment Agency spend £120k per annum on the Kielder Hatchery, which is used to stock the River Tyne in north east England (Environment Agency, personal communication). Historically, stocking with hatchery-bred fish has been seen as a rapid solution to declining numbers of fish (Milner *et al.,* 2004; Fraser 2008). However, the literature remains equivocal on the effectiveness of the practice and there is a lack of evidence regarding the success of stocking (Finnegan & Stevens 2008; Fraser 2008; O Maoileidigh *et al.,* 2008; McGinnity *et al.,* 2009; Griffiths *et al.,* 2011). More recently the negative impacts of stocking, such as those on the genetic diversity and population structure of endemic populations and ecological implications have been described (Einum & Fleming, 2001; Ayllon *et al.,* 2006; Griffiths *et al.,* 2009; Griffiths *et al.,* 2011). O Maoileidigh *et al.* (2008) reviewed the success of stocking practices in Ireland between 1995 – 2008 in 45 individual rivers and concluded that the extensive stocking programmes (mean of 7.6 (4.5 – 10.8) million eggs per annum produced by all stocking programmes) have made little contribution to the productivity of Irish salmon rivers or to restoring self-sustaining salmon runs. Salmon became extirpated from the River Rhine in the 1950s due to poor water quality (Bolscher *et al*., 2013) and despite extensive and coordinated stocking since the 1980s salmon have yet to re-establish a self sustaining population (Schneider, 2011; Monnerjahn, 2011). Monnerjahn (2011) cited several reasons that salmon have not established a self-sustaining population, including river fragmentation and barriers to upstream passage, silting of key habitats, lack of access to spawning habitat, poor habitat resulting from previous river modifications, residual industrial waste and poor water quality. However, there are some examples of the successful use of stocking to restore salmon populations such as the River Taff (South Wales) (Aprahamian *et al*., 2003), the River Morrell (Canada) (Bielak *et al.*, 1991) and the River Dove, a tributary of the River Trent in England (Milner *et al.*, 2004). There are also examples of salmonid populations being successfully introduced, through stocking, as non-native species; Chinook salmon to a river of the Atlantic basin of Patagonia (Ciancio *et al*., 2005) and to New Zealand rivers (McDowall, 1990), and trout into a number of rivers in New Zealand and the Falklands Islands (Thorpe, 1994).

Salmon were once abundant in the River Tyne, North East England, until deterioration in water quality led to the near extirpation of salmon during the 1950s (Champion, 1991; Milner *et al.,* 2004). Salmon catches began to recover in the mid 1960s in response to improving conditions largely a result of closure of a factory producing fertilisers in 1967, legislative change and increased powers to control pollution in the 1970s, the implementation of the 1974 Control of Pollution Act in the 1980s and the construction of a sewerage system in 1980 which by 1993 treated all major outfalls into the estuary (Figure 2.2) (Milner *et al*., 2004). Since the 1970s an estimated £250-300 million has been spent improving water quality in the River Tyne (Environment Agency, personal communication). As compensation for a loss of salmonid habitat caused by the construction of Kielder reservoir in the headwaters of the River Tyne, a major restocking programme was undertaken from 1979 onwards, stocking 100,000, 0+ and 60,000, 1+ salmon annually into the Tyne (Champion, 1991; Milner *et al*., 2004) at a cost of £120k per annum (Environment Agency, personal communication).

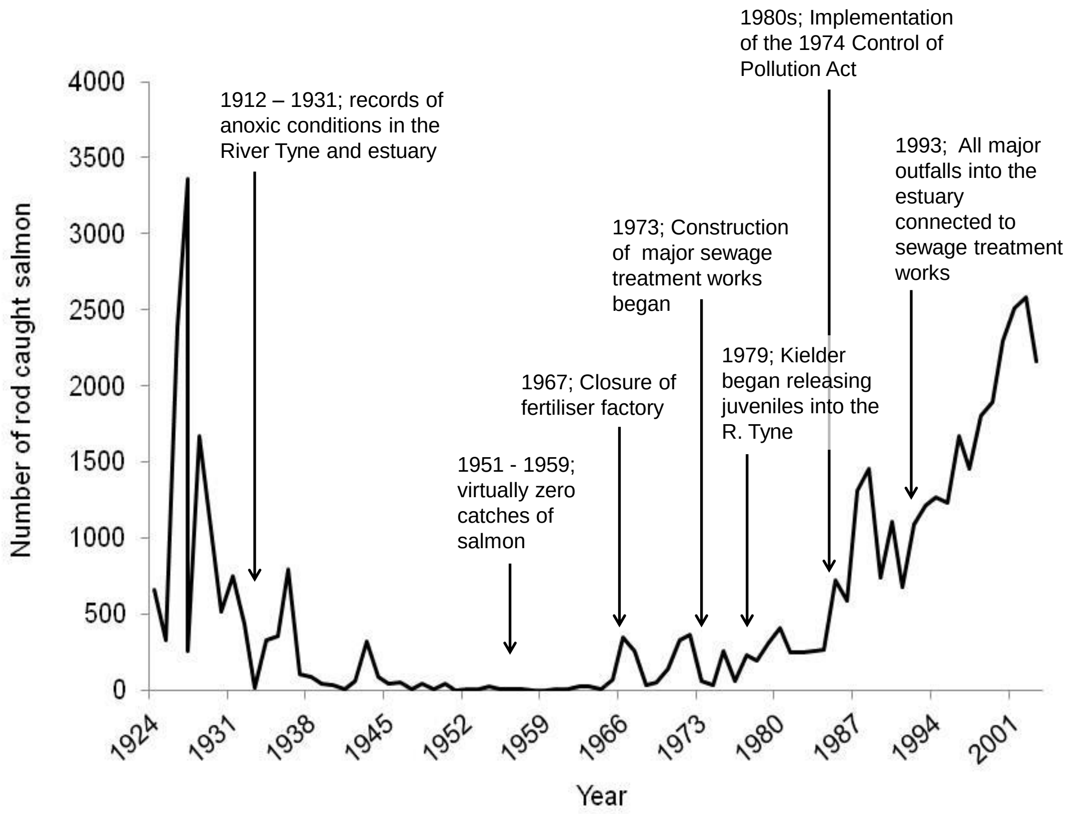


Figure 2.2 River Tyne rod catch data (EA, unpublished data) and key milestones (Milner *et al*., 2004).

Data from a micro-tagging exercise by the Ministry of Agriculture Fisheries and Food suggest the returns of stocked fish to the River Tyne were so low that it casts considerable doubt of the efficacy of stocking the Tyne (Champion, 1991). Catches of sea trout (*Salmo trutta trutta* L.) in the Tyne followed the same pattern as salmon but were not the subject of a stocking programme, further suggesting the return of salmon was driven by natural process (Champion, 1991). Champion (1991), Milner *et al.* (2004) and Griffiths *et al.* (2011) suggested that although the Tyne hatchery programme may have a role to play in short term mitigation and increase of salmon in the River Tyne it is highly likely that improvements in river quality and natural recolonisation through straying was the dominant process involved in the return of salmon. Fraser *et al*. (2007) described two successful reintroduction programmes of salmon to rivers in the Bay of Fundy, Canada, as being similarly questionable as the Tyne. Fraser *et al.* (2007) noted that nearby rivers were naturally recolonised after the removal of barriers and the genetic diversity within the rivers, which had received reintroduced fish, was maintained through immigration from nearby rivers.

In recent years a growing number of natural recoveries through straying have been documented; trout in Norway (Knutsen *et al.,* 2001) and Germany (Schreiber & Diefenbach, 2005); salmon in France (Perrier *et al.,* 2010), Baltic rivers (Vasemagi *et al*., 2001), Germany (Bolscher *et al*., 2013) and England (Griffiths *et al.,* 2011); coho salmon in Pacific north-western U.S.A. (Anderson & Quinn 2007; Kiffney *et al.,* 2009). As such, river restoration through improved water quality and connectivity is now recognised as an alternative to stocking to facilitate natural recolonisation (Ikediashi *et al*., 2012). Lawton *et al.* (2010) suggested conservation strategies should seek to restore ecosystem function and continuity, whereupon it seems likely that populations will re-establish naturally. However, some managers continue to prefer reintroductions to natural colonisation through straying due to the low numbers of founders and the time taken to establish a self sustaining population (Fraser *et al*., 2007).

2.3.5. Summary

1. Salmon have a highly developed ability to locate and use natal spawning grounds. Along with a genetic component, olfactory cues are thought to play a key role in allowing salmon to locate native streams and gravels.

2. Although the reasons or triggers to stray are not yet fully understood, straying is thought to be a natural component of salmon population biology with an adaptive role in allowing the colonization of newly available habitats, counteracting the possible effects of inbreeding, reducing dependence on a single breeding or nursery site and maintaining the genetic diversity of the stock.

3. Conservation efforts are now seen as an alternative management strategy to the stocking of salmon when attempting to restore salmon populations to catchments or rivers. A growing number of natural recoveries resulting from improved water quality and river connectivity have been documented in the literature.

The historical reasons for the extirpation of salmon form the Mersey are well documented (Wilson *et al*, 1988; Burton, 2003; Jones, 2006). However, the effects of current poor water quality, man-made barriers and the complex and regulated nature of the Mersey catchment on salmon is unknown. The following chapters will build on the key requirements of salmon identified in the literature review and identify what factors may affect or limit a potential recolonisation of the Mersey catchment by salmon.

3 HISTORY OF THE MERSEY CATCHMENT AND CURRENT STATUS OF ATLANTIC SALMON

Chapter objectives

This chapter will describe the Mersey catchment and the rivers that make up the study area. It will review the industrial history of the area and chart the deterioration in physicochemical conditions and the impacts on fish stocks for the period 1700 – 2000. This chapter will also review the current physicochemical conditions in the catchment and potential barriers to salmon and the current state of the salmon population in the Mersey catchment. In so doing, the chapter will chart the progress of the recolonisation and identify any potential barriers to migrating adult salmon.

3.1 THE MERSEY CATCHMENT

The Mersey catchment is situated in the North West of England and discharges into Liverpool Bay and the Irish Sea. The River Mersey and its tributaries drain an area of 4680 km^2. The main River Mersey is 110 km long, 26 km of which is estuary and has 13 major tributaries. The area of study includes the lower and upper River Mersey, the Manchester Ship Canal (here within referred to as the Ship Canal) and their main tributaries, the rivers Goyt, Tame, Etherow, Bollin and the Glaze (Figures 3.1 and 3.2).

The upper River Mersey begins as the Rivers Goyt and Tame join, in Stockport, south Manchester, at an altitude of 40 m (Figure 3.1). The River Tame (Figure 3.2) drains the eastern edge of the Manchester conurbation and the westerly edge of the Pennines and has a catchment area of 146 km^2. The River Goyt (Figure 3.2) rises on Whetstone Ridge, to the south west of Buxton, at an altitude of 520 m. The River Goyt has a catchment area of 365 km^2 and flows north through two large reservoirs, Errwood and Fernilee, and several small towns before turning west and joining with the River Tame (Figure 3.1). Both the rivers Tame and Goyt flow through urban areas with the riverine habitat heavily modified with walls, redundant mills, millraces and weirs. From Stockport the upper River Mersey flows in a westerly direction, initially in an artificial walled channel for 4 km, until it reaches Heaton Mersey (Figure 3.2). Here, the River Mersey meanders across the flood plain until joining the Ship Canal at Irlam weir. As the urban area of Manchester has expanded, development along the banks of the upper River Mersey has led to most of the river corridor being narrowed through embankments to control flooding (Figure 3.2). On joining the Ship Canal the flow of the River Mersey is contained within the canal and flows south west for 6.6 km, where the river leaves the canal as the lower River Mersey and resumes its natural course. On leaving the ship canal the lower River Mersey flows for 9 km through Warrington until reaching Howley weir, the tidal limit. Downstream of Howley weir the River Mersey widens into an estuary, being 5 km wide at its widest point. The estuary then narrows between Liverpool and Birkenhead to a width of 1.2 km becoming strongly tidal and continues into Liverpool Bay and the Irish Sea.

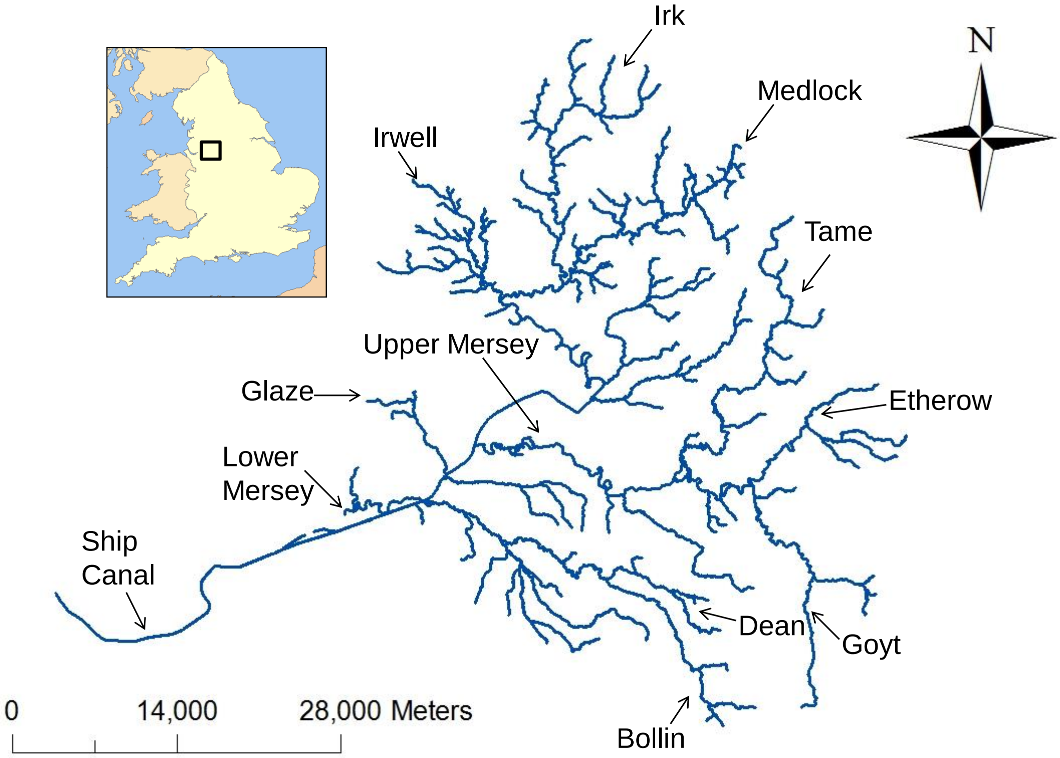


Figure 3.1 The study area and rivers of the Mersey Catchment.

The Ship Canal (Figure 3.2) has a total length of 57 km and originates in Manchester and flows into the Mersey Estuary. Other than the River Mersey, the Ship Canal has three other major tributaries, the rivers Irwell, Bollin and Glaze. The River Irwell is 63 km in length and joins the Ship Canal in Salford, south Manchester, where its course was altered in the 19^{th} Centaury to form the Ship Canal. The River Glaze (sometimes referred to as the Glaze brook) originates south of Leigh and drains a catchment area of 169 km^2, is 116.4 km in length, and discharges into the Ship Canal, south east of Cadishead (Figure 3.1 & 3.2).

	
River Goyt	River Goyt
	
River Etherow	River Etherow
	
River Tame	River Tame
	
River Irwell	River Medlock

Figure 3.2 Photographs of typical stretches of rivers in the Mersey Catchment.

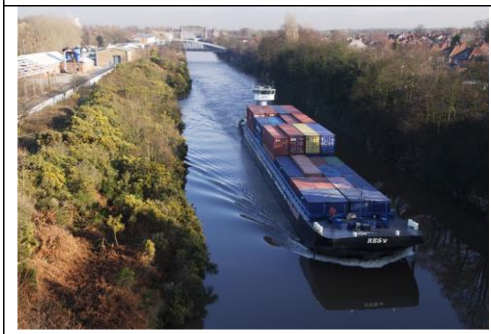
	
Upper Mersey	Upper Mersey
	
Manchester Ship Canal	River Glaze
	
River Bollin	River Bollin
	
Lower River Mersey	Lower River Mersey

Figure 3.2 (continued) Photographs of typical stretches of rivers in the Mersey Catchment.

The River Bollin (Figures 3.1 & 3.2) joins the ship canal directly opposite the confluence of the lower River Mersey with the Ship Canal in an area of the canal called 'Bollin point'. The River Bollin rises in the foothills of the Pennines and flows for 26 km draining the urban areas of Macclesfield, Alderley Edge and south Manchester before joining the Ship Canal.

The Ship Canal dominates the study area and was constructed by canalising parts of the Rivers Irwell and Mersey. The rivers Bollin and Glaze run into the Ship Canal as well as a large number of outfalls, including storm-water outfalls. The water level in the Ship Canal is controlled by five sets of sluices and two weirs and under normal flow conditions an automatic control system controls the sluices to maintain water levels in the canal to enable safe navigation of vessels (Figure 3.2).

3.2 HISTORY OF THE MERSEY CATCHMENT

3.2.1 The Industrial Revolution period (1700 to 1820)

Anecdotal evidence suggests water quality in the River Mersey was good before the start of the Industrial Revolution (Burton, 2003) and the Mersey catchment supported a wide range of locally important fisheries, particularly salmon (Wilson *et al.*, 1988). A number of records exist describing the prevalence of salmon in the Mersey, one example from 1656 cited by Burton (2003) describes the "the great stores of salmon" in the River Mersey.

Severe pollution in the Mersey catchment began with the Industrial Revolution and the establishment of the cotton industry in the Manchester area in the 1700s (Burton, 2003) (Figure 3.3). The cotton industry was the first industry in the area to pollute on any significant scale (Bracegirdle, 1973). Processes associated with cotton production such as dyeing, bleaching and printing also increased (Jarvis & Reed, 1999) and in 1799 chlorine-based bleaching began, significantly increasing the levels of pollutants coming from cotton works and entering local water courses (Burton, 2003).

In the 1770s and 1780s innovations such as the Boulton and Watts rotative steam engine, allowed the mass production of a range of cotton and other goods to begin (Briggs, 1963; Burton, 2003). This, coupled with the proximity of the Lancashire coal mines and Liverpool docks allowing for the import of cotton and export of cotton goods, meant huge numbers of factories were located along the River Mersey and its tributaries (Jarvis & Reed, 1999).

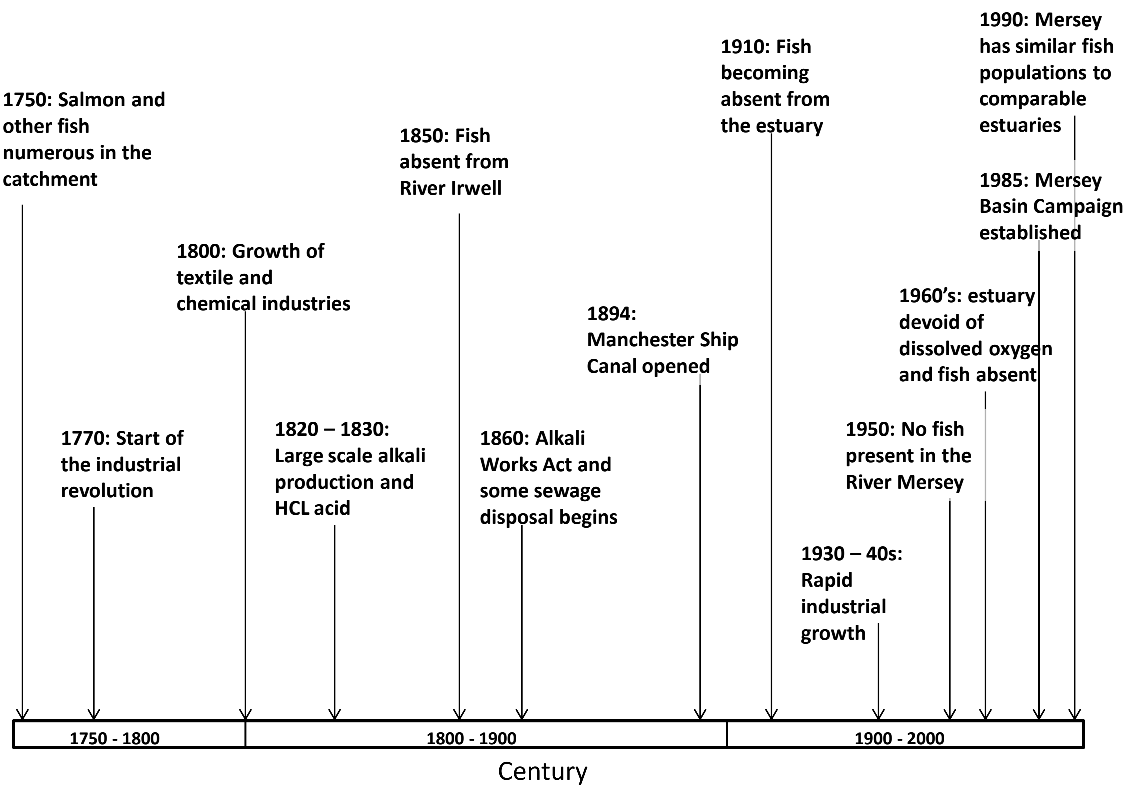


Figure 3.3 Time line summarising significant events in the Mersey catchment (Wilson *et al.*, 1988; Head & Jones 1991; Elliott & Dewailly, 1995; Jones, 2000; Burton, 2003; Jones, 2006).

Records exist of fish still being prevalent in the River Mersey and its tributaries in 1813 (Burton, 2003). In the 1820s, fish in the River Irwell were described as "dense were the shoals, so numerous the fish rising to the flies." (cited in Bracegirdle, 1973). Alabaster & Lloyd (1980) suggested that prior to the 18th Century dissolved oxygen (DO) levels in the River Mersey remained >5 mg l^{-1} based on the invertebrate population present at the time, well above the <1 mg l^{-1} Freshwater Fish Directive imperative standard for salmonids (section 2.1).

The early 1800s saw the expansion of several industries in the area. This included steam printing (1814), which led the way for the expansion of textile printing (Jarvis & Reed, 1999). This period saw the arrival of large scale alkali production (1820) and, making use of Liverpool's large salt resource, the beginning of the chemical industry in the area, for which the River Mersey was becoming a focal point and remained so until the 1880s (Jarvis & Reed, 1999; Burton, 2003) (Figure 3.3). Alkali production was focussed around Liverpool, Runcorn, Widnes and St. Helens leading to severe pollution of the River Mersey and Ditton and Sankey Brooks (Burton, 2003). In 1836 it was discovered that hydrogen chloride gas could be converted to hydrochloric acid, which, in an effort to reduce air pollution, was allowed to run off into surrounding rivers as liquid waste (Clow, 1952; Burton, 2003). Burton (2003) suggested this may have gone someway to lowering the water quality such that fish could not survive. Although no records exist of actual pH in the Mersey at this time it is worth noting the sensitivity of salmon to pH (section 2.2.5).

Industrial prosperity attracted huge numbers of people to the Merseyside and Manchester area and urban population growth accompanied the expansion in industry (Handley & Wood, 1999). In the 1830s, Manchester was considered "a phenomena of the age" (Briggs, 1963) and the population increased from 77,000 people in 1801 to over 316,000 in 1851 (Douglas *et al.*, 2002). Liverpool's population followed a similar trend (Lawton, 1953; Olsen, 1997). Uncontrolled and unplanned rapid development in all urban areas in the Mersey catchment led to poor drainage, frequent flooding and increased urban effluent run off (Redford & Stafford, 1939). This added to the polluting of the River Mersey and surrounding rivers, so much so that, by the start of the 19th Century the rivers Irwell and Medlock were described as "open sewers that bore to the sea refuse of many towns on a stream so slow that the sparrows could find footing on the filth that encrusted its surface" (cited in Burton, 2003).

There are no records of any sewers in the Mersey catchment in the 1750s and it wasn't until 1786 that the first sewage advancement was seen in Manchester and the early 1800s in Liverpool (Burton, 2003). There was no sewage treatment and early sewers increased the waste disposal into the rivers, with rivers becoming grossly polluted as a result (Redford & Stafford, 1939; Burton, 2003). Victorian river pollution reformers considered domestic sewage to be the worst form of pollution entering the River Mersey (Walklett, 1993). An article from 1832 cited by Burton (2003) gives an indication of the conditions in Manchester:

> "..where there were sewers, they drained directly or indirectly into the rivers, which were becoming rapidly more pestilential. The need for water power in earlier generation and the trapping of rivers as feeders for canals, had reduced the force of the river currents and diminished their capacity for carrying off the refuse. The towns lower down the streams became receptacles for the sewage of the towns higher up; Manchester received the filth of the townships higher up the Irk and the Irwell. "

(Redford & Stafford Russell, 1940). However, the prevailing theory at the time was that the strong tides and the great volume of water of the River Mersey and its estuary meant the river could receive any amount of untreated sewage (Jones, 2000).

3.2.2 Continuing expansion and government intervention in industrial practices and urban infrastructure, 1820 to 1900

The 1820s saw an expansion of several more industries (Figure 3.3). The Cheshire salt and leather industry went through a period of expansion (Gregory *et al.*, 1953; Burton, 2003), as did the glass industry which grew, benefiting from the Leblanc process, a process enabling sodium carbonate to be produced from salt, a crucial part of glass production (Lawton & Smith, 1953). The paper industry grew up along the banks of the River Irwell (Bracegirdle, 1973). Engineering, transport links and ship building also grew to supply the growing local industries, and in the 1830s the Liverpool – Manchester railway was built (Burton, 2003). The cotton and coal industries were still heavily polluting the waterways of the Mersey catchment (Burton, 2003). In 1863 the Alkali Works Act was passed in an attempt to lessen the release of hydrogen chloride gas and required that at least 95% of hydrogen chloride gas was condensed to hydrochloric acid, which led to an increase in hydrochloric acid being discharged into rivers (Walklett, 1993).

By the 1850s, fish were reportedly absent from the River Irwell (Bracegirdle, 1973; Holland & Harding, 1984; Struthers, 1997; Burton, 2003) (Figure 3.3). Burton (2003) documented the last recorded instance of a salmon being caught in the Irwell was in 1847. From 1855 waterweeds were noted to be disappearing from the River Mersey and its tributaries resulting from an increase in toxic substances (Holland & Harding, 1984). In the 1860s, the water level of the River Irwell was rising 6 – 9 cm annually such was the quantity of pollution (Burton, 2003). A temperature sample taken at 05:00 am on July 1869 from the River Irwell was 24.4°C compared to 12.5°C of the air (Douglas *et al.*, 2002). In the 1860s there were 280 miles of sewers in Manchester, but still no sewage treatment (Burton, 2003).

The 1860s and 1870s saw the first active government involvement. A Royal Commission report inquiring into the best means of preventing pollution in rivers was published in 1870 and used the Mersey valley, particularly the River Irwell, as an example (Burton, 2003). This led to the formation of the Rivers Pollution Prevention Act in 1876 (Burton, 2003). However, this was ineffective as existing or developing manufacturers were exempt from new legislation and existing Local Government Boards did little as they were major polluters themselves (Hassan, 1998; Burton, 2003). In response, County Councils were formed in 1888 enabling committees to be created to apply the Rivers Pollution Prevention Act of 1876 (Bracegirdle, 1973). In 1891 the Mersey and Irwell joint committee was formed and applied pressure on industries to reduce pollution and improve sewage treatment (Burton, 2003). Improvements were often as little as retention of solids or adding percolating filters such as those installed at Salford Sewage Treatment Works (Bracegirdle, 1973; Burton, 2003). This, combined with some of Liverpool's sewage being dumped as sludge into Liverpool Bay, began to reduce the impact of domestic pollution in the Mersey catchment (Belshaw, 2000; Burton, 2003).

The Mersey system and the estuary were also subject to physical modifications. Eight weirs were constructed in 1734 in an effort to make the rivers Mersey and Irwell navigable (Owen, 1983). Other significant physical alterations included: the construction of piers in the River Mersey for the Runcorn railway bridge (1856), the construction of the Manchester Ship Canal and its associated reclamation of river and tidal water (1894), tipping of slag to form an embankment in the north-east side of the estuary between Runcorn and Hale head (1896) and dredging of the estuary channels carried out intermittently from the 1890s (Tonk *et al.*, 2002; Thomas *et al.*, 2002). By the 1900s most water courses in the Mersey catchment had structures preventing the passage of fish (Jones, 2006).

The deposition of silt and debris became a problem to navigation and by 1870 half the capacity of the upper reaches of the River Irwell was lost due to dumped coal and furnace deposits and cinders from domestic fireplaces making it impassable to boats in low flows, compared to 1840 when vessels with a draught of 1.5 m could pass (Gray, 1993). By the time the Manchester Ship Canal was opened in 1894 the River Mersey and its tributaries were heavily polluted, longitudinal connectivity had been lost, salmon effectively eradicated from the rivers of the catchment and the fisheries in the upper estuary severely limited (Wilson *et al.*, 1988; Jones, 2006) (Table 3.1. and Figure 3.3).

3.2.3 An ecologically dead catchment and subsequent improvement, 1900 to 1990

By 1910 salmon were reportedly absent from the River Mersey (Coward, 1910; Hardy, 1931; Ellison & Chubb, 1962), and by the 1920s the commercially important fisheries in the estuary had been displaced downstream to the middle part of the estuary having disappeared from the upper estuary (Wilson *et al.*, 1988) (Figure 3.3).

The chemical and cotton industries began to decline from 1915 (Burton, 2003) but were replaced with emergent industries such as the state supported dyeworks, resulting in organic and cyanide pollution (Chanloner, 1962), and the tanning industry contributing high carbon and nitrogen loads to rivers (Gregory *et al.*, 1953; Burton, 2003). See section 2.2.5 for the effects of ammonia and nitrogen on salmon.

Table 3.1. Typical pollutants in the impacting the Mersey catchment (taken from Burton, 2003).

Industry	Greatest Intensity	Pollutants
Farming	Increased in intensity since 1841	Nitrates, phosphates and drainage from cow sheds
Cotton	1841-1950	Suspended solids and lime
Wool	1841-1931	Suspended solids, Na_2CO_3, H_2SO_4 and grease
Viscose rayon	1940s	H2SO4
Metal manufacture	1861-1891	H2SO4, metals (Cu, Zn, Ni, C), chromate, cyanides
Glass	Increased 1841-1951	Fluorides
Chemicals	1891-1971	Ammonia, acids, phenols, heavy metals, nitro compounds, amino compounds
Paper manufacture	Increased from 1841	Starch, free chloride, fibre, high BOD, may contain sulphides
Dye manufacture	1921-1961	Phenols
Dying & bleaching	1921-1961	Free chloride, sulphides, alkalis, suspended solids for calico printing waste
Tanning	1921-1951	Phenols, Cr, high in organic matter, suspended solids, sulphide, oil and grease
Rubber/glue manufacture	1921-1951	Zinc
Brewing	1921-1951	Suspended solids, yeast, carbohydrates, detergents, sugars, BOD

The 1930s – 1940s saw substantial growth in industry surrounding the Mersey Estuary (Wilson *et al.*, 1988). Areas such as Ellesmere Port, Bromborough and Port Sunlight became established and developed several industries including the petrochemical industry, pharmaceuticals, paints, frozen food, sugar refining, printing, glass manufacture and the vehicle industry (Burton, 2003). The expansion of industry resulted in a mixture of toxic inorganic and organic chemicals polluting the Mersey resulting in severe detrimental effect on river biology (Burton, 2003). Discharge of cooling water increased the temperature of the water and reduced the levels of DO (Porter, 1973). These further deteriorations resulted in anoxic conditions within the estuary being common and fish reportedly absent for much of the years in the early 20th Century (Wilson *et al.*, 1988; Jones, 2000). In the 1930s it was noted that DO in the River Mersey sometimes fell to 0 mg l^{-1} downstream of Widnes (Porter, 1973; Burton, 2003).

By 1905 the whole of the sewage of Manchester was being treated by bacterial processes (Redford & Stafford Russell, 1940). In 1935 an activated sludge treatment plant was opened to deal with surplus sewage that could not be treated by bacterial bed; this improved effluent quality (Redford & Stafford Russell, 1940; Klein, 1957; Burton, 2003). However, in 1954 the ratio of sewage effluent to river water in the River Mersey was 9:1 (Burton, 2003).

Anecdotal evidence suggests that fishing was poor during the 1930s and 1940s but by the 1950s there were no fish reported in the River Mersey (Jones, 2000). During the 1950s and 1960s water quality was at its worst (Head & Jones, 1991; Jones, 2000; Burton, 2003) and over 25 km of the estuary became devoid of DO (Jones, 2000; Burton, 2003). Wilson *et al.* (1988) reported that throughout the 1950s and early 1960s anoxic conditions in the estuary were common and all fish species were reportedly absent from the upper estuary for much of the time (Figure 3.3).

The 1960s saw the first real signs of a halt in the declining water quality and attempts to understand the problem. In the early 1960s the newly established Pollution Control Authority began monthly water quality surveys with the aim of establishing the prevailing conditions and long term trends in the River Mersey and the estuary (Jones, 2000). The exercise focused on basic parameters such as temperature, dissolved oxygen, salinity, suspended solids and nutrients and found long anoxic stretches and high concentrations of ammonia (>12 mg l^{-1}, significantly higher than the <1 mg l^{-1} recommended as the imperative standard by the FFD for salmonids (Table 2.1)) in the River Mersey (Jones, 2000). This period saw The Mersey and Weaver River Authority effectively controlling discharges (Hassan, 1998) and initiating further improvements to sewage treatment works and the construction of several large effluent treatment plants (Harland *et al.*, 2000; Burton, 2003). In 1971, in response to a report published by the Mersey and Weaver River Authority detailing the prevailing conditions in the estuary (Anon, 1971), a steering committee was set up with representatives from local government and industry (Burton, 2003). The committee was tasked to address the water quality issues of the Mersey catchment (Jones, 2000; Burton, 2003). In 1974 responsibility for pollution control was transferred to the newly established North West Water Authority which led to a regional approach to the management of the Mersey catchment (Jones, 2000). The North West Water Authority inherited both the results from the 1971 Mersey and Weaver River Authority report and the responsibility for implementing its recommendations (Jones, 2000). Two main objectives were adopted, firstly that the estuary should, at all times, contain dissolved oxygen to obviate odour nuisance and secondly, the foreshore and beaches should not be subject to fouling by crude sewage or fats from industrial effluents. The basic nature of these two objectives gives an indication of the state of the Mersey catchment in the 1970s.

The 1970s saw increased concern regarding heavy metals and tests on fish caught in Liverpool bay revealed elevated levels of metals such as lead, cadmium and mercury in tissues sampled (Jones, 2000). A wide array of potentially harmful organic compounds were present in the estuary at this time, including polychlorinated biphenyl (PCBs) a compound of chlorine and dichlorodiphenyltrichloroethane (DDT), an organochloride (Jones, 2000). Jones (2000) suggested approximately 300 different compounds could be found in the Mersey estuary in the 1970-80s, the biological effects of which were unknown. A study of endocrine disruption in flounder (*Platichthys flesus* L.) sampled from 11 estuaries and 5 coastal sites in and around the UK found flounder from the Mersey estuary to be most affected (Matthiessen *et al.*, 1998).

In 1980 North West Water Authority, the water company which supplied the Mersey catchment area and manufacturing industries, embarked on a 15 year programme costing £90 million to deliver the objectives set out in the 1971 Mersey and Weaver River Authority report (Jones, 2006). In 1983 a Mersey Conference was convened, which led to the creation of a collaborative programme, the Mersey basin campaign, which began in 1985 and was charged with facilitating the clean-up of the River Mersey and its tributaries (http://www.merseybasin.org.uk/) (Jones, 2000; Burton, 2003; Jones 2006) (Figure 3.3). In 1999 The Mersey Basin campaign became the inaugural winner of the International Thiess River prize for best river system clean up (http://www.riverfoundation.org.au). By 2007 United Utilities, who took over North West Water Authority, had invested over £1 billion to tackle the poor conditions in the river and estuary (Jones, 2007).

In 1976, the North West Water Authority initiated a regular monitoring programme by collecting fish from two industrial intake screens at Stanlow and Runcorn on the Ship Canal. In the first year of monitoring the intake screens, 19 species were caught, four of which were freshwater species (Wilson *et al.*, 1988; Jones, 2006). By 1987 the species list had risen to 40 species, ten of which were fresh water although most of these species were encountered rarely (Wilson, *et al.*, 1988; Jones, 2006). In 1981 beam trawl surveys were undertaken in the upper and middle estuary and found a total of 14 species (Wislon, *et al.*, 1988; Jones, 2000). Infrequent and anecdotal records of salmon, along with grey mullet (*Mugil cephalus* L.) and codling (*Gadus morhua* L.), being caught in the estuary occurred in the 1980s, but these species were not captured in the trawling or on the intake screens (Wilson *et al.*, 1988).

During 1991 and 1992 a number of *ad hoc* fisheries surveys were undertaken on behalf of the Mersey Barrage Company as part of an environmental impact assessment for a proposed tidal barrage (Jones, 2000). Twenty seven species were recorded over a two-year period, which Elliott & Dewailly (1995) indicated was a structure similar to other comparable estuaries in the UK and Europe (Figure 3.3). Jones (2000) suggested this indicated that the Mersey estuary was now functioning as a typical estuary in terms of types of species present.

3.3 PHYSIOCHEMICAL CONDITIONS IN THE MERSEY CATCHMENT, 1980 TO 2014

3.3.1 Introduction

Physicochemical requirements of salmon are well documented (reviewed in Chapter 2). This section uses available environmental and biological data to provide a review of the contemporary physicochemical conditions and accessibility of the Mersey catchment. This chapter will not review the conditions required for spawning and juvenile salmon which will be done in Chapter 6. This chapter will test the hypothesis that conditions in the Mersey catchment meet the basic physicochemical requirements of migrating adult salmon.

3.3.2 Data collection and analysis

Unless otherwise stated all environmental data were collected by the Environment Agency (EA). Much of the data collection has been driven by the Water Framework Directive (Directive 2000/60/EC) (WFD), which the EA has been responsible for implementing in England and Wales since 2000 (Anon, 2000). The WFD uses biological, hydromorphological, physico-chemical and chemical quality to characterise a waterbody's ecological and chemical status. A waterbody is defined as an area of land from which all surface run-off flows to a particular point, such as a river confluence. The WFD is an operational tool that sets the objectives for water protection and commits European member states to achieve 'good status' in all waterbodies. The study area contains 43 WFD waterbodies. WFD is delivered in 6-year cycles; the current cycle started in 2009 and unless otherwise stated, all WFD classifications and associated data referred to below are from the 2009 – 2015 cycle. Some of the data in this chapter are presented using Arc Geographic Information

System (GIS) database. The EA stores all WFD and associated spatial data in GIS as Polygon Shapefiles or Layerfiles. All GIS data in this chapter were identified using the 'search by location' function and a 'study area river selection', a GIS river shapefile manually created by selecting river stretches that make up the river network of the study area from a WFD river master shapefile.

Physical barriers and modifications

Information about potential barriers to migration was gathered from three sources:

- The EA's GIS database of river obstructions (I:\Local\Physical\Hydrology\River_obstructions.shp) was used to identify possible obstructions to migrating salmon which were located in rivers in the study area. The obstructions Shapefile was produced by the EA using the locations of weirs and other barriers recorded in the Ordnance Survey Mastermap and the Digital River Network GIS files.

- Records of potential obstructions gathered during walkover surveys undertaken by APEM Ltd (www.apemltd.co.uk) on the rivers Bollin, Goyt and Tame and their main tributaries in 2004, 2006, 2008, respectively (see Hendry, 2004; Hubble *et al.*, 2006; Dennis & Campbell, 2008). Barriers were classed as major, partial or minor on the River Bollin and on the River Goyt and Tame as either a barrier or an impassable barrier during Q90 flows (the flow that is exceeded 90% of the time).

- Interviews with EA Fisheries Officers working in the study area were conducted to identify barriers that may prevent upstream migration and to corroborate the GIS and APEM barrier data. Information on fish passes and obstruction mitigation measures was gathered from EA records and personal communication (personal communication, Ben Bayliss, Project Manager of 'North West fish pass programme' and Katherine Causer, Project Manager of 'Mersey Life').

Under the WFD, river waterbodies are classified as either artificial, a heavily modified waterbody (HMWB) or not designated a heavily modified waterbody (EU Water Framework Directive, 2000) (Anon, 2000). Where an artificial waterbody is a 'body of surface water created by human activity' and a heavily modified waterbody is a 'body of surface water which as a result of physical alterations by human activity is substantially changed in character, as designated by the Member State in accordance with the provisions of Annex II (of the WFD)' (Article 2 of the WFD). WFD modification classification data for rivers in the study area were reviewed.

Ecological quality

The WFD requires the characterisation of all waterbodies into one of five ecological status classes (high, good, moderate, poor or bad). This is done through the assessment of four biological quality elements (BQE), fish, macroinvertebrates, macrophytes and phytoplankton and supporting quality elements (SQE), such as hydromorphological conditions, that together lead to an ecological classification status. The WFD requires the assessment to be made against type specific reference conditions (Anon, 2005; Ferreira, 2007). The final WFD ecological classification uses a 'one-out all-out' approach meaning that the quality element with the lowest status at a site effectively decides the status for a river waterbody. The EA's GIS WFD database was interrogated and the WFD ecological classification of each of the 43 waterbodies was reviewed.

Freshwater water quality

As part of WFD, surface waterbodies are given a chemical classification status of either good, not good or does not require classification (does not require classification status are waterbodies with an estimated reduced likelihood of chemical pollution. This was estimated from an EA desk based assessment in 2009 in an effort to reduce sampling effort). The chemical classification is derived from Priority Substances (Annex X to the WFD) and List I Dangerous Substances (Annex IX to the WFD) quality elements. The status will be 'not good' if the quality standard of one or more relevant priority substances or dangerous substances is exceeded. The EA's GIS WFD database was interrogated and the chemical classification for river stretches data was reviewed.

Under a range of EU directives the EA has a statutory duty to collect water quality data (for collection methodology, see Anon, 2010). These data are stored on the EA's Water Information Management system (WIMS). WIMS was interrogated for dissolved oxygen (mg l^{-1}) and ammonia (mg l^{-1}) data for the rivers Bollin, Upper Mersey, Tame, Goyt and Etherow. Only samples collected as part of a routine monitoring programme (sampled as part of FFD, WFD and Urban Waste Water Treatment Directive (UWWTD) programmes were reviewed as these provided consistent and continual data. For each river two sites were selected as on reviewing the data two sites provided an adequate temporal and spatial representation of the river and kept the amount of data manageable. One site was selected to represent the upstream and the other the downstream sections of the rivers; annual means were calculated for 1974 – 2012.

WIMS was interrogated for dissolved oxygen saturation (%) at three sites: Irlam Locks on the Ship canal and sites immediately upstream of Howley and Woolston weirs on the lower River Mersey (Figure 3.4). WIMS contains the results from monthly spot checks taken by handheld water quality meters (www.YSI.com). Year-on-year plots and a 'seasonal model' were generated using Aardvark software package (www.wrcplc.co.uk) at each site for 2000 to 2015. Aardvark applies a sine-cosine model (y = a + b*sin(t) + c*cos(t), where t = time of year in radians (i.e. t = 2 *pi * DayOfYear / 365)) to the data to generate a seasonal model. Aardvark does not report statistical significance.

Dissolved oxygen (mg l^{-1}) and ammonia (mg l^{-1}) data were gathered at a single site, Caddishead, on the Ship Canal (NGR SJ7213692418) (Figure 3.4) using a stationary multi parameter SONDE (www.ysi.com) from 2012 to 2014. The SONDE was fitted with dissolved oxygen and ammonia probes in a flow through chamber which recorded said parameters every 15 minutes. As described in Anon (2012) the SONDE data were recovered monthly, the data downloaded and the SONDE cleaned, calibrated at an EA laboratory and then redeployed. The data were converted into daily means and graphed.

Estuary water quality

The monitoring of coastal and estuarine (transitional) waterbodies is a requirement of the WFD. The Mersey estuary is made up of a transitional waterbody and a coastal waterbody for which the WFD chemical classifications were reviewed. The WFD ecological classification of the transitional waterbody was also reviewed. The chemical classification is derived from the Priority Substances and List I Dangerous Substances quality elements as described above and the ecological classification is generated through the assessment of four BQE and SQE as described above.

In addition, dissolved oxygen data (% saturation) from two monitoring stations in the Mersey estuary, which provided consistent temporal and suitable spatial coverage from 1995 – 2014, were reviewed. These data were collected as part of the Environmental Quality Standards Directive (EQS) (2008/105/EC) and involve taking *ad hoc* samples of estuary water by helicopter or boat, which was later analysed at Environment Agency laboratories (personal communication, Environment Agency).

Hydrometry

River flow data were collected from 1996 – 2012 by the EA for the rivers Bollin, Upper Mersey, Tame, Goyt, Etherow, Glaze, Irwell, Medlock and Irk. As no suitable gauging station exists the flow of the lower River Mersey was estimated by combining the flows of those rivers already mentioned and combining the flow from the River Sankey, a large tributary of the river Mersey, to provide a more accurate estimation of the total freshwater flow of the lower River Mersey.

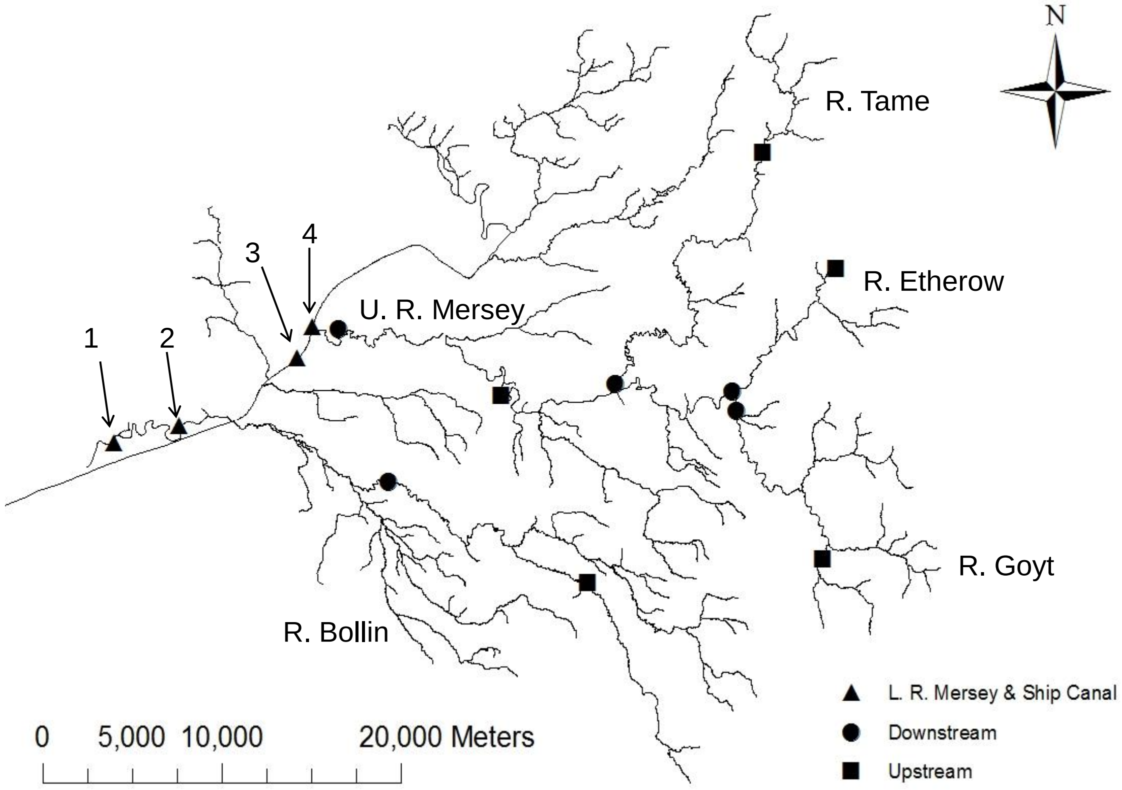


Figure 3.4 Site locations of (1) Howley and (2) Woolston Weirs, (3) Caddishead and (4) Irlam lock and the upper catchment up and downstream water quality sites.

Flow data were gathered at gauging stations and at all but one site were derived from stage measurements. The stage is measured using a shaft encoder, with a float and counter weight, deployed inside a stilling well. Flow was derived by the EA from a stage-discharge relationship established at each site using an acoustic dopler current profiler to establish actual flow and stage reading of the shaft encoder. The flow of the River Glaze was measured using an ultrasonic system that measures the velocity of the water at various levels throughout the channel and combines this with channel dimensions and the time the acoustic signal takes to cross the channel to give an estimation of flow. Flow (Cumecs (Q) ($m^3 s^{-1}$)), was converted to annual means.

Flow duration curves were also plotted for each river using the EA hydrometric archive database (WISKI) which automatically generated flow duration curves. Flow duration curves plot the percentage of time that flow is equal to or exceeds a specified flow. Each flow duration curve is compared to a modelled natural flow estimated by the EA using the Region of Influence Model (RIM). RIM models flow statistics for a river based on a small pool of similar catchments which RIM selects from 90 representative sites across the UK where the run-off has been calculated using the relationship between rain, evaporation and soil hydrolgeology (personal communication, Environment Agency). This allows actual flow in a river, as described by the flow duration curve, to be compared to a modelled natural flow, i.e. the flow of that river without artificial influences such as abstractions or impoundments. In addition to flow data, artificial influence data (volumes of abstractions, discharges and net impoundments and releases, e.g. reservoirs) were gathered by interrogating WISKI, which holds records of all discharge and abstraction permits.

3.3.3 Results

Physical barriers

The EA's GIS obstructions database contained 1167 possible obstructions in the rivers within the study area (Figure 3.5). These data contain no information on which of these are actual barriers to salmon and only identify structures in rivers as recorded in Ordnance Survey Mastermap.

Walkovers identified 116 potential obstructions to migration: 15 barriers were identified on the River Tame one of which was classified as impassable; 21 barriers were identified on the River Goyt and its tributaries the River Sett and Black Brook, 15 of which were recorded as impassable; 22 barriers on the River Bollin, Dean and Mobberley Brook which were classed as major, 14 as partial and 44 as minor (Figure 3.5). Interviews with Environment Agency Fisheries Officers confirmed those barriers classed as either impassable or major barriers as being impassable to salmon under Q95 flows (n = 38).

The Ship Canal contains 5 locks (Anon, 2011a) all of which were considered impassable as they are >20 m in height. Interviews with Environment Agency Fisheries Officers confirmed the 5 locks on the Ship Canal as barriers to salmon and identified an additional 7 potentially impassable barriers, two of which are thought to be passable under certain flow conditions (Woolston weir on the Lower River Mersey and Irlam weir on the Upper River Mersey) and one barrier which has collapsed allowing for fish passage (Figure 3.5). The EA has provided mitigation measures on 11 obstructions in the rivers Mersey, Bollin, Goyt, Dean and Tame through the building of fish passes and pre-barrage works, works immediately downstream of the obstruction to make it passable for migrating adult salmon (Figure 3.5 and Table 3.2).

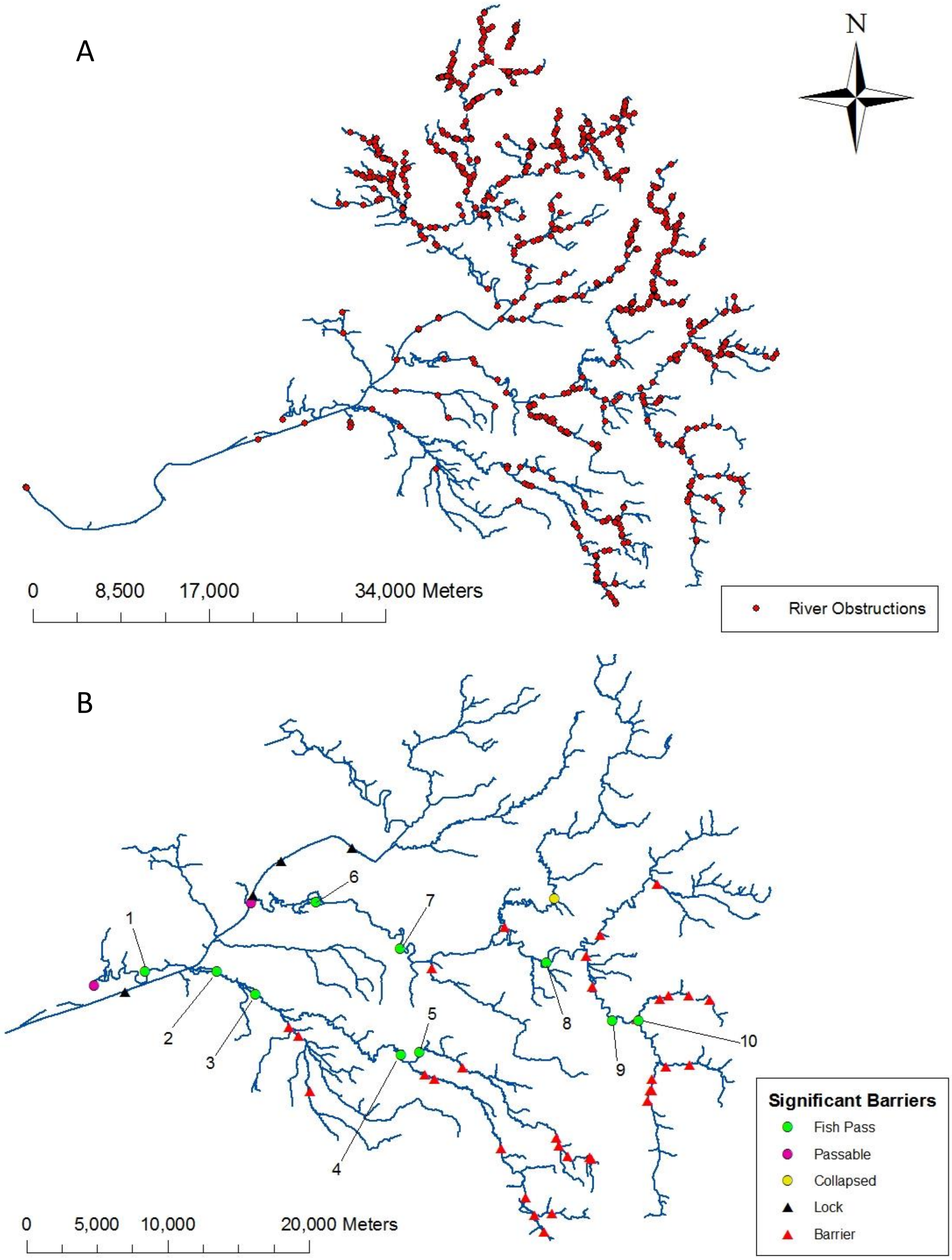


Figure 3.5 Map of (a) obstructions recorded in GIS and (b) significant barriers to migration identified during APEM walkover surveys and by EA Fisheries Officers and the location of fish passes (Table 3.2). Note; map B does not show the upper reaches of the River Irwell.

Table 3.2 Location and construction date of fish passes shown in Figure 3.5.

Map reference	River	Barrier	Date of construction
1	Mersey	Woolston weir	1999
2	Bollin	Heatley weir	2009
3	Bollin	Little Bollington weir	2009
4	Bollin	Styal wier	2014
5	Dean	Stanneylands Guaging Weir	2012
6	Mersey	Ashton weir	2012
7	Merey	Northenden weir	2008
8	Goyt	Otterspool weir	2011
9	Goyt	Disley weir	2013
10	Goyt	Torrs weir	2009

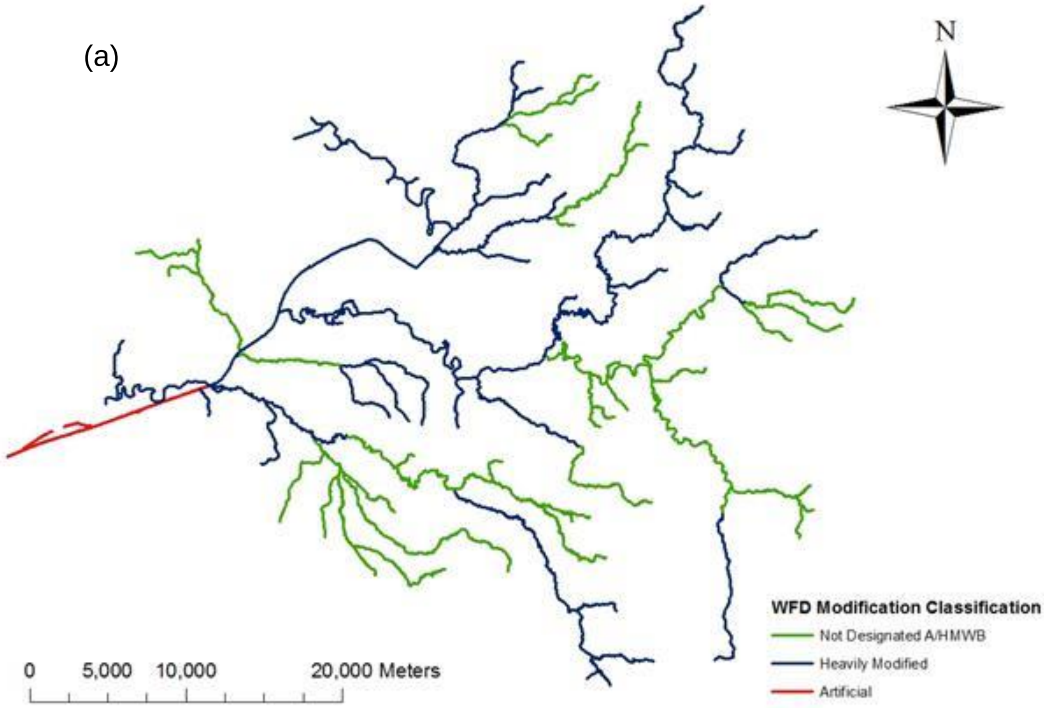
Interviews with Fisheries Officers did not include the rivers Irwell, Irk, Medlock and their tributaries as these river stretches are upstream of the 3 locks on Ship Canal (Figure 3.5) and were discounted from further analysis.

Of the 43 WFD waterbodies in the study area, 22 are classified as heavily modified and 1 as artificial (figure 3.6). The Ship Canal is classed as a single artificial stretch downstream of the lower Mersey confluence and as a heavily modified stretch upstream of the lower Mersey confluence. Lower stretches of the rivers Goyt and Etherow and middle stretches of the Bollin are classed as not designated a heavily modified, however, most other river stretches in the study area are classed a heavily modified (Figure 3.6).

Ecological quality

Of the 43 waterbodies that make up the study area one had an ecological quality of good, 27 as moderate, 11 poor and four bad (Figure 3.6). The entire lower River Mersey, the River Tame and some of the upper reaches of both the rivers Bollin and Goyt were classed as moderate. The lower reaches of the Bollin, mid stream of the Goyt and the entire Glaze were classified poor. The lower Goyt, before joining with the River Tame to form the lower River Mersey, and the upper reaches of the Medlock were classified as bad. A tributary of the River Etherow was classified as good. There weren't any waterbodies classified as high ecological quality.

(a)



(b)

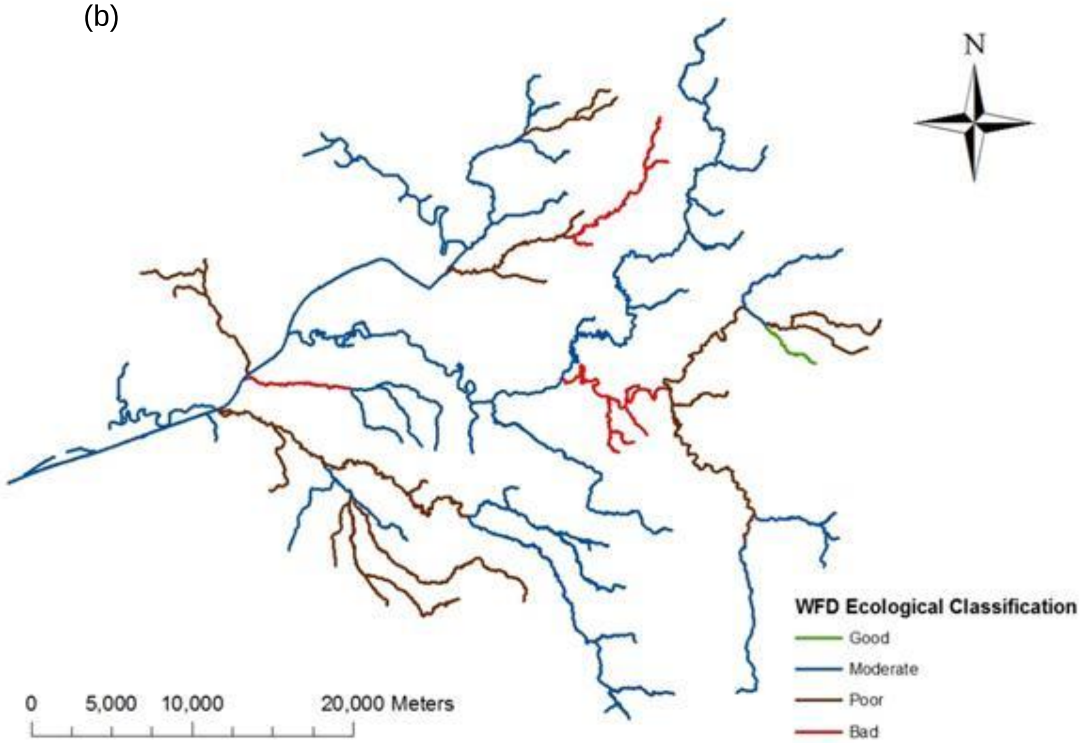


Figure 3.6 Water Framework Directive classifications of river stretches in the Mersey Catchment: (a) modification classification, (b) ecological classification and (c) chemical classification.

(c)

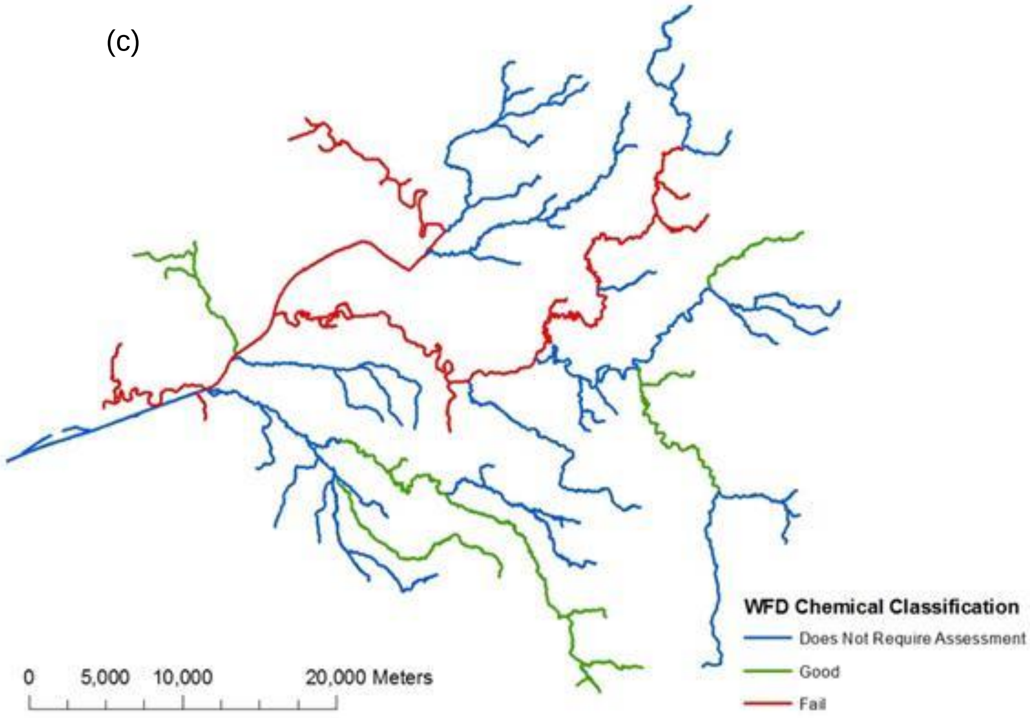


Figure 3.6 (continued) Water Framework Directive classifications of river stretches in the Mersey Catchment: (a) modification classification, (b) ecological classification and (c) chemical classification.

Freshwater water quality

Much of the Mersey catchment is unclassified with 33 of the 43 WFD waterbodies classed as not requiring a chemical classification (Figure 3.6). Six stretches of the River Goyt above the confluence with the Etherow and the upper reaches of the rivers Etherow and Bollin were classified as good. Four stretches of the Manchester Ship Canal and the rivers Mersey (lower and upper), Irwell and Tame were all classed as failing. The DO and ammonia data showed the catchment to be improving and recently meeting the requirement of the FFD, although dissolved oxygen data were only available from 1975 to 1995 (Figure 3.7.). DO was routinely above the FFD imperative concentration of >9 mg l^{-1} for 50% of the time in the rivers Bollin, Tame, Etherow and Goyt. However, the dissolved oxygen in the Upper River Mersey routinely falls below 9 mg l^{-1} at both upstream and downstream sites although shows a slight improvement from 1989 to 1995.

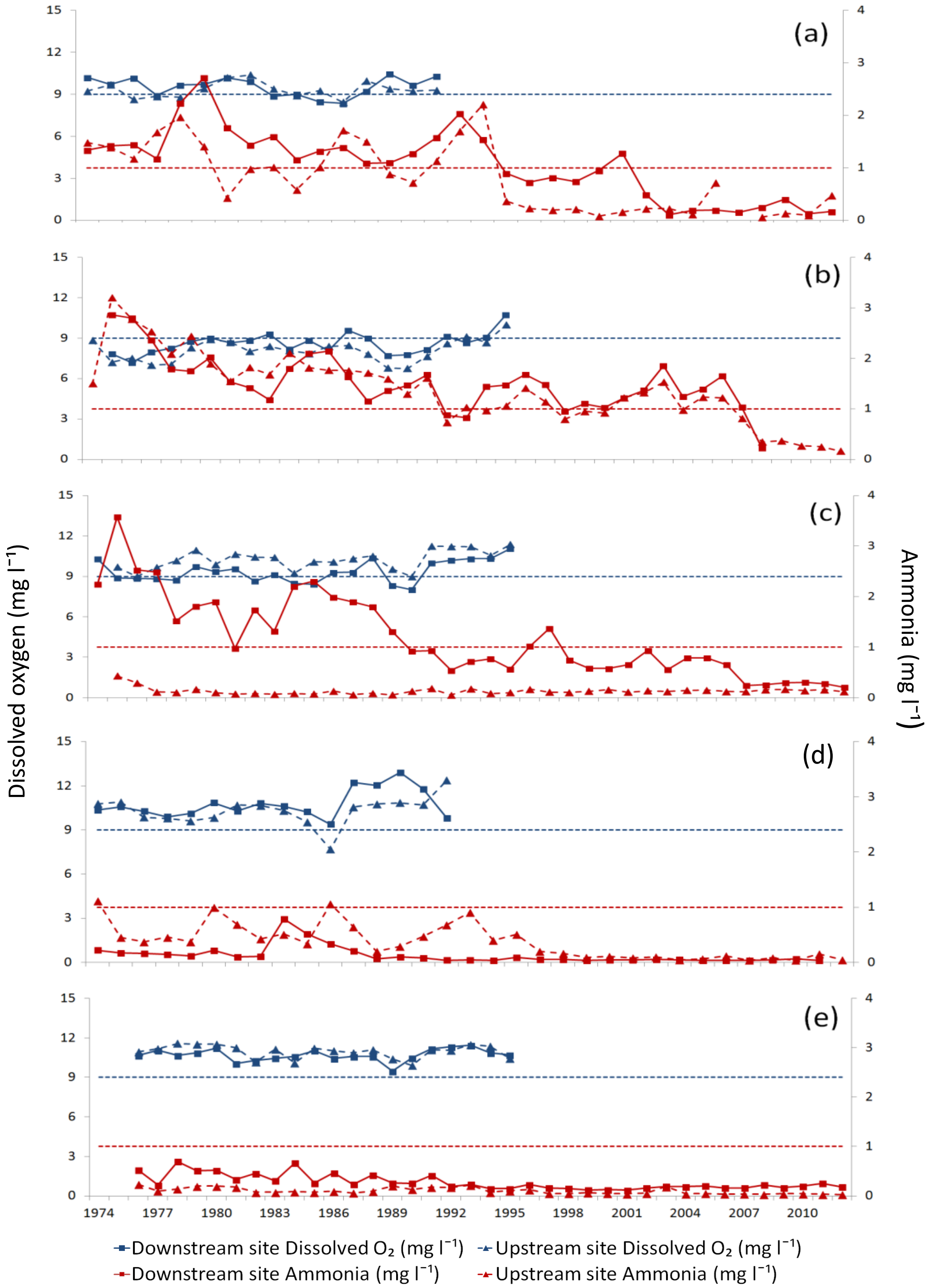


Figure 3.7 Dissolved oxygen (mg l^{-1}) and ammonia (mg l^{-1}) concentrations at up and down stream sites on the rivers (a) Bollin, (b) Upper River Mersey, (c) Tame, (d) Goyt and (e) Etherow (Figure 3.4) including the FFD imperative values (Table 2.1) of > 9 mg l^{-1} of dissolved oxygen (blue dotted line) and <1 mg l^{-1} ammonia (red dotted line).

All sites showed a reduction in ammonia concentration most markedly in the rivers Bollin, upper Mersey and Tame (Figure 3.7). Concentrations of ammonia at the upstream and downstream sites are similar in all rivers except the Tame where the downstream site reduces from >9 mg l^{-1} to the FFD imperative concentration of <1 mg l^{-1} from 1974 – 2012 whereas the upstream site has consistently been <1 mg l^{-1}. This is likely to be a result of the cumulative impact of all upstream discharges showing at the downstream site and a reduction in the toxicity and/or volume of discharges since 1974. Ammonia concentration does, however, exceed the FFD Guideline concentration of <0.04 mg l^{-1} in all rivers all the time, except for some years in the upstream site on the rivers Etherow and Goyt.

Water Quality in the Lower Mersey and Manchester Ship Canal

Dissolved oxygen (% saturation) at the Howley weir site tended to range between 70 – 100% saturation and 70 – 80% during May – September (Figure 3.8), the typical time of the year for salmon to enter estuaries in the North West of England (Anon, 2010b). There were some low saturation events of <50% in 2000 - 2003. Dissolved oxygen at the Woolston weir site ranged from 40 – 90% and 30 – 60% during May – September with some <20% events in 2001 and 2006 (Figure 3.8). The site just downstream of Irlam Locks ranged from 40 – 80% and 50 – 55% in May – September. All sites exhibited a seasonal pattern of reduced dissolved oxygen saturation in the summer months and increased saturation in the winter months. These data were checked with technical experts at the EA (personal communication) as there are <10% and >100% (supersaturation) events and the data are considered correct.

Daily dissolved oxygen means (mg l^{-1}) at Caddishead in the Ship Canal showed a similar seasonal trend to that identified at Howley and Woolston weirs and Irlam locks (Figure 3.9). Here, dissolved oxygen routinely fell below the FFD imperative of <9 mg l^{-1} for 50% of the time. Of the 844 days of data, dissolved oxygen was <9 mg l^{-1} for 84% of the time, <6 mg l^{-1} for 51.5% of the time and <4 mg l^{-1} for 26% of the time. Mean dissolved oxygen for the summer months was 4.51 (May), 4.83 (June), 4.78 (July), 3.5 (August) and 4.7 mg l^{-1} (September) (Figure 3.9). Daily ammonia concentration (mg l^{-1}) means routinely exceeded the FFD imperative concentration of <1 mg l^{-1}. The mean concentration of ammonia for the period was 1.12 mg l^{-1} and of the 835-day sampling period, the daily mean was <1 mg l^{-1} for only 47% of the time and <0.04 mg l^{-1} for just 3 days.

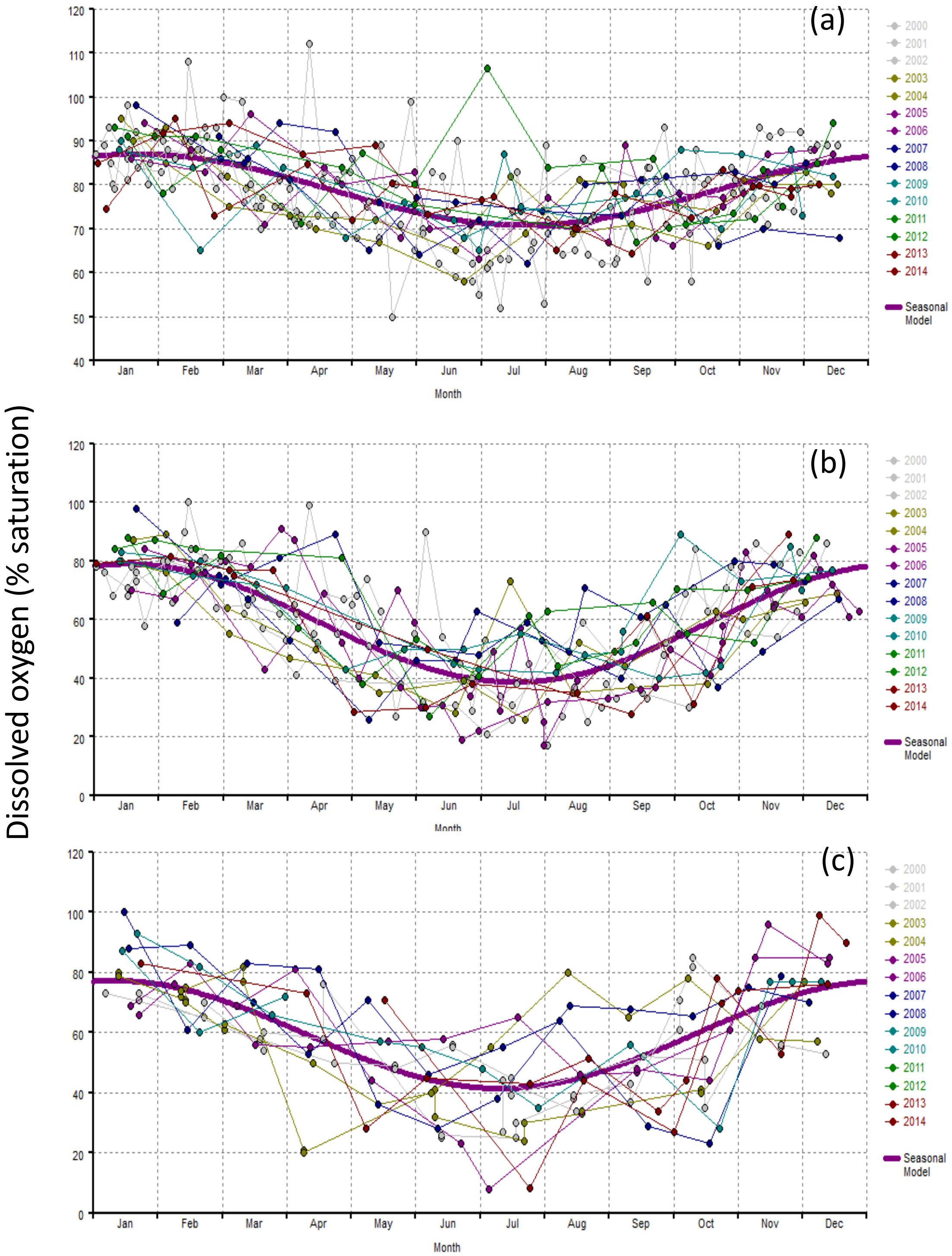


Figure 3.8 Year-on-year dissolved oxygen (% saturation) plots and seasonal model at (a) upstream of Howley weir, (b) upstream of Woolston weir and (c) Irlam locks on ship canal (Figure 3.5) as generated by Aardvark.

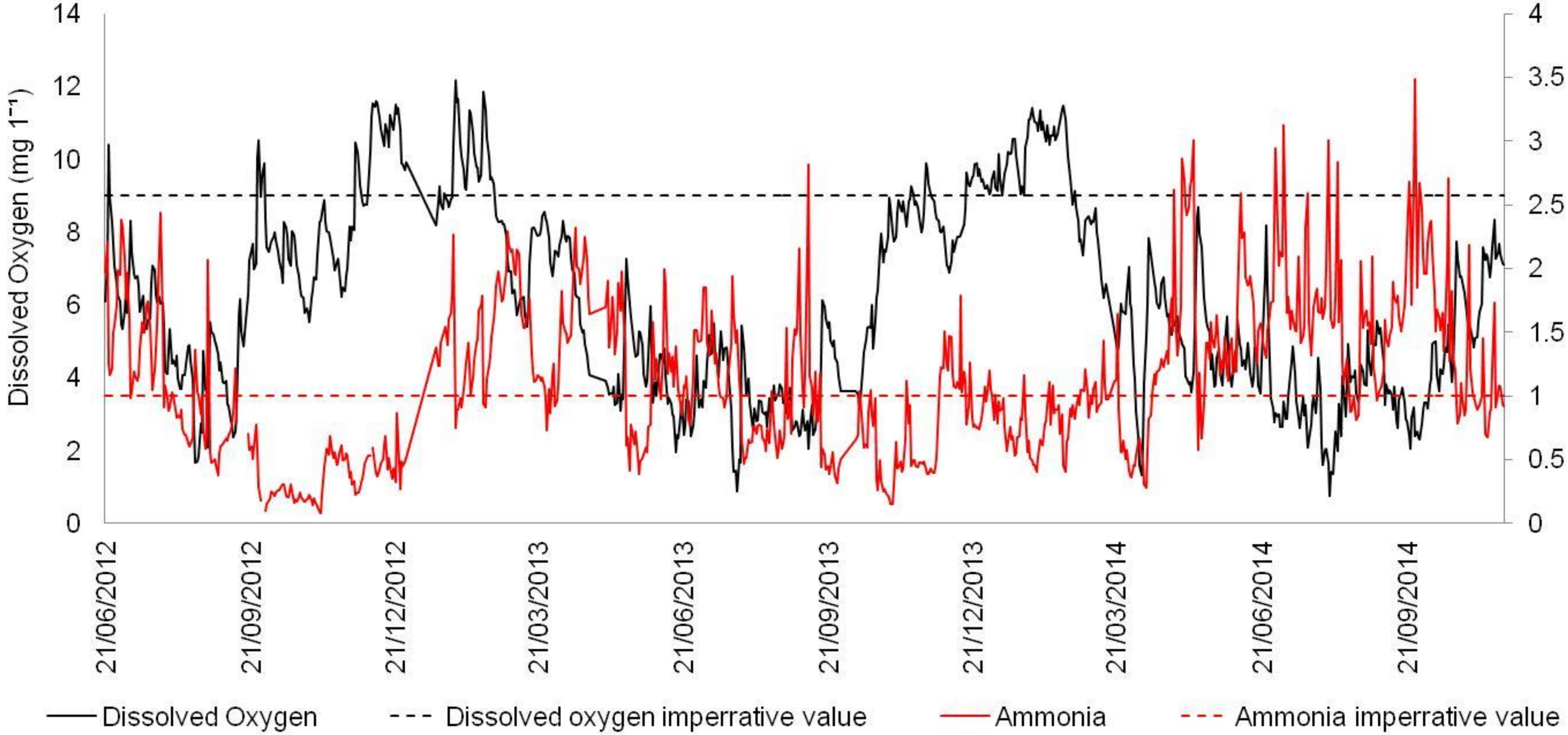


Figure 3.9 Dissolved oxygen (mg l⁻¹) and ammonia (mg l⁻¹) daily means at Caddishead (Figure 3.9) including the FFD imperative values (Table 2.1).

Water Quality in the Mersey Estuary

The two transitional waterbodies of the Mersey estuary have a WFD chemical and ecological classifications of fail and bad, respectively, and the coastal waterbody has a WFD chemical classification of fail (Figure 3.10).

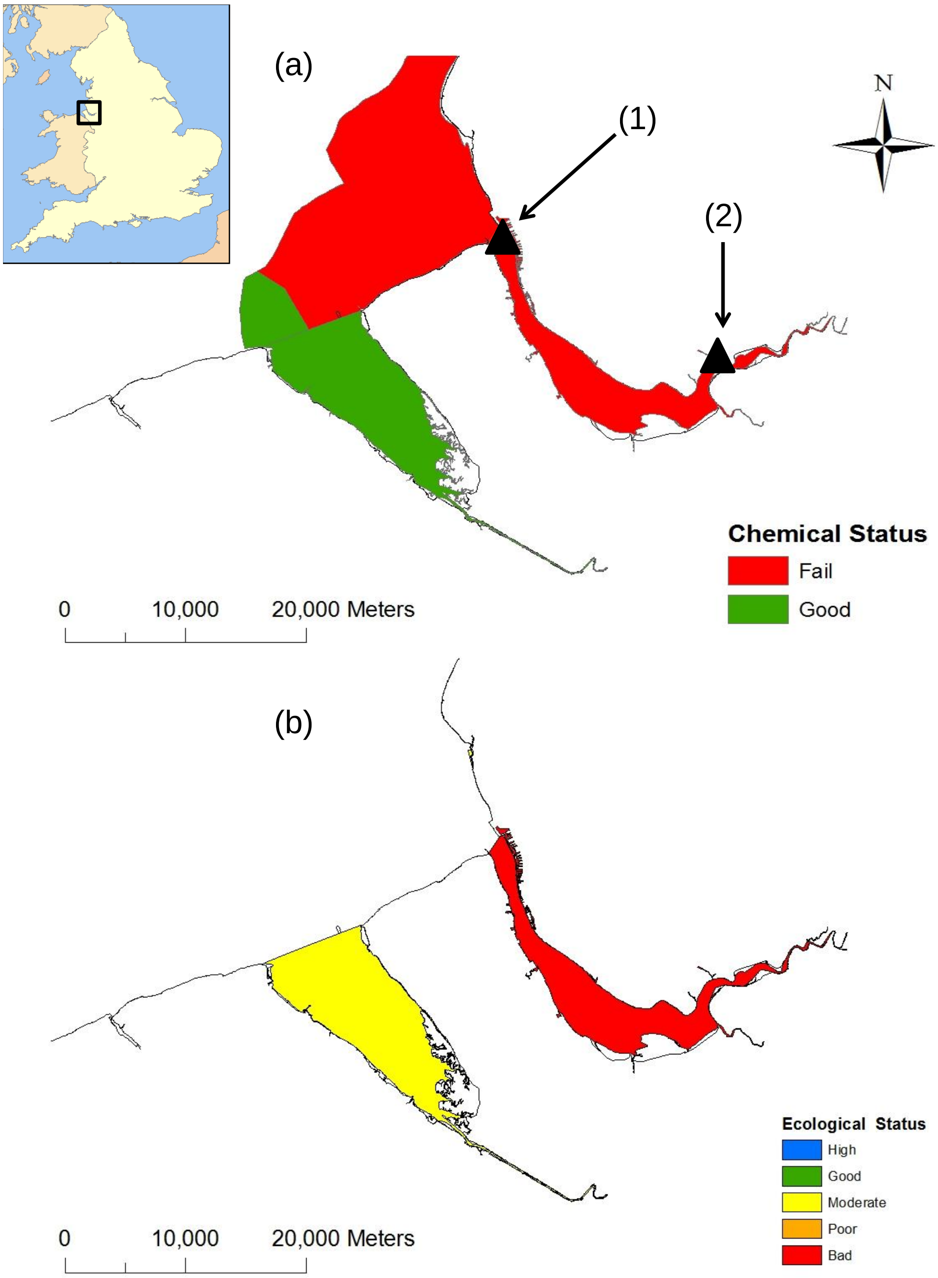


Figure 3.10 WFD (a) chemical and (b) ecological classifications of the Mersey estuary and coastal waters and the locations of estuary water quality monitoring stations; (1) New Brighton and (2) Runcorn denoted by triangles.

The mean dissolved oxygen (% saturation) between 1994 and 2014 at New Brighton was 93.39% (61.8 – 134%) and at Runcorn 72.05% (29.4 – 106%) (samples n=191 and n=366, respectively) (Figure 3.11). The downstream station at New Brighton had a higher dissolved oxygen concentration than Runcorn, consistently >65% saturation. The Runcorn site exhibited an increase in dissolved oxygen concentrations, with a mean concentration of 81.8% for 2009 – 2014.

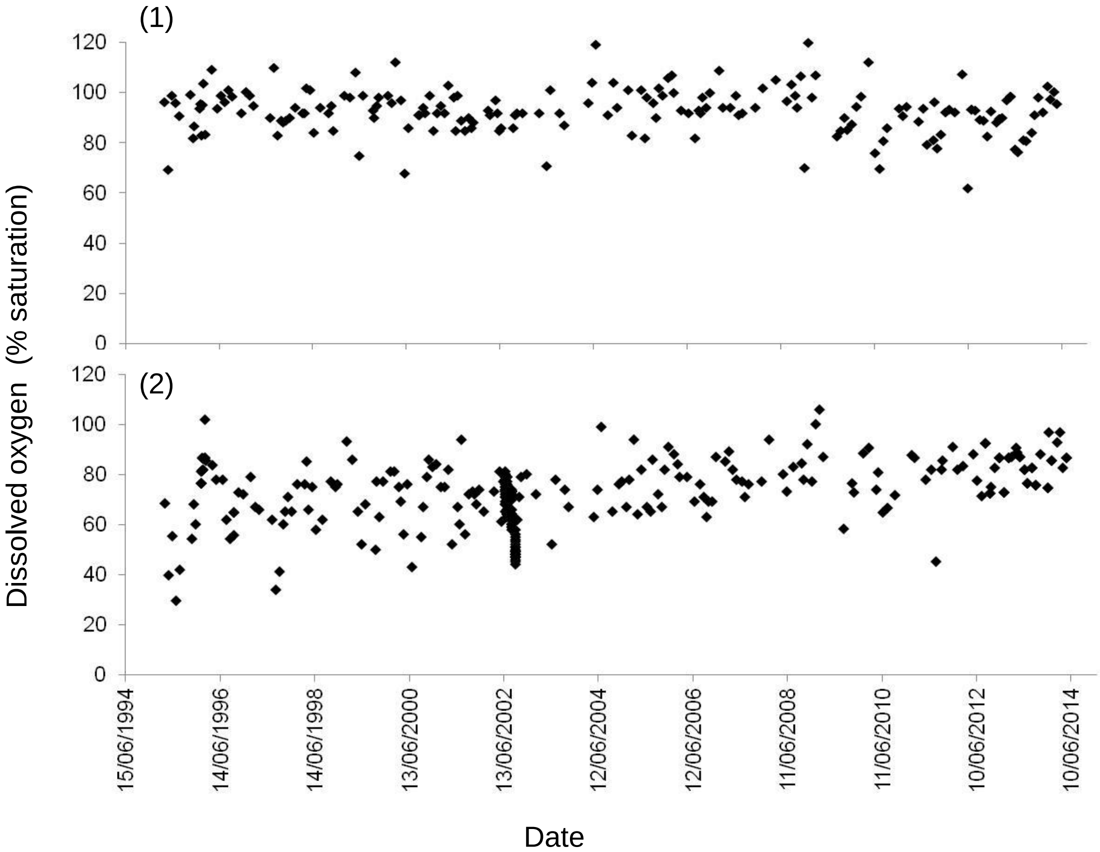


Figure 3.11 Dissolved oxygen (% saturation) at (1) New Brighton and (2) Runcorn in the Mersey estuary (Figure 3.10).

Hydrometery

Between 1996 and 2012 the lower River Mersey had an average daily flow of 42.92 $m^3 s^{-1}$, the Irwell 17.1 $m^3 s^{-1}$, the upper River Mersey 14.5 $m^3 s^{-1}$ and the mean of the upper River Mersey's tributaries ranged between 3.3 – 4.2 $m^3 s^{-1}$ (Figure 3.12 and Table 3.3). Flows of all rivers flowing into the Ship Canal and the upper River Mersey were different to those expected under modelled natural flow conditions with a typical trend of reduced higher flows and low flows below Q75 augmented above natural levels (Figure 3.13).

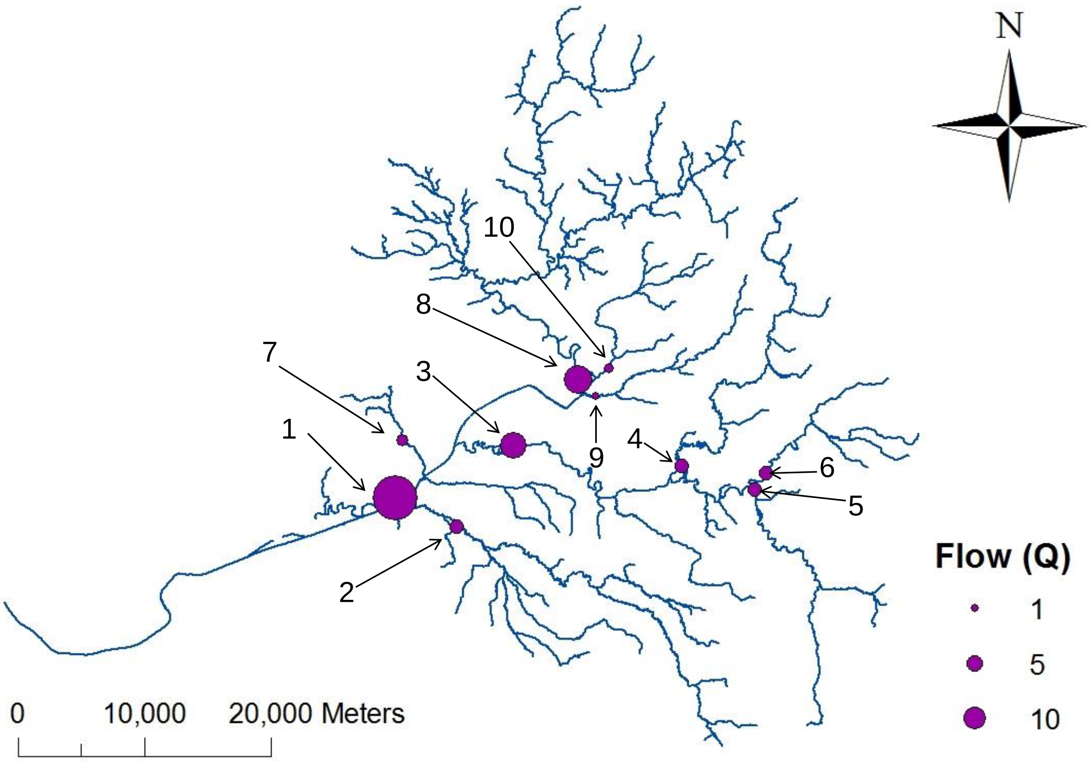


Figure 3.12 Mean annual flows between 2009 – 2014 for the Rivers (1) the Lower Mersey, (2) Bollin, (3) Upper Mersey, (4) Tame, (5) Goyt, (6) Etherow, (7) Glaze, (8) Irwell, (9) Medlock and (10) Irk. Points represent locations of gauging stations and points at which flow duration curves were calculated.

All rivers are subject to artificial influences (Table 3.3) with >10% of the flow of the rivers Tame, upper Mersey and Bollin made up of artificial discharges. All rivers except the Glaze have large volumes of water impounded (negative impoundment release volume), which reduces higher flows, particularly in the autumn months. Reservoirs also contribute to the general trend of reduced low flows due to compensation flow releases. Releases from sewage treatment works (STW) also serve to augment the natural flow, especially in and downstream of urban areas.

No flow data were available for the Ship Canal. The Ship Canal has a huge influence on flows in the lower River Mersey. As previously mentioned, the Ship Canal's water level, and so flow, is controlled using a series of five sluice gates and two weirs which control the amount of water entering the canal from the Rivers Irwell and upper Mersey, as well as other downstream inputs including the River Weaver and high tides in the estuary (Anon, 2011a).

Table 3.3 Mean flows and a summary of the mean of artificial influences for the period 1996 – 2013 for rivers entering the Ship Canal downstream of Irlam locks and their main tributaries. All data is in Cumecs (Q) ($m^3 s^{-1}$).

	Etherow	Goyt	Tame	Upper Mersey	Bollin	Irwell	Glaze
Mean Annual Flow (Q)	4 (2.92 - 6)	3.87 (2.85 - 5.26)	4.2 (3.42 - 5.37)	14.5 (10.9 - 19.9)	4.18 (2.9 - 6.97)	17.1 (14.1 - 21.2)	3.28 (2.3 - 4.6)
Proportion of flow which is artificial (%)	3.8%	2.9%	16.7%	10.7%	13.5%	11.8%	3.3%
Annual mean of Artificial Influences (Q)							
Sewage Works Abstraction	0.000	-0.074	-0.229	-1.105	-0.003	-1.659	-0.006
Ground Water Abstraction	-0.016	-0.007	-0.043	-0.230	-0.615	-0.756	-1.358
Discharges	1.763	1.384	8.457	19.433	7.063	26.328	5.539
Net Impounded Releases	-13.712	-10.686	-6.683	-31.803	-1.227	-14.126	0.000

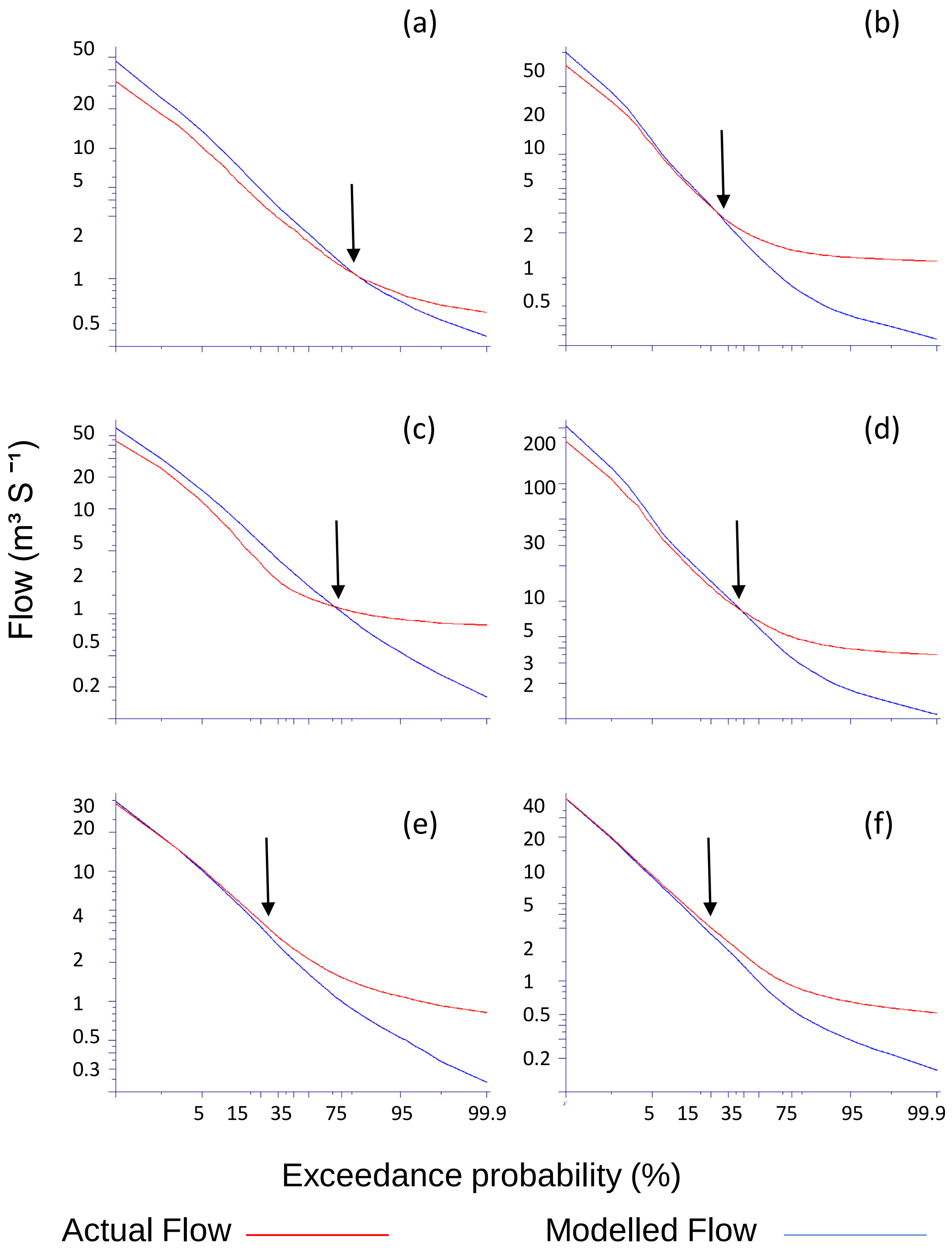


Figure 3.13 Flow duration curves based on average flow data from 1996 – 2012 for the Rivers (a) Goyt, (b) Tame, (c) Etherow, (d) upper Mersey, (e) Bollin and (f) Glaze. The blue line is the modelled flow under natural conditions and the red line is actual flow. Rivers upstream of Irlam locks on the Ship Canal have not been included. Arrows denote the point at which flow is augmented above modelled natural flows (Q30 – Q75).

Although an estimate of flow has been made for the lower River Mersey, flow is ultimately dictated by the volume of water in the section of canal between Irlam and Latchford locks, which the Lower Mersey flows out of. There are records of sporadic and quick reductions in flow in the lower Mersey due to the operation of locks in the Ship Canal and one record of the River Mersey flowing upstream due to a failure in Latchford Locks causing the ship canal to drain in this section (Environment Agency, personal communication).

3.3.4 Summary

1. Over half of the WFD waterbodies that make up the study area are classified as either heavily modified or artificial. There are large numbers of potential obstructions to upstream salmon migration. Salmon migration in the Ship Canal is limited to the stretch downstream of Irlam and upstream of Latchford locks.

2. Of the 43 waterbodies that make up the study area, one has an ecological status of good, 27 as moderate, 11 poor and four bad. Dissolved oxygen and ammonia concentrations suggest the catchment to be improving and recently meeting the requirement of the FFD. However, ammonia concentrations exceed the FFD Guideline concentration of <0.04 mg l^{-1} in all rivers.

3. There were low dissolved oxygen events in both the Ship Canal and immediately upstream of Woolston Weir, with dissolved oxygen routinely <9 mg l^{-1} in the Ship Canal. The Ship Canal ammonia concentrations routinely exceed the FFD imperative concentration of <1 mg l^{-1}.

4. The Mersey estuary waterbodies have a WFD chemical and ecological classification of fail and bad, respectively. The two water quality stations in the estuary recorded dissolved oxygen concentration of >80% over the last 5 years.

5. All rivers in the study area are subject to artificial influences from both discharges and impoundments and their flows are different to those expected under modelled natural flow conditions. There is a typical trend of reduced higher flows and low flows above Q75 augmented above natural levels.

3.4 CURRENT STATUS OF SALMON POPULATIONS IN THE MERSEY CATCHMENT

3.4.1 Introduction

There was anecdotal evidence of salmon returning to the Mersey estuary in the 1980s (Wilson *et al.*, 1988) and reports and evidence of their return to the estuary in the 1990s (Jones, 2000, 2006: Environment Agency, unpublished data). There is anecdotal evidence of adult salmon and sea trout entering the freshwater River Mersey and its tributaries in the mid-1990s and video evidence of salmon attempting to leap weirs on the River Bollin was captured in 1999 and 2000 (Jones, 2006; Environment Agency, unpublished data). The EA began an *ad-hoc* salmon monitoring programme in the Mersey catchment in 2001. This consisted of the trapping of migrating adult salmon at Woolston Weir fish trap on the lower River Mersey (Figure 3.16) and the training of electro-fishing survey teams in the identification of salmon and careful attention being given to identifying juvenile salmonids caught during electro-fishing surveys at all sites in the Mersey catchment.

3.4.2 Catches of salmon in the Mersey catchment

Trapping of adult salmon

Woolston weir was built between 1990 and 1994 to replace the former Woolston weir constructed in 1890 and plays a strategic function in the governance of water levels within the Manchester Ship Canal (Anon, 2011a). Woolston weir is situated 6 km upstream of Howley weir and is 3.3 km downstream of where the River Mersey departs from the Manchester Ship Canal. Because of Woolston weir's position in the catchment all migrating adult salmon must pass Woolston weir to move upstream of the Lower River Mersey (Figure 3.4). The total width of the weir is 76.5 m and it is split into three constituent sections, the central siphon (36 m wide) with two flanking, two tier, ogee weirs, on either side (each 17.75 m in width) (Figure 3.14). Each of the ogee weirs has three steps and is 7.9 m in height with a downstream water depth of 2.25 m. Woolston Weir is considered impassable to salmon except in extreme high flows (EA, personal communication).

A notch and pool fish pass was built adjacent (right hand bank) to Woolston Weir during its construction. In 2000 the fish pass was adapted to include a top chamber with a moveable penstock at the exit and a gate at the entrance allowing for the trapping and monitoring of migratory fish (Figure 3.14).

Figure 3.14 Photographs of Woolston weir; (a) the right hand flanking ogee weirs and (b) the trapping of salmon. Note the moveable pen-stock (closed) in the top left hand corner of the picture denoted by an arrow.

In 2001 the EA undertook the first programme of trapping, which was repeated until October 2003 when emergency works rendered the site unsafe and trapping was suspended until 2005, after which it was undertaken on an annual basis until 2011 (Table 3.4). During the 2003 to 2005 break in trapping the fish ladder was altered. Prior to this the pass was set up as a stream flow pass with a series of pools separated by notched weirs providing ‘ladders’ for fish to climb.

Table 3.4 Catches of adult salmon at Woolston Weir and the trap operating periods between 2001 – 2013. Note, the 2012 and 2013 catches are those of the intensive monitoring only.

Year	Trap operation	Number salmon (n)	Number of total trapping days (n)	Catch per day (n)
2001	1st - 26th November	3	18	0.17
2002	23rd September - 26th November	26	48	0.54
2003	13th - 20th October	1	6	0.17
2005	18th October - 4th November	42	10	4.20
2006	26th October - 24th November	8	21	0.38
2007	2nd October - 13th December	35	41	0.85
2008	11th September - 18th November	45	20	2.25
2009	2nd - 5th November	3	4	0.75
2010	1st September - 6th October	32	24	1.33
2011	30th August - 12th October	16	30	0.53
2012	3rd September - 30th November	17	65	0.26
2013	6th August - 1st November	10	64	0.16

In 2004 the EA national fish pass panel found the fish pass to be poorly designed and had unsuitably located and sized notches and as a result of this the notch height between weirs was increased. When in operation the trap is set in the morning, then inspected and re-set 24 hours later. Fishing effort from 2001 – 2011 was inconsistent in terms of the time of year the trap was operated, the total number of trapping days and number of consecutive days the trap was operated. In 2012 and 2013 monitoring at the Woolston Weir fish trap was undertaken by APEM Ltd on behalf of the EA. During 2012 and 2013 monitoring was consistent and included intensive sampling which was undertaken five days a week, every week, during the period thought to correspond to the peak run of adult salmon (August – October, inclusive) and non-intensive monitoring which was undertaken each day for one week a month (Figure 3.15). No salmon were caught during the non-intensive monitoring of the fish trap except one fish during the week commencing the 4/11/2013 and only 17 and 10 salmon were captured during the intensive sampling periods in 2012 and 2013, respectively. A total of 238 salmon were captured at Woolston weir fish trap between 2001 and 2013, including those caught during the intensive and non-intensive sampling of 2012 and 2013.

Trapping effort has been inconsistent. With the exception of trapping from 2010 to 2013 trapping days when no salmon were captured (‘no catch’) have not consistently been recorded. As such, the total number of trapping days from 2001 to 2009 does not accurately reflect actual fishing effort and so the catch per day estimate for these years may be over-estimated. For the years when ‘no catch’ data were accurately recorded (2010 – 2013) the mean catch per day (CPD) was 0.57 fish per day (mean CPDs of 1.33 in 2010, 0.53 in 2011, 0.26 in 2012 and 0.16 in 2013). If this mean is extrapolated over the period August to November (122 days), the peak salmon run in North West England (Environment Agency, personal communication; Anon, 2010), (0.57 x 122 days), it suggests approximately 70 adult salmon could be entering the Mersey and moving upstream of Woolston weir during the peak salmon run. It is worth noting the lower CPD of the intensive sampling period (mean CPD over 2012 and 2013 is 0.21) which is likely to reflect actual numbers more accurately, due to the longer and more consistent sampling, which results in an estimate of 26 salmon moving upstream of Woolston Weir a year during the period August to November. The monitoring periods at Woolston weir were inconsistent and too few salmon have been caught to discern a peak run of adult salmon entering the River Mersey.

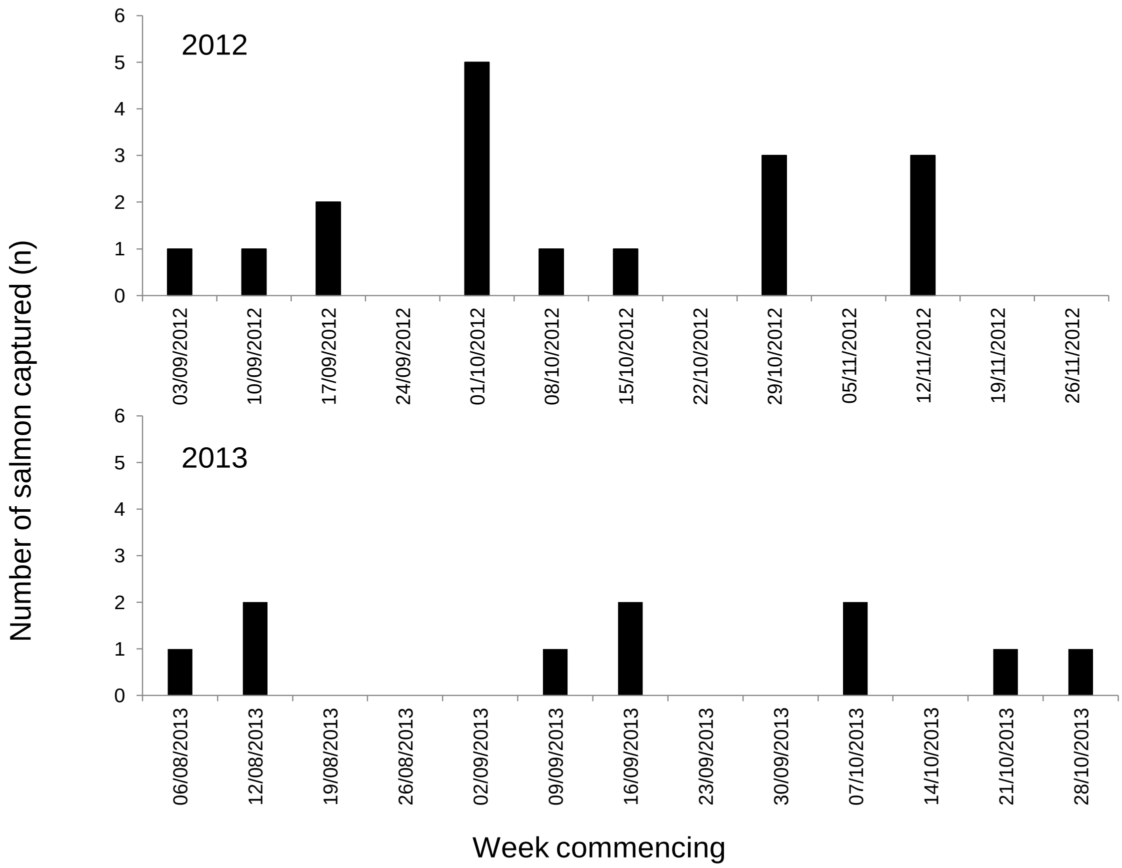


Figure 3.15 Numbers of salmon during 2012 and 2013 intensive monitoring.

It should be noted, the efficacy of Woolston Weir fish pass is unknown and that salmon captured at Woolston Weir may not reflect actual numbers of salmon entering the River

Mersey but rather those successfully negotiating the fish pass (this will be explored in Chapter 5).

Juvenile salmon and smolt

The EA carries out an annual electric fishing programme as part of its statutory duty to monitor fish stocks in England and Wales. The EA's National Fisheries Population database (NFPD) holds records of all catch statistics of all EA electrofishing surveys. The NFPD was interrogated and all surveys where salmonids (any fish recorded as salmon, sea trout, brown trout and grayling (*Thymallus thymallus*)) were caught were identified. A total of 821 surveys took place over 244 sites between 1993 and 2014 in which salmonids were captured. A total of 26,278 brown trout, 197 grayling and 21 juvenile salmon were captured (Figure 3.16). No salmonids were captured in the Lower River Mersey (except those adults at Woolston weir fish trap), the Upper Mersey or the River Glaze. This was expected due to habitat conditions in these rivers, typically, wide, deep and slow flowing with river beds dominated by silt and clay. There are large numbers of sites were brown trout were captured in the upper reaches of the Irwell, Goyt, Etherow and Bollin and their tributaries.

Twenty one juvenile salmon were caught between 2005 and 2011 at one site on the River Bollin and seven sites on the River Goyt (Figure 3.16 and Table 3.5). Juvenile salmon were aged at the EA national fish laboratory by examining scales under a microfiche projector and by counting the number of annuli (for method see Chapter 6). The ages of the juveniles were then used to predict the year of parent entry into the Mersey catchment (Table 3.5). Sampling effort and surveillance has been extensive throughout the catchment as discussed above, however, no smolts have ever been captured or reported to the EA.

3.4.3 Summary

1. There are reports and evidence of salmon entering the Mersey estuary and freshwater Mersey from the 1990s and in 1999 and 2000 video evidence was captured of salmon attempting to leap weirs on the River Bollin.

2. Low numbers of adult salmon have been captured at Woolston Weir fish pass. Catch per day estimates range from 0.21 - 0.57, which suggests approximately 25 to 70 adult salmon may be moving upstream of Woolston weir during the peak salmon run.

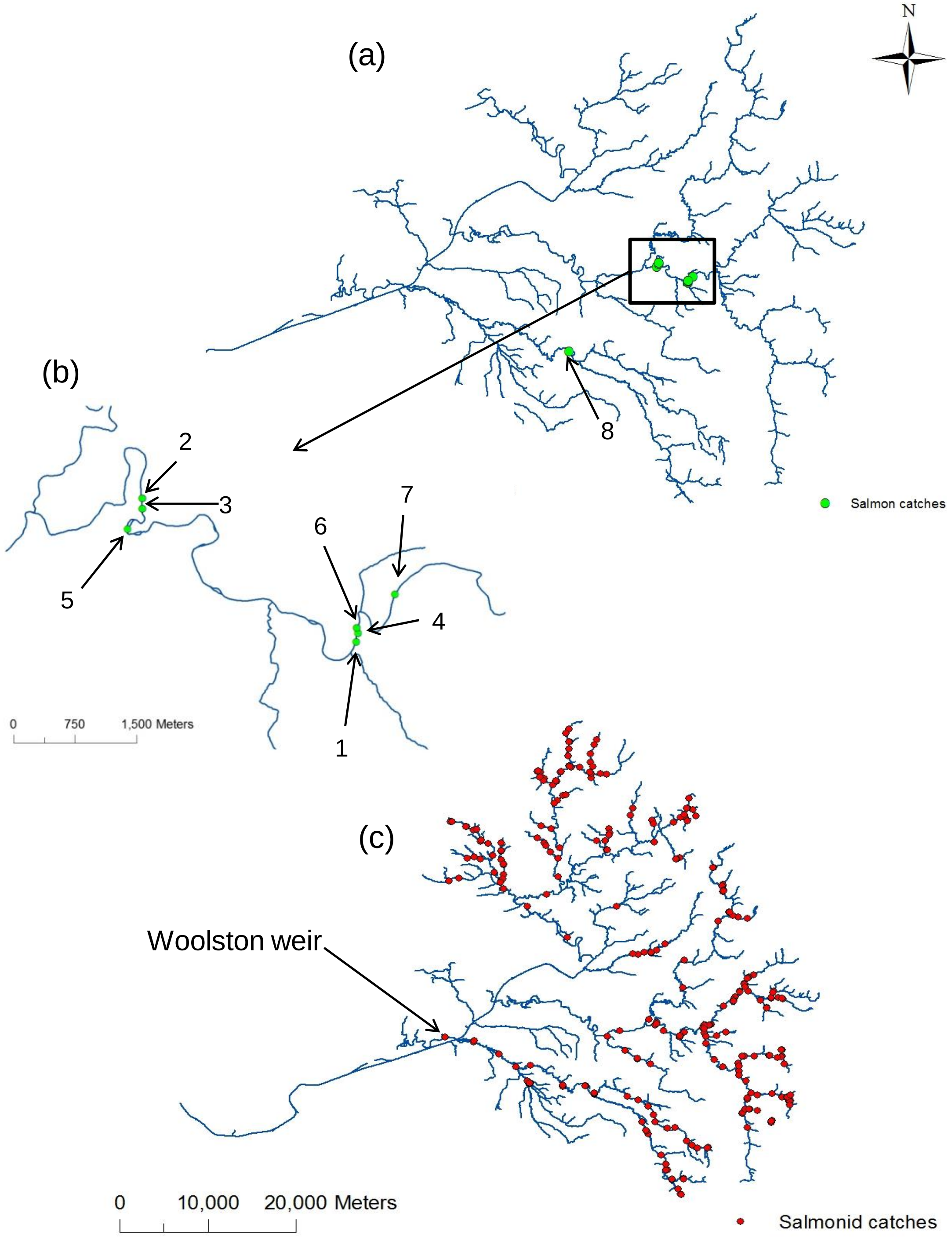


Figure 3.16 All sites at which (a) and (b) only juvenile salmon (table 3.5) and (c) all adult and juvenile salmonids have been captured.

Table 3.5 The age of the 21 juvenile salmon caught in the Mersey catchment and predicted year of parent entry. Refer to Figure 3.16 for location of sites.

Survey Date	Site	Length (mm)	Age	Year Class	Year of adult entry
08/08/2005	1	72	0	2005	2004
08/08/2005	1	73	0	2005	2004
08/08/2005	1	78	0	2005	2004
18/08/2005	2	88	0	2005	2004
15/08/2006	3	73	0+	2006	2005
15/08/2006	3	160	1+	2005	2004
15/08/2006	4	86	0+	2006	2005
15/08/2006	4	78	0+	2006	2005
15/08/2006	4	82	0+	2006	2005
15/08/2006	5	79	0+	2006	2005
05/10/2007	6	191	1	2006	2005
05/10/2007	6	101	1	2006	2005
05/10/2007	6	111	1	2006	2005
05/10/2007	3	120	1	2006	2005
13/08/2009	6	79	0	2009	2008
13/08/2009	6	80	0	2009	2008
13/08/2009	6	89	0	2009	2008
13/08/2009	6	89	0	2009	2008
14/08/2009	7	201	1	2008	2007
03/08/2010	8	151	1	2009	2008
06/07/2011	2	206	1	2010	2009

3. Only 21 juvenile salmon have been captured in the study area and there are no signs of increasing numbers of juveniles.

4. Juvenile salmon growth data provide evidence of successfully spawning adult salmon entering the Mersey from 2004.

5. Smolts have never been caught by or reported to the EA as present in the Mersey catchment.

3.5 DISCUSSION – THE CURRENT SALMON POPULATION IN THE MERSEY CATCHMENT AND NEED FOR FURTHER INVESTIGATION

Salmon became locally extinct from the Mersey catchment during 1940 – 1950s as a result of a catastrophic deterioration in water quality and an increase in barriers to migration beginning at the start of the Industrial Revolution. After significant improvements in water quality (Jones, 2007), the Mersey estuary was considered to have a fish assemblage comparable to similar estuaries (Elliott & Dewailly, 1995) and after an absence of 40 years salmon were recorded entering the River Mersey and its tributaries in the early 2000s (Jones, 2006) (Figure 3.17). Fifteen years on salmon have not recolonised the Mersey catchment and there are no signs of increasing numbers of either returning adults or juveniles, and no records of smolts exist. Therefore, a self-sustaining population is not thought to exist in the River Mersey and the river appears to remain in the early stages of an on-going process of natural recolonisation reliant on straying (section 2.3.2).

A number of studies document salmon forming naturally occurring self sustaining populations through natural straying and the mitigation of historic limiting factors alone (Schreiber & Diefenbach, 2005; Anderson & Quinn, 2007; Kiffney *et al.*, 2009; Perrier *et al*., 2010; Griffiths *et al.*, 2011; Ikediashi *et al.,* 2012). There are several examples of newly available river systems and tributaries being colonised and supporting self sustaining salmon populations over relatively short time frames (Hendry *et al*, 2004; Quinn 2005), with some occurring within as little as 1 – 5 years after the salmon first began entering a newly available river (Bryant *et al*, 1999; Glen, 2002). The time period for colonisation and establishment of self sustaining populations, regardless of whether the new habitat is newly opened or re-opened, very rarely exceed thirty years and most occur within twenty years (Withler, 1982; Burger *et al*., 2000; Milner *et al*., 2008; Kiffney *et al*., 2009). Several examples of natural recoveries through straying have been documented (section 2.3.4) including The River Tyne, UK, a comparable river to the Mersey (Milner *et al.,* 2004; Griffiths *et al.*, 2011). Therefore, it could be expected that the Mersey catchment should by now have a self sustaining salmon population.

Several factors exist that may potentially be limiting a recolonisation in the Mersey catchment but it is not immediately evident what factors may be functioning as bottlenecks preventing a successful recolonisation by salmon.

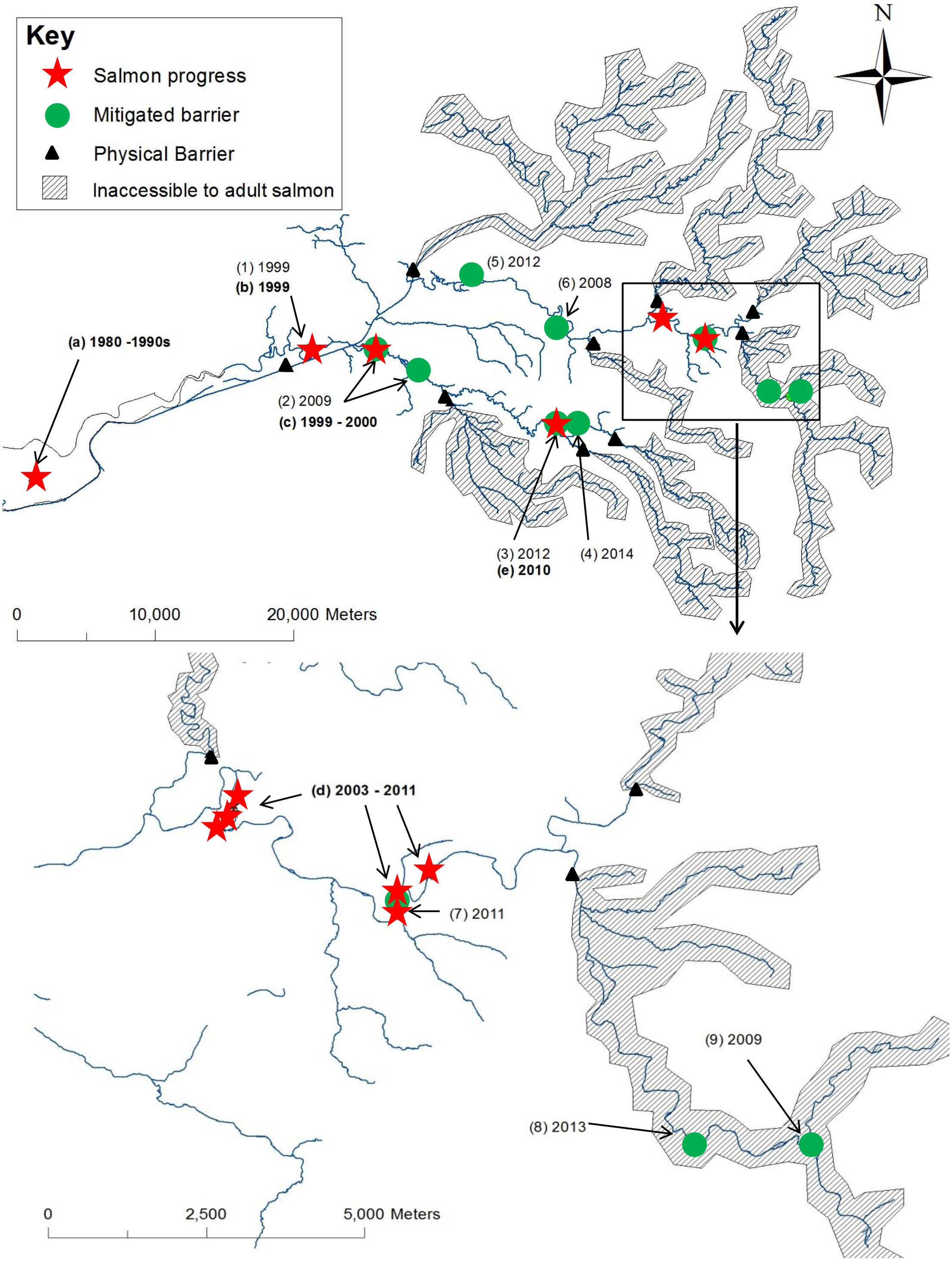


Figure 3.17 Current understanding of the present distribution and penetration of migrating adult and juvenile salmon in the Mersey catchment. Mitigated barriers are denoted with a reference number (Table 3.2) and date of mitigation in brackets and records of salmon denoted with a letter and date of record in brackets (in bold), where (a) is anecdotal evidence of salmon entering the estuary, (b) salmon captured at Woolston weir, (c) salmon filmed attempting weirs on the Bollin and (d) and (e) juvenile salmon captured on the Bollin and Goyt, respectively.

The Mersey catchment is heavily modified, in places artificial, and is highly complex with controlled flows, abstractions, discharges and impoundments. There is a general trend of augmented low flows due to compensation flow releases from reservoirs (flows below Q75 augmented above natural levels (Figure 3.13)), particularly in the autumn months, due to impoundments and a reduction in some higher flows. Increase in flow is known to stimulate upstream movement in salmon (section 2.2.4) and the reduction in the range of flows and a reduction in flow during autumn, a time when salmon typically migrate into fresh water and move upstream (Chapter 2), may impact on salmon migration in the Mersey catchment. The effects of flow are highly site specific and flow in the lower Mersey catchment is unlikely to be preventing fish migration in itself, as enough flow exists to allow upstream passage and the range in flows, which includes some peaks, to satisfy most behavioural dependencies on flow changes. However, flow is likely to play an influential role in the upstream movement past physical barriers, even in larger rivers when movement would otherwise be independent of flow (Milner *et al.,* 2012) and especially during low flows (Hawkins & Smith, 1986; Solomon *et al*., 1999). The specific criteria that either allow or limit the passage of salmon at any site will be unique (Solomon *et al*., 1999) and requires further investigation.

There are large numbers of potential and known barriers to salmon migration in the Mersey catchment, and longitudinal connectivity may be a factor limiting the recovery of salmon in the River Mersey and requires further investigation. Much of the upper catchment is upstream of barriers to migration (Figure 3.17) The cumulative effect of passable barriers are also likely to negatively impact on a potential recolonisation by reducing the motivation of salmon to migrate and increasing the energetic cost and time associated with upstream movement (Thorstad *et al*., 2005; section 2.2.6).

There is a general trend of fail or bad – moderate ecological and chemical WFD classifications of waterbodies in the Mersey catchment and the estuary. The estuary's dissolved oxygen concentration of >80% saturation over the last 5 years is unlikely to be acting as a barrier to adult migration but could have been historically. The extended periods of low dissolved oxygen in the Ship Canal and immediately upstream of Woolston Weir may be impacting on salmon. Low dissolved oxygen concentrations can act as a barrier to salmon migration (Crisp, 1996; Alabaster, 1990; Alabaster *et al*., 1991; Elliott & Elliott, 2010; Jonsson & Jonsson, 2011). The low dissolved oxygen concentrations upstream of Woolston weir is worth noting as this potentially presents an immediate barrier or significant stress factor to fish having just moved upstream via the fish pass from the well oxygenated water of the weir plunge pool. High speed swimming or burst activity needed to move upstream of a fish pass (Katopdis, 1994; Colavecchia, 1998) is known to carry a large metabolic cost and the fall in arterial oxygen content can take up to 2 hours to recover from (Tufts *et al.,* 1990). As such salmon recovery time and so motivation, especially that of straying fish (section 2.3.2), may be impacted.

Ammonia concentrations in the Ship Canal routinely exceed the FFD imperative concentration for salmonids of <1 mg l^{-1}. The most common source of ammonia in fresh water is sewage effluent, silage and manure (Alabaster, 1982). It worth noting the volume of discharges, especially sewage treatment works, into the Mersey catchment (Table 3.3) which are likely to be a significant source of ammonia and nitrite pollution. Ammonia poisoning can result in mortality of salmonids from damage to the gill epithelium and a range of chronic effects including skin, kidney and liver damage when exposed to sub-lethal levels (section 2.2.5). Some studies suggest salmon are able to survive in elevated levels of ammonia as long as sufficient levels of dissolved oxygen levels are maintained (Alabaster, 1959; 1972; White & Williams, 1978). However, as already mentioned, there are low levels of dissolved oxygen in the Ship Canal. Avoidance behaviour and refuge seeking and use in salmon in response to unfavourable environmental conditions are well documented (Gray, 1983; Atland, 1998; Spoor, 1990; Ytrestoyl *et al.,* 2001; Thorstad *et al.*, 2008; Broadmeadow, *et al*., 2010; Elliott & Elliott, 2010; Moore *et al*., 2012). However, refuge seeking behaviours are likely to be ineffective in the Ship Canal owing to the widespread and chronic nature of the water quality issues.

The effects of poor water quality on salmon are well documented and sub-lethal effects may include a reduction in motivation to move upstream, and decreased fitness, lowered resilience to pathogens and poorer swimming performance (Wedemeyer & McLeay, 1981; Koltes, 1985; Svobodova *et al*., 1993; Moore & Waring, 1996; 1998; Waring & Moore, 1997; Scholz *et al*., 2000; Ytrestoyl *et al.,* 2001; Lower & Moore, 2007; Tierney *et al.,* 2010; Moore *et al*., 2012). The combined sub-lethal but chronic water quality issues in the Ship Canal and lower River Mersey may impact on salmon and may reduce the likelihood of recolonisation and require further investigation. However, dissolved oxygen and ammonia concentrations for reaches upstream of the Ship Canal routinely meet the FFD imperative concentrations of dissolved oxygen >9 mg l^{-1} for 50 % of the time and ammonia concentrations of >1 mg l^{-1} and are therefore potentially not acting as a significant barrier to recolonisation.

This chapter began with the hypothesis that conditions in the Mersey catchment meet the basic physiochemical requirements of migrating adult salmon. After reviewing current conditions in the catchment it is hypothesised that several factors preventing the recolonisation of the Mersey catchment by salmon remain. These include: the numbers of adults entering the Mersey catchment, longitudinal connectivity and impassable barriers, water quality issues in the lower River Mersey and the Ship Canal, the modified structure of the Mersey catchment and their combined and cumulative effects. Investigating and diagnosing which factor or factors are preventing salmon establishing a self sustaining population is essential to direct future management efforts to ensure recovery of both the River Mersey and the salmon population therein; these factors are explored in subsequent chapters.

4 ORGINS OF ATLANTIC SALMON ENTERING THE RIVERS MERSEY, LUNE, RIBBLE AND DEE

4.1 INTRODUCTION

Straying is a natural part of salmon population biology (section 2.3.2); it has an obvious adaptive role enabling colonisation of new habitats, avoidance of detrimental environmental conditions and the resulting gene flow can alleviate the adverse effects of inbreeding depression and optimise reproductive fitness (Chapter 2). Straying usually takes place between proximate rivers (Vasemagi *et al*., 2001; Griffiths *et al*., 2011), although some recent studies have documented long distance straying (Perrier *et al*., 2010; Ikediashi, *et al*., 2012). It is considered that recolonising salmon originating from similar (generally local) rivers, in which resident salmon are locally adapted, may exhibit some pre-adaptation to any proximal un-colonised river (Finnegan & Stevens, 2008). However, colonisers of newly available rivers or catchments from multiple source rivers may be potentially beneficial for the long-term survival of the population as the increased genetic diversity will allow for an increased ability to adapt to changing conditions (Perrier *et al.* 2010; Ikediashi, *et al*. 2012).

Management practices, in particular stocking practices (Potter & Russell, 1994; Jonsson *et al*., 2003) and fish farms (Milner & Evans, 2003), affect the numbers of straying salmon, therefore the source-sink dynamics of systems. The reduced homing ability of hatchery reared salmon compared to wild counterparts is well documented (Potter & Russell, 1994; Jonsson *et al*., 2003; Pedersen *et al*., 2007) and escaping salmon are a common feature of salmon farms, occurring through low level leakage and through episodic events such as storms (Naylor *et al*., 2005). As such, hatcheries and fish farms can contribute a significant number of strays into a system; escaped farmed salmon have been documented successfully breeding in the wild in Norway, Ireland, UK and eastern North America (Lura & Saegrov, 1991; Hansen *et al*., 1997; Thorstad *et al*., 2008). Worldwide production of farmed salmon has been over one million tonnes per year since 2002 (Anon, 2012b). In 2012, ICES (Anon, 2012b) reported North Atlantic production was in excess of 1 million tonnes; an 8% increase on 2010 and a 26% increase on the previous five-year mean in farmed salmon in the Northern Atlantic. Therefore, the potential for escaped and straying farmed salmon is increasing. This is of concern; escaped farmed salmon may compete directly with wild salmon for habitat and food and their juveniles tend to be faster growing and more aggressive than wild salmon giving them a competitive advantage often displacing their wild counterparts (Thorstad *et al*., 2008). There is also strong evidence that progeny from both farmed and hybrid fish may be less viable than the local stock (Brannon, 1982; Bailey, 1987; Candy & Beacham, 2000). This, coupled with evidence that farmed salmon have decreased survival rates (Einum & Fleming, 2001), means that large numbers of escaped and stray farmed salmon may be detrimental to native populations or to the recolonisation of newly available habitats.

Philopatry to natal rivers in salmon has resulted in the reproductive isolation of populations and the development of large numbers of genetically distinct populations (Spidle & Lubinski, 2001; Verspoor, 2005; Finnegan & Steven, 2008). Each of these represents a distinct set of genealogical lineages (Verspoor *et al*., 2007), which present an opportunity to identify the native population that a salmon originates from (Griffiths *et al*., 2010; Ikediashi *et al*., 2012). Historically, tagging or marking salmon has been used to identify the origins of adult fish entering fresh water (Griffiths *et al*., 2010). However, recent studies have used advances in genotyping salmon and access to a robust and comprehensive genetic baseline for salmon throughout their European range to identify the probable source populations of salmon entering rivers across Europe (Griffiths *et al*., 2010; Ikediashi *et al*., 2012).

Microsatellite DNA is non-coding nuclear DNA consisting of repeating base pair sequences (Verspoor *et al.*, 2007). Microsatellites are typically short therefore easy to amplify and analyse and have high variability compared to other genetic markers, such as allozymes, making them the preferred marker in population studies and in assigning individuals to populations (Verspoor *et al.*, 2007). Tissue samples in the form of scale samples or a fin clip are usually used to extract microsatellite DNA from salmon (Perrier *et al*., 2010; Griffiths *et al*., 2010; Ikediashi *et al*., 2012). Microsatellite DNA is amplified using Polymerase Chain Reaction (PCR) which uses template DNA and two primer molecules which are complimentary to the sequences of the DNA of interest. PCR can generate unlimited copies of any fragment of DNA (see chapter 4 Verspoor *et al.*, 2007 for a full explanation). Products of PCR, copies of the microsatellite DNA in question, can then be compared to that of known populations in the form of a microsatellite baseline. Research such as Griffiths *et al*. (2010) and the SALSEA programme (Anon, 2005b) has established a standardised genetic baseline database for regional, and in some cases, river-specific salmon populations. This allows an individual salmon to be assigned to a population where its microsatellite DNA (referred to as genotype) is most likely to occur giving the probable source population or region of that salmon (Griffiths *et al*., 2010; Ikediashi *et al*., 2012).

Since 2001, 146 adult salmon have been captured entering the River Mersey and 21 juvenile salmon have been captured in the rivers Bollin and Goyt. Sampling effort and surveillance has been extensive during this period and a defined run of returning adult salmon or a run of smolts have yet to be detected, and as such a self-sustaining population is not thought to exist in the River Mersey (Chapter 3). As such, the salmon entering the River Mersey are considered straying salmon.

The ability to differentiate between stocks in a fishery is of vital significance for the management and conservation of a fishery (Griffiths *et al*., 2010). Without this information it is difficult to predict the outcomes of conservation and management plans, quantify the contribution and exploitation of each stock or implement effective stock rebuilding programmes. The identification of salmon entering a newly accessible catchment is also of vital importance as this may indicate possible levels of pre-adaption and on which rivers and dispersal mechanisms a recolonisation might depend. In general, marine migratory behaviour in Atlantic salmon is not well understood (Mills, 2000) and salmon migration has never been studied in the Irish Sea in detail (Milner & Evans, 2003).

This chapter identifies the region of origin of 146 adult salmon entering the River Mersey between 2001 and 2011, three juvenile salmon caught from the River Goyt between 2005 and 2011 for which genetic material (scale samples) was available and 308 adult salmon captured in 2008 entering the rivers Lune, Ribble and Dee. This chapter aims to elucidate the origins of salmon entering the River Mersey and the factors influencing the straying of salmon in the Irish Sea and into the River Mersey.

4.2 METHODS

4.2.1 Fish sampling

Of the 238 ascending adult salmon caught at Woolston weir fish trap on the River Mersey (Figure 3.14) since 2001 (section 3.4) a total of 146 had scales removed for aging purposes which were subsequently stored. Salmon were captured during August – October in 2001, 2002 and annually between 2005 – 2010, with fishing effort being dependent of EA resources and so was *ad hoc* over this period (Table 3.4). In addition scales were available from: eighty one adult salmon captured from the River Lune at Forge weir fish trap, near Halton, Lancashire (SD 5132 6478) approximately 3 km upstream of the tidal limit between 30 July – 15 October 2008 and an additional 2 spring running salmon were caught on 25 April and 8 May 2008. The River Lune had an average annual run of 7403 (5314 – 10,827) adult salmon between 2000 – 2010 (Environment Agency, unpublished data); three samples of 60 salmon each captured from the River Dee at the Chester Weir trap (SJ 4067 6580) between 20 August - 30 September 1991, 20 August - 30 September 1994 and 27 August – 30 September 2008. The River Dee had an average annual run of 4692 (3109 – 6181) adult salmon between 2000 and 2010 (Environment Agency, unpublished data); forty five salmon captured from the River Ribble at Waddow Hall weir fish trap (SD 7355 4251) between 30 July and 8 October 2008. The River Ribble had an average annual run of 2843 (1023 - 4269) adult salmon between 2000 and 2010 (Environment Agency, unpublished data). All salmon were measured (mm), weighed (g) and several scales removed for ageing and genotyping. Scales were placed in and subsequently kept in small envelopes, allowed to dry and stored in dry conditions in office drawers at EA offices. Scale material was available for three juvenile salmon caught during EA electric fishing surveys on the River Goyt between 2003 and 2006.

4.2.2 DNA extraction

DNA from individual salmon was genotyped using microsatellites from a panel of 14 neutral loci (Ikediashi *et al*., 2012). ‘Neutral’ describes DNA that does not change adaptive fitness within a population as a result of mutation or change and ‘loci’ is the physical position of a specific DNA fragment. Neutral loci are used as they do not change in response to selection pressure so serve as a consistent marker to genealogical lineages (Hendrick, 2001). The panel of 14 neutral loci were selected as all have been successfully used in previous salmon assignment studies (McConnell *et* *al*., 1995; O'Reilly *et al.*, 1996; Sanchez *et al*., 1996; Paterson *et al*., 2004; King *et al.* 2005; Griffiths *et al*., 2010).

Microsatellite DNA was extracted from individual scales using a chelex-based protocol that involves homogenising the tissue samples, adding chelex resin and boiling and spinning the mixture in a centrifuge (Estoup *et al*., 1996). Chelex resin protects the DNA sample from enzymes (DNAases) that may destroy the DNA. The loci of interest were amplified using PCR. PCR reactions were carried out in 10 µl reactions containing approximately 50 ng of extracted salmon template DNA, 3 µl water, 5 µl of Qiagen Taq PCR Mastermix and 1 µl of primer mixture. PCR conditions were as follows: an initial denaturation step of 5 min at 95 °C, followed by a touchdown PCR consisting of eight cycles with a 30 s denaturation step at 95 °C, a 90 s annealing step starting at 62 °C and decreasing the temperature 2 °C every two steps until 47 °C was reached, with 3 minutes of extension at 72 °C. The reaction ended with a final 10 minute extension at 72 °C.

4.2.3 Genetic baseline

The genetic baseline database developed by Griffiths *et al.* (2010) was supplemented with genotypes from additional populations from rivers in Ireland, Eastern Scotland and Norway from the SALSEA-Merge database (Anon, 2005b; Gilbey *et al.,* unpublished) to create a genetic baseline for this study covering potential source rivers. The baseline comprised 5194 salmon from 129 sampling sites within 60 rivers from North and West Scotland, Northern Ireland, England and Wales, Northern France and Norway. To address the possibility that adult salmon sampled in the River Mersey were escapees from salmon farms, four populations from Norway were included in the baseline as surrogates for farmed salmon. The vast majority of salmon farmed in Britain are descended from Norwegian stock (Knox and Verspoor, 1991) and recent research indicates a high degree of similarity between the genetic signatures of farmed salmon and those of wild Norwegian salmon (J.R. Stevens, personal communication).

4.2.4 Assignment of salmon to reporting regions

Individual salmon were assigned to reporting regions made from grouping rivers from the baseline into broader, genetically based, regions adapted from those proposed by Griffiths *et al.* (2010). Reporting regions were created by pooling data from rivers based on their genetic similarity. Genetically similar groups were identified using the programs BAPS 5 (Corander *et al.*, 2003) and STRUCTURE v. 2.3.3 (Pritchard *et al*., 2000). The Δ*K* method of Evanno *et al*. (2005), which tests the genetic relatedness of groups, was then used to infer the most likely number of distinct genetic groups, or clusters (K). The reporting regions were then also tested for effectiveness using the leave-one out tests (where each salmon used in the baseline is systematically removed from the baseline population before having its own origins estimated) in GeneClass 2 (Piry *et al*., 2004) and ONCOR (Kalinowski *et al.*, 2008). Assignment of individual salmon to the designated reporting regions was carried out using the programs GeneClass 2 and ONCOR. Both tests give probability, or a likelihood score (%), of assignment to a reporting region and both tests use a threshold of ≥5% to assign a salmon to a reporting region.

4.2.5 Scottish salmon farm production

Scottish fish farm production information was collated to assess the potential impact of and numbers of straying salmon, These Scottish salmon farming data were reviewed because Scotland accounts for 12% of the total salmon production in the Northern Atlantic (second only to Norway, which produces 78%) (Anon, 2012b). Salmon farming data for England were not collated as there are no salmon farms present on the Northwest coast of England (Environment Agency, personal communication). Scottish Fish Farm Production Survey 2013 (www.gov.scot/publications) and fish farm escape statistics reports for 2002 to 2012 (www.aquaculture.scotland.gov.uk) were reviewed.

4.2.6 Prevailing currents in the Irish Sea

The directional nature of environmental factors is known to influence salmon movement (Hanfling & Weetman, 2006; Palstra *et al.*, 2007). As such, a literature search was undertaken and the UK Hydrographical Office web-page (www.ukho.gov.uk) was interrogated to review and report the prevailing currents in the Irish Sea.

4.3 RESULTS

4.3.1 Reporting regions

The Δ*K* method identified the optimum number of genetic units, or reporting regions, from the STRUCTURE analyses to be 7, which were named as follows: Scotland, Solway & Northwest England, Southwest England & Wales, Southern England, Northern Ireland, France and Norway (a surrogate for Scottish farmed fish) (Figure 4.1). After the formation of reporting regions, the leave-one out test found 78% and 79% of salmon used in the baseline in GeneClass 2 and ONCOR, respectively, (results not shown) of salmon were assigned back to the region from which they were sampled.

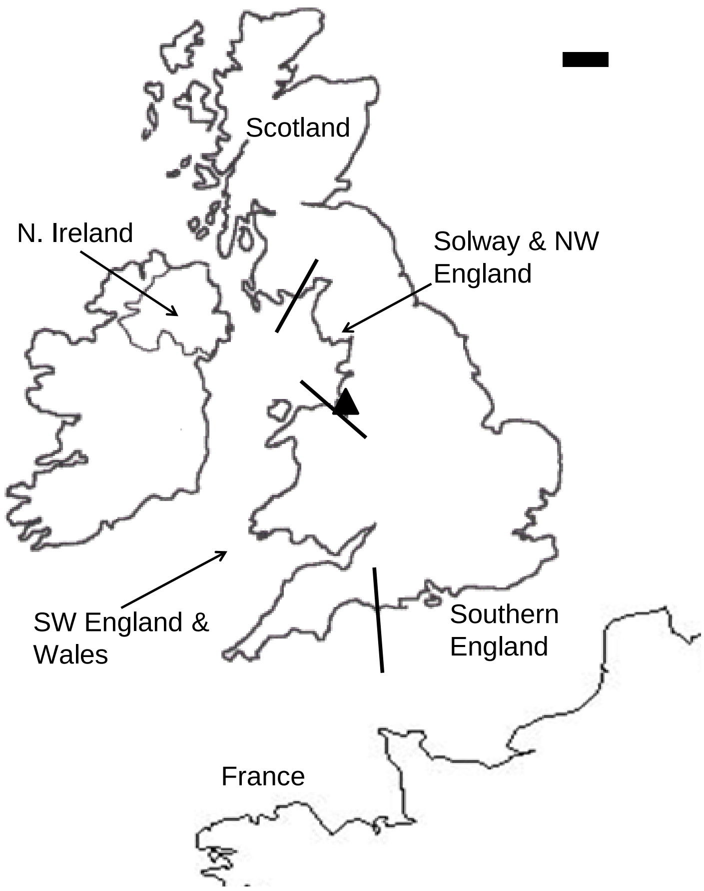


Figure 4.1 Reporting regions used for assignment as identified using the Δ*K* method. Lines denote the boundaries between reporting regions along the coast and the Mersey estuary is denoted with a triangle.

4.3.2 Assignment results

See Appendix 1 for individual assignment likelihood scores of each individual salmon for both assignment tests

Mersey salmon

Of the 149 River Mersey salmon sampled, DNA from 134 adults and 1 juvenile were successfully amplified at 10 or more loci out of 14. Unfortunately, due to the condition of the very limited amount of scale material collected, amplification was not successful from two of the three juveniles sampled. The probability of 21 of the 135 salmon sampled from the River Mersey assigning to any of the recognized reporting regions was less than 5% and these salmon were discounted form further analysis. The remaining salmon (n = 113 adults and 1 juvenile) were assigned with scores between 32 – 99% (GeneClass 2) and 36 – 99% (ONCOR) likelihood of assignment.

Genetic assignment showed the successfully genotyped salmon from the River Mersey to have a range of origins (Figure 4.2). Both tests found the largest proportion of the Mersey salmon to be from th Solway & Northwest England region; 44% (n = 49) in GeneClass 2 and 59.3% (n = 67) in ONCOR. Both tests found the next largest contributors to be Scotland, 26.9 (GeneClass 2) and 23% (ONCOR), followed by Southwest England & Wales 18.7 (GeneClass 2) and 13.3% ONCOR) (Figure 4.2). Two salmon were assigned to France by ONCOR, while the same two salmon and one other were assigned to France by GeneClass 2. Three salmon were assigned to Northern Ireland in ONCOR and four in GeneClass 2. Four salmon were assigned to Norway in GeneClass 2, but none were assigned to Norway in ONCOR (Figure 4.2). A single salmon was assigned back to the Southern England region in GeneClass 2 but not in ONCOR. The single juvenile that was sufficiently genotyped was assigned to Solway & Northwest England by both programs.

Dee salmon

Of the 180 samples of DNA, 170 adult salmon were successfully amplified at 12 or more loci out of 14. Of these, 170 and 166 adults in GeneClass 2 and ONCOR tests (2008 = 60, 1994 = 60, 1991 = 50 in GeneClass 2 and 46 in ONCOR) were assigned to a recognized reporting region with a probability >5% (range of 32 – 99% in GeneClass 2 and 31 – 99% in ONCOR) likelihood of assignment, respectively. Assignment showed the salmon from the River Dee to have a range of origins with salmon from the Solway & Northwest England and Southwest England & Wales reporting regions dominating in both GeneClass 2 and ONCOR (Figure 4.2).

Assignment showed a decrease in salmon captured from the River Dee assigning back to its respective reporting region, the Southwest England & Wales region, from 1991/1994 to 2008; in 1991 52% and 44% salmon assign back to the region Southwest England & Wales, 54% and 41% in 1994, and in 2008 38% and 36% (ONCOR and GeneClass 2). Both tests also showed an increase in assignment back to Northwest & Solway from 22% and 23% in 1991 (GeneClass 2 and ONCOR) and 18% in 1995 and 32% in 2008 in both tests (Figure 4.2). No salmon were assigned to Southern England. Northern Ireland, France and Norway were represented by low numbers totalling 7, 11 and 6 in 1991, 1994 and 2008, respectively, in both tests.

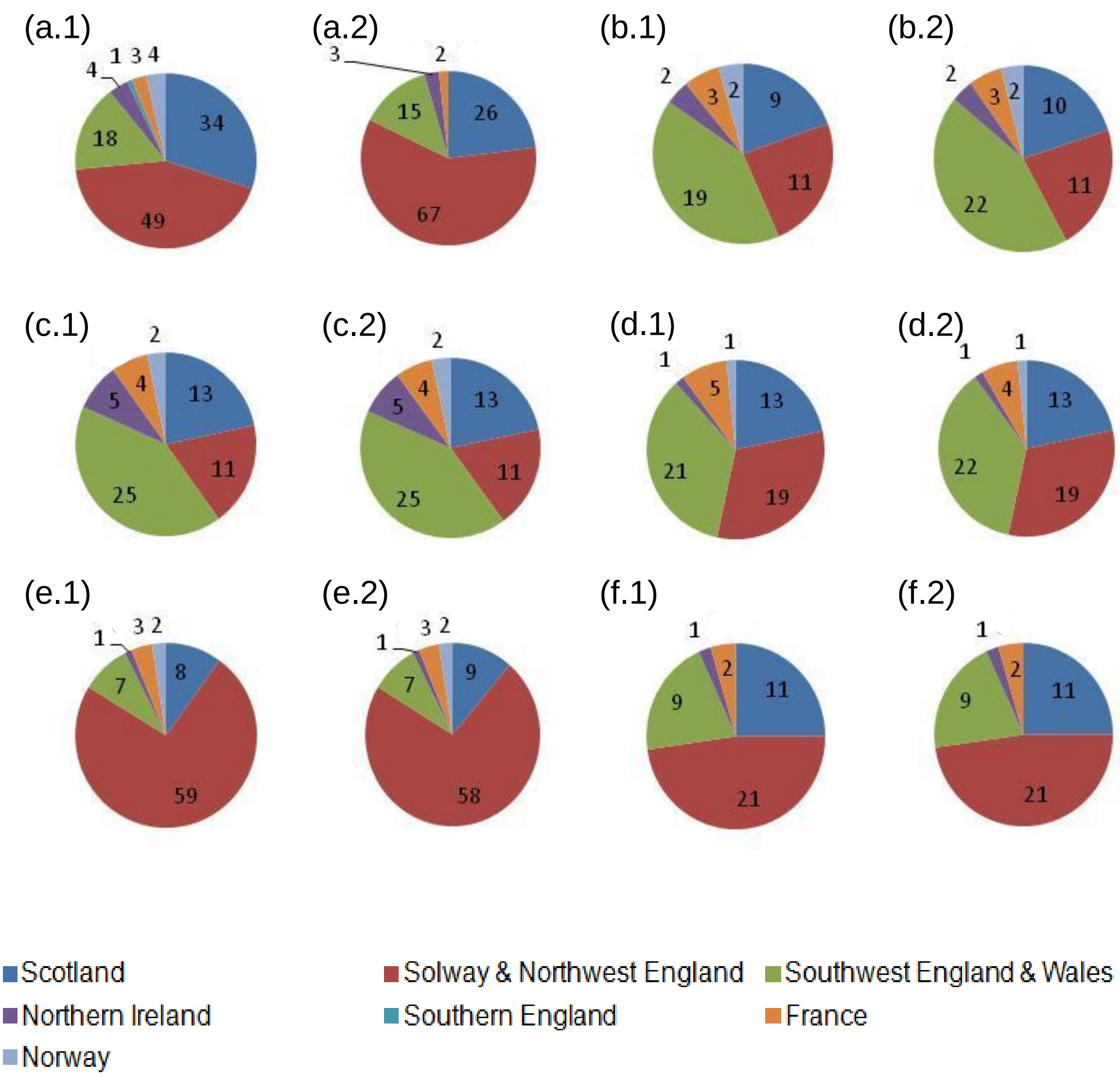


Figure 4.2 Pie charts representing proportions of salmon sampled form the River (a) Mersey 2001 – 2010 (adults only), (b) Dee 1991, (c) Dee 1994, (d) Dee 2008, (e) Lune 2008 and (f) Ribble 2008 assigning back to reporting regions for (1) GeneClass 2 and (2) ONCOR assignment tests. Numbers of salmon assigned to reporting region displayed on graphs.

Lune salmon

DNA from 80 of the 83 salmon from the River Lune amplified successfully at 12 or more loci out of the 14. All salmon were assigned with a likelihood score of >5% ranging from 37 – 99% (GeneClass 2) and 38 – 99% (ONCOR) likelihood of assignment. The River Lune exhibited high assignment back to its respective reporting region (Solway & Northwest England) in both GeneClass 2 and ONCOR, 73.8% and 72.5%, respectively (Figure 4.2). Salmon originating from the Scotland and Southwest

England & Wales reporting regions accounted for the majority of the remaining salmon entering the River Lune; totalling 18.75% and 20% (GeneClass 2 / ONCOR). Seven and half percent of salmon were assigned to the Northern Ireland, France and Norway reporting regions and no salmon was assigned to Southern England in either test.

Ribble salmon

DNA from 44 of the 45 salmon from the River Ribble amplified successfully at 12 or more loci out of the 14. All salmon were assigned with a likelihood score of >5% ranging from 36 – 99% (GeneClass 2) and 35 – 99% (ONCOR). 47.7% of salmon sampled from the River Ribble assigned back to the respective reporting region, the Solway & Northwest England (Figure 4.2), in both tests. South West England & Wales and Scottish reporting regions accounted for 45% of the remaining salmon of assignment in both tests. Similar to the River Lune low numbers of salmon were assigned to the Northern Ireland (n = 1), France (n= 2) and Norway (n = 0) reporting regions in both tests and no salmon was assigned to Southern England in either test.

4.3.3 Scottish salmon farm production

In Scotland in 2013 there were 257 registered active sites producing adult salmon for harvest; 253 of these involved production in sea cages and the remaining four in sea tanks, producing 163,234 tonnes of salmon (Figure 4.3) (Anon, 2014). Salmon production increased from 48,691 t in 1993 to 169,736 t in 2003, after which it decreased and reached a plateau at 128,000 – 320,000 t a year between 2005 and 2008. Production then increased from 2009 to 2014 (Figure 4.3). Nearly two million (1.9 million) adult salmon were reported to have escaped farms between 2002 and 2012 (no data for 2011), 877,883 of which escaped in 2005 (Figure 4.4) (www.aquaculture.scotland.gov.uk). Apart from 2005 there appears to be a gradual decrease in the numbers of salmon escaping from 2002 to 2012 (Figure 4.4). In 2013 there were 27 companies authorised by the Scottish Government that were actively engaged in the commercial freshwater production of salmon ova and smolts over 102 sites producing an average of 41,242,076 (range of 36,662,000 – 50,086,000) smolts to sea from 2004 to 2013 (Figure 4.5) (Anon, 2014). All data represent the entire salmon farming industry operating in Scotland, which covers Western and Northern Scotland and the Orkney, Shetland and Western Isles.

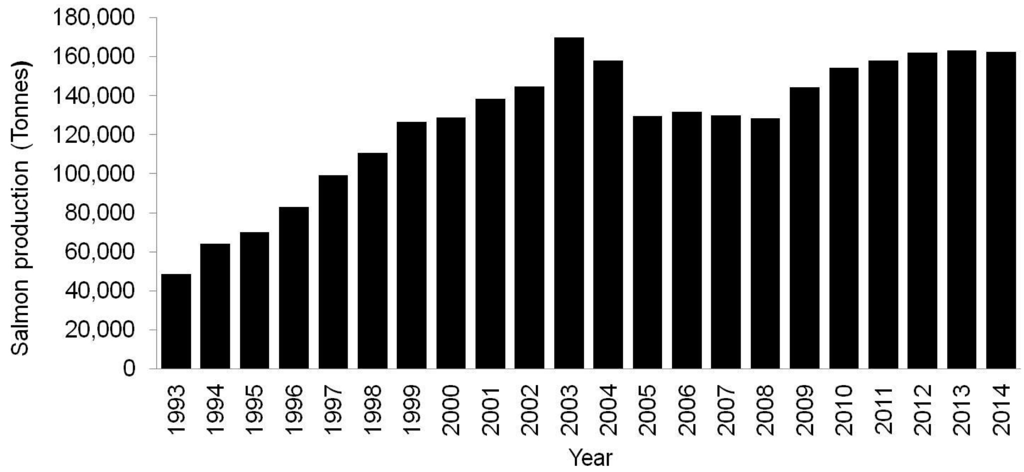


Figure 4.3 Annual production of salmon (tonnes) during 1993 to 2014 for the entire salmon farming industry operating in Scotland.

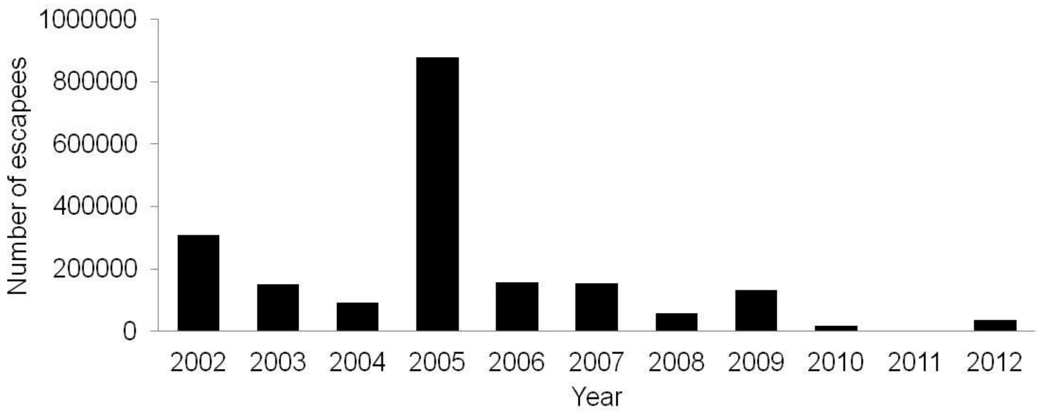


Figure 4.4 Numbers of reported escaped adult salmon form Scottish fish farms from 2002 – 2012 for the entire salmon farming industry operating in Scotland.

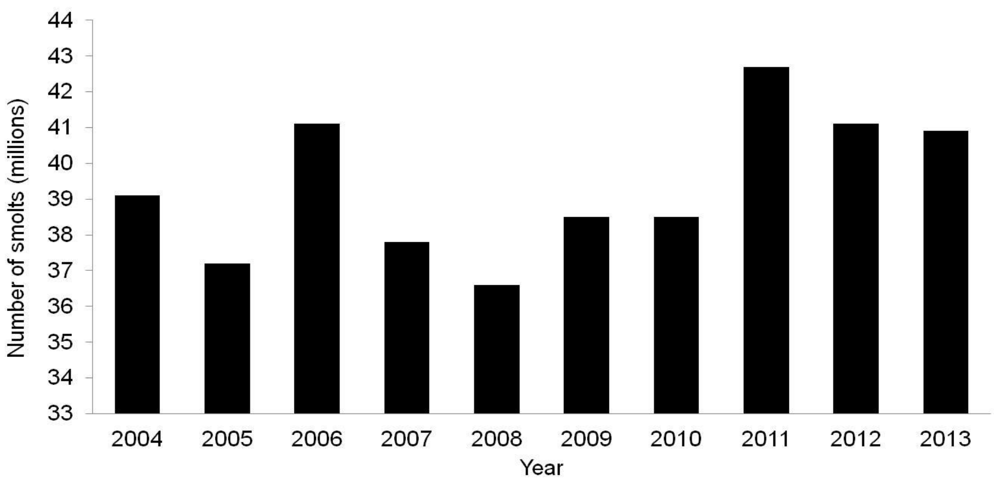


Figure 4.5 Actual smolts put to sea (millions) from 2004 – 2013 from registered Scottish salmon farms.

4.3.4 Prevailing currents in the Irish Sea

Currents in the Irish Sea are driven by both density currents, currents driven by the difference in density between water masses due to salinity or temperature, or by the prevailing wind. The density currents cause a clockwise gyre in the eastern Irish Sea, which along with their associated current, run southwards down the coast of Northwest England for much of the year (Figure 4.6). However, sometimes wind induced currents can produce an anti-clockwise gyre and density currents can cause flow out of Liverpool Bay going north and west.

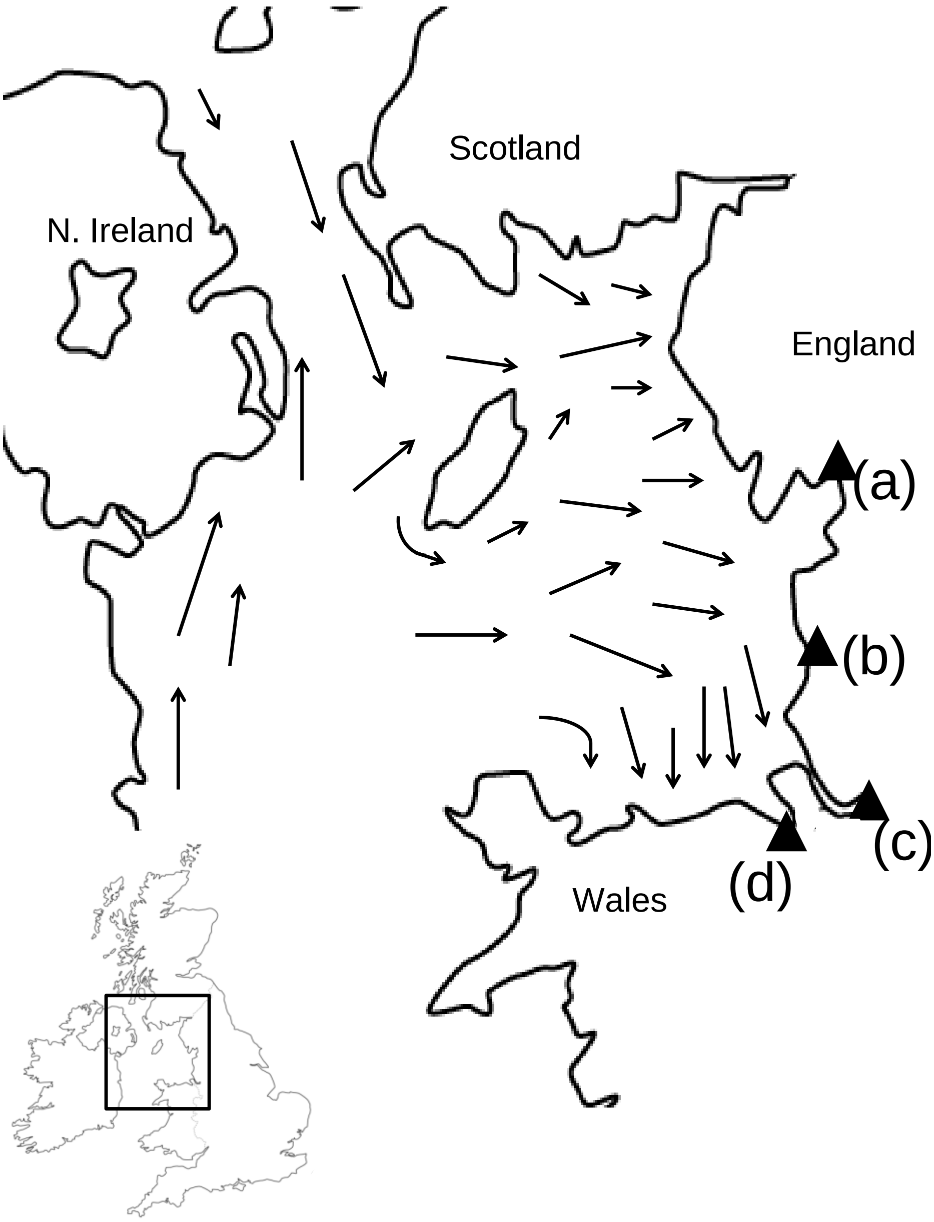


Figure 4.6 Prevailing currents in the Irish Sea denoted by arrows and the locations of the estuaries of the Rivers (a) Lune, (b) Ribble, (c) Mersey and (d) Dee denoted by triangle.

4.4 DISCUSSION

The reporting regions used in this study match those identified by Griffiths *et al.* (2010) and appear valid units for assignment based on the leave one out test and the high degree of probability salmon were assigned to reporting regions.

4.4.1 Assignment of salmon and regional genetic structure

The homing abilities of salmon are well-documented (section 2.3.1), however, studies have reported long distance straying in salmon. Perrier *et al*. (2010) reported two out of seven straying salmon entering the River Séine in France were assigned to a foreign baseline group better than any French regions included in their analysis.

Griffiths *et al*. (2011) reported one of 16 salmon sampled from the River Thames to be from a French population and Makhrov *et al.* (2005) found evidence of historic long distance straying, and subsequent colonisation of the Russian Arctic, by North American salmon following the retreat of the Pleistocene glacier. This study of salmon entering rivers discharging into the Irish Sea confirmed salmon are capable of long distance straying with two or three salmon entering the River Mersey assigned to the France reporting region (depending of assignment method) and has demonstrated long distance straying is also occurring into other rivers discharging into the Irish Sea. The 1991 and 1994 River Dee samples suggest long distance straying has been a feature of the region for over 20 years and is perhaps a natural component of Irish Sea salmon populations. The findings also found salmon entering and potentially recolonising the River Mersey are from multiple source rivers, similar to the River Seine (Perrier *et al.,* 2010). Indeed, salmon from a range of reporting regions were found to be entering each of the rivers and across all years, demonstrating strays from multiple sources being a feature of the region (Figure 4.2).

The high genetic diversity resulting from both long-distance straying and multiple source rivers should be of benefit to a newly establishing River Mersey salmon population providing a broader genetic base for adaptation to local and changing conditions (Fraser *et al.,* 2007; Perrier *et al*., 2010). A high genetic diversity has been suggested as being especially important during the early phase of recolonisation as a mechanism to buffer the impact of loss of genetic variability linked to the low number of colonisers (Perrier *et al*., 2010). There was a reduction in the numbers of salmon assigning back to the French reporting region moving further north and the Scottish reporting region moving south. This is in line with other studies suggesting proximity is an important factor in the origins of strays entering rivers (Potter & Russell, 1994; Vasemagi *et al*., 2001; Griffiths *et al*., 2011). Gene flow resulting from salmon straying, even at low levels, could put populations at risk of outbreeding depression (Lynch, 1997; Candy & Beacham, 2000), where the offspring of salmon form two populations reducing pre-adaption to specific river conditions and so a reduced fitness or reproductive success. However, straying rates do not reflect spawning success; a number of studies have documented much lower levels of gene flow than would be assumed from observed straying rates (Stahl, 1981; Tallman and Healey, 1994; Youngson *et al.,* 2003) with barriers to the reproductive success of straying salmon having been reported by Jonsson *et al*. (2003) and Anderson & Quinn (2007).

Griffiths *et al.* (2010) suggested that although populations from rivers of the British Isles are genetically distinct they show little regional structure but high genetic diversity, especially Scotland, Ireland, Northwest England and Wales (Parrish *et al.*, 1998; Consuegra *et al.*, 2002; Asplund *et al.,* 2004). This could be due to a long history of stock transfers and salmon farming (Griffiths *et al*., 2010), a factor of the British Isles having been the central meeting region connecting all possible postglacial colonisers into a diverse mixture (Asplund *et al.,* 2004) or populations in the North Sea and British Isles having been derived from a relatively large and so diverse marine refugium (Asplund *et al.,* 2004). The British Isles are also thought to have a complex population structure and a reduced association between genetic and geographic distance resulting from salmon colonizing rivers or even tributaries from different phylogeographic lineages (Consuegra *et al.*, 2002; Griffiths *et al*., 2010). Therefore, the genetic impact of short distance straying (within region or between adjacent regions) on established populations may be relatively less important in the British Isles as it would be in other regions. Twenty one salmon assigned using GeneClass 2 and 25 salmon assigned using ONCOR in this study were found to have a likelihood of assignment scores of <5% and were not assigned to a reporting region of origin. The genetic baseline was extensive (Griffiths *et al*., 2011) and it is unlikely these 21 or 25 salmon originated from outside the area covered by the baseline and more likely their genetic signatures are too general to assign the salmon to a specific reporting region with a sufficiently high score. This supports the suggestion of a weak regional structure in the British Isles.

The River Mersey is on the border between two of the designated reporting regions (Figure 4.1). The River Dee, 11 km south of the Mersey estuary, is in the Southwest England & Wales region and the River Ribble, 40 km north of the Mersey, is in the Solway & Northwest England region. The majority of salmon captured in the Mersey originate from rivers north of the Mersey, specifically, from the Solway & Northwest

England reporting region (44% GeneClass 2 and 59.3% ONCOR). There were low numbers of salmon originating in the neighbouring Southwest England & Wales reporting region entering the Mersey (18.7% GeneClass 2 and 13.3% ONCOR). This is especially important as the River Dee, an established salmon river, which had an average annual return of 4692 salmon between 2001 – 2010, is just 11 km south of the River Mersey. This may be due to the prevailing clockwise gyre in the eastern Irish Sea and an associated current, which for much of the year runs southwards down the coast of Northwest England (Heaps & Jones, 1977; www.ukho.gov.uk) (Figure 4.6). Salmon have been documented displaying negative rheotaxis in the absence of directional cues (Hard & Heard, 1999) and therefore would be influenced by the direction of currents (Palstra *et al.*, 2007). The clockwise gyre and associated current may act to simultaneously move salmon from the rivers of North Wales away from the River Mersey and carry stray salmon from North England and potentially Scotland down the coast towards Liverpool Bay and the Mersey estuary. Other studies have found dispersal of straying salmon a function of the directional nature of environmental factors (Hanfling & Weetman, 2006; Palstra *et al.*, 2007). Straying salmon from Southwest England & Wales reporting region and those south of it therefore may not enter rivers in the Northwest of England and Scotland in great numbers. Indeed, both the rivers Lune and Ribble have relatively high proportion of salmon assigning back to their respective reporting region, the Solway & Northwest England (Figure 4.2).

Salmon in the River Lune had a high assignment back to the respective reporting region, the Solway & Northwest England reporting region, but the lowest percentage assignment back to the Scottish reporting region, which was surprising, due to the proximity to the Scottish reporting region and the prevailing clockwise gyre in the eastern Irish Sea. The reasons for this are unclear. Studies have documented flow (Unwin & Quinn, 1993; Thorstad *et al*., 2008; Milner *et al*., 2012) and freshwater discharge and the associated reduction in salinity (Alabaster *et al.*, 1991; Jonsson *et al.*, 2007) stimulating salmon to enter an estuary and river, both of which will occur in the River Lune estuary and surrounding waters. A possible explanation may be that the River Lune discharges into Morecambe Bay (Figure 4.6) and stray Scottish salmon may not pass close enough to the bay and estuary to be attracted by either the flow or reduction in salinity. Heaps & Jones (1977) report a coastal density induced current sometimes moving north in this region of the Irish Sea (equal to the latitudes spanned by the northern part of the Isle of Man) (Figure 4.6). It may be this current is limiting the number of Scottish fish entering the River Lune. The literature is equivocal about the relationship between native population size and straying (Hindar, 1991; Quinn *et al.*, 1991; Jonsson, 2003). The River Lune has the largest run of the rivers included in this study, a mean of 7403 adults returning annually between 2000 and 2010, and although it is unknown if run size attracts strays to a river, the larger run size may have served to reduce the relative proportion of strays found in this study.

Compared with other rivers in this study, relatively few of the salmon captured in the River Dee were assigned to the respective reporting region, Southwest England & Wales. Assignment of salmon to Southwest England & Wales also decreased from 1991 and 1994 to 2008; there was also an increase in salmon being assigned back to the Solway & Northwest England reporting region over this time. This may indicate a loss of the regional structure of salmon populations in the Irish Sea and that the boundary between the Solway & Northwest England and Southwest England & Wales regions could be changing with time, with salmon from the Solway & Northwest England region moving southwards and introgressing into the Southwest England & Wales region. However, this is based on limited data from 1991, 1994 and 2008 and any inferences and conclusions must be treated with caution. Loss of regional population structure in Atlantic salmon resulting from the introgression of non-native salmon has been documented (Ayllon *et al*., 2006) and further research is required to understand if a loss of regional structure resulting from straying is occurring in the Irish Sea and, if occurring, what the key drivers are.

A small proportion of salmon recolonisers entering the River Mersey and of the stray salmon entering other rivers included in this study originated from the Northern Ireland, France and the Southern England reporting regions. Griffiths *et al.* (2010) found salmon from the Southern reporting region to be distinct from other reporting regions of the British Isles suggesting there is limited straying into this region. This study suggests there is also limited straying from this region to the North Irish Sea. The distance between the Southern England and France reporting regions and the rivers used in this study and the westerly direction of the prevailing currents off the south coast of England and France and in the English Channel (www.ukho.gov.uk) are most likely to account for the reduced number of salmon from these reporting regions.

The Northern Ireland reporting region is close to western Scotland (20 – 30 miles apart) and the surrounding sea currents move in a southerly direction into the Irish Sea. The small number of stray salmon assigning back to this region in this study is surprising. In August 2001 several thousand (exact number unknown) adult salmon escaped from a fish farm in Glenarm Bay, Northern Ireland (Milner & Evans, 2003). Only 180 of these salmon were reported to have entered rivers along the English coast, although this number is likely to under-represent actual numbers. In the Rivers Lune and Dee, rivers containing fixed salmon traps, two and six Glenarm Bay fish farm escapees were reported in 2001, respectively. The prevailing current, moving southerly down the Irish coast (www.ukho.gov.uk), may take salmon down the coast of Ireland rather than moving them towards Northwest England (Figure 4.6). However, the reasons for the low number of strays originating from the Northern Ireland reporting region found in this study remain unclear and would be an area for further research.

An important caveat to this study is that although 146 adult salmon were captured at Woolston weir in the River Mersey, 135 of which were genotyped, these salmon may not have ascended into the upper reaches of the river. During this study it was identified that this issue required further research and therefore will be the focus of Chapter 5 and 6. However, one juvenile salmon was successfully genotyped and was assigned to the Solway & Northwest England reporting region but no conclusions can be drawn based on a single individual. Salmon from the Solway & Northwest England reporting region are the salmon most likely to spawn because they make up the largest proportion of strays entering the River Mersey and can be expected to have some level of pre-adaptation to in-river conditions similar to their proximal rivers and region of origin (Finnegan & Stevens, 2008).

Several studies have documented stray salmon successfully breeding (Vasemagi *et al*., 2001; Knutsen *et al.,* 2001; Milner *et al.,* 2004; Schreiber & Diefenbach, 2005; Anderson & Quinn 2007; Kiffney *et al.,* 2009; Perrier *et al.,* 2010; Griffiths *et al.*, 2011). In conclusion, if no other limiting factors existed there is no reason that stray salmon entering the Mersey catchment could not successfully spawn and establish a self sustaining population, particularly if they have some level of pre-adaptation and there is a broad genetic base allowing the population to adapt to local and changing conditions. It must also be noted, as this study used regions to assign salmon to it was unable to distinguish if any of the adult salmon were in fact 'Mersey salmon' in that their parents had successfully spawned in the Mersey catchment and were returning to the River Mersey as adults. However, as discussed in Chapter 3 this is considered unlikely as the presence of smolts have never been recorded in the Mersey catchment.

4.4.2 Escaped farm salmon

One explanation for the shift in salmon reporting region boundaries in the Irish Sea could be related to salmon farming. Salmon farming has increased globally; in 2012 ICES (Anon, 2012b) reported a 26% increase on the previous five-year mean in farmed salmon in the Northern Atlantic, with Scotland accounting for 12% of the total production. Scotland supports a large number of salmon farms (section 4.3.3).

Potentially both adult and juvenile escapees from Scottish salmon farms may be increasing the number of strays entering the Irish Sea and so impacting on the reporting region boundaries and the regional structure in the Irish Sea. In 2002 reporting escaped adult salmon from Scottish fish farms became law and, except in 2005, there has been an appreciable decline in the number of reported escaped farmed adult salmon from Scottish fish farms since 2002 (www.gov.scot) (Figure 4.4). This suggests it is unlikely that farm escapees are significantly increasing in numbers and driving any change to the regional structure or reporting region boundaries in the Irish Sea. Indeed, this study used Norwegian populations as a surrogate for farmed fish as the vast majority of salmon farmed in Britain are descended from Norwegian stocks (Knox and Verspoor, 1991; Ikediashi, *et al*., 2012). Very few salmon were found to assign to the Norwegian reporting region which suggests there are relatively few escaped farmed salmon straying into English and Welsh rivers in the Irish Sea.

The literature contains examples of high numbers of farmed salmon escaping and often entering established salmon rivers (Hansen *et al*., 1999; Naylor *et al*., 2005; Fiske *et al*., 2006; Morris *et al*., 2008). However, there have been few reported incidences of escapees caught in English and Welsh rivers, which is thought to be due to the absence of coastal salmon farming in England and Wales (Milner & Evans, 2003; Anon, 2013a). In 2003 the EA and Centre for Environment, Fisheries and Aquaculture Science (Cefas) initiated a sampling programme to identify any salmon suspected of being from farmed origins in the England and Welsh commercial salmon catch. The programme was discontinued after a few years (number unknown) after no farmed salmon were identified (Anon, 2013a). Escaped farmed salmon are visually distinctive, often appearing emaciated with eroded fins and more scale loss than wild salmon (Lund *et al*., 1991; Milner & Evans, 2003), and, as such, the zero incidences of adult escapees is likely to be correct. Those salmon from farmed origin that escape or are released as juvenile salmon, however, will have had longer to acquire the appearance of adult salmon (Crozier, 1998) and so may go undetected (Milner & Evans, 2003) and therefore may be contributing to the strays entering English and Welsh rivers discharging into the Irish Sea. Although farmed salmon are escaping from Scottish fish farms (Figure 4.4) they do not appear to be impacting on English and Welsh rivers in the Irish Sea and the previously mentioned weak regional structure in the Irish Sea, and indeed the British Isles, is therefore more likely to result from historical natural factors (Consuegra *et al.*, 2002; Asplund *et al.,* 2004; Griffiths *et al*., 2010). It has been widely reported that escaped farm salmon tend to enter rivers in close proximity to their farms (Webb & Youngson, 1992; Youngson *et* al., 1997; Crozier, 1998; Fiske *et al*., 2006) and despite the southerly direction of the currents in the Irish Sea many strays may not move far south enough to reach English rivers. As such farmed salmon are unlikely to disrupt any recolonisation of the Mersey catchment.

4.4.3 Summary

1. The majority of stray salmon entering the River Mersey were from the river's respective reporting region, the Solway & Northwest England. There was also evidence of long distance straying, with salmon from a range of reporting regions and beyond entering the River Mersey. The potential increased genetic diversity may be advantageous providing a broader genetic base for adaptation to local and changing conditions.

2. There was a southerly direction of straying by Atlantic salmon in the eastern Irish Sea, which is possibly a function of the clockwise gyre, the directional nature of which was likely influencing the source of the salmon entering the River Mersey.

3. A single juvenile caught in the River Goyt (Mersey tributary) was successfully assigned to the Solway & Northwest England reporting region. It was assumed salmon from this reporting region may potentially show some kind of pre-adaptation to river conditions due to the close proximity of their natal rivers, which will share similar conditions.

4. Salmon in rivers of the British Isles are genetically distinct, but there is little regional structure, a high genetic diversity of salmon and a reduced association between genetic and geographic distance.

5. The high genetic diversity of salmon in the British Isles is probably due to historical natural reasons and not due to salmon farming practices in Scotland. This study found very few salmon entering rivers in the Irish Sea to be of farmed origin.

This chapter has demonstrated that stray salmon are entering the river Mersey and could potentially spawn and establish a self sustaining population if no other limiting factors existed. The next chapters will investigate what limiting factors may exist that could prevent a recolonisation.

5 AN INVESTIGATION INTO THE BEHAVIOUR AND ROUTE CHOICE OF STRAYING ATLANTIC SALMON (*SALMO SALAR*) IN THE MERSEY CATCHMENT

5.1 INTRODUCTION

Movement is a behaviour that enables fish to respond to changing environmental conditions and to maximise fitness, survival and reproductive success (Taylor & Cooke, 2014). Recently, behavioural syndromes, defined as a suite of behavioural traits that co-vary across contexts or situations (Sih *et al*., 2004), have been demonstrated across a broad range of species, including salmonids (Conrad *et al*., 2011). Behavioural syndromes imply plasticity in behavioural traits and may be limited and therefore constrain the ability of an animal to behave in an optimal fashion in all situations (Conrad *et al*., 2011).

The migratory behaviour of adult salmonids from self-sustaining healthy populations in un-modified rivers is well defined (Hawkins & Smith, 1986; Milner, 1990; Laughton, 1991; Solomon *et al.*, 1995; Milner *et al.*, 2012; Kennedy *et al*., 2013; Chapter 2) and a range of environmental factors have been shown to influence adult salmon migratory behaviour in fresh water (Alabaster *et al*., 1991; Erkinaro *et al*., 1999; Thorstad *et al*., 2002; Anderson & Quinn, 2007; Thorstad *et al*., 2008; Kennedy *et al*., 2013). Kennedy *et al*. (2013) categorized Atlantic salmon behaviour as either erratic, wherever considerable upstream movement and downstream movement was evident or, non-erratic, showing directional upstream migration, either step-wise or continuous towards a final spawning position. Salmon require access to spawning habitat in the upper reaches of rivers to complete their life cycle and anything impeding access to these habitats may potentially limit spawning or prevent recolonisation (Thorstad *et al.,* 2008; Lucas *et al.*, 2009). Stray salmon entering rivers with no native population may suffer reduced success resulting from a poor choice of migratory route due to a lack of either or both olfactory or other cues of a native stream (Candy & Beacham, 2000; Keefer *et al.*, 2008) and/or conspecifics imprinting the water with chemical cues or acting as guides (Nordeng, 1971; Solomon, 1973; Candy & Beacham, 2000).

Advances in fish telemetry (Lucas & Baras, 2000; Heupel *et al*., 2006; Klimley *et al*., 2013) have dramatically improved biologists and conservation managers ability to identify and understand specific factors affecting fish populations on a range of scales from the oceanic (Welch *et al*., 2003), catchment (Okland *et al.*, 2001), river (Gerlier & Roche, 1998; Karppinen *et al*., 2002) or site (Smith *et al*., 1997; Kennedy *et al*., 2013). Studies have been able to direct often limited conservation resources to key issues or factors affecting fish populations, for example, the need for improve migration passages at dams (Gerlier & Roche, 1998), to increase flow in fish passes (Karppinen *et al*., 2002), the importance of woody debris and overhead shade in rehabilitation efforts (Zajanc *et al*., 2013) or to identify the effect of minor dams (Lucas & Frear, 1997).

In the preceding chapters it has been demonstrated that straying salmon are entering the Mersey catchment in low numbers and have successfully spawned, albeit in localised areas (section 3.4.2 and Chapter 4). It has also been demonstrated that the Mersey catchment is heavily modified and contains several potential barriers to upstream migration (section 3.3.3). It is unknown how potential barriers and the complex, highly modified nature of the lower Mersey catchment, specifically the Ship Canal, impact on upstream migration of adult salmon.

This chapter investigates the route choice, behaviour and fate of stray salmon entering the Mersey catchment using fish telemetry. The migratory behaviour of adult salmon is used to identify the factors that may impede or prevent a potential recolonisation in the lower Mersey catchment. This will inform conservation and management recommendations made later in this thesis. The chapter will test the hypothesis that lower Mersey catchment does not inhibit salmon migration to spawning areas upstream of the Ship Canal.

5.2 METHODS

5.2.1 Data collection

Tagging and tracking salmon

Ascending adult salmon were caught in a fish trap fitted to a notch and pool fish pass built into Woolston weir, a siphon weir and an impassable barrier to salmon (personal communication, EA), located in the lower River Mersey 6.2 km upstream of the tidal limit (Figure 3.5). Thirty and 14 salmon were tagged between 1/09/2010 and 06/10/2010 and 30/08/2011 and 03/10/2011, respectively (Appendix 2). Salmon were caught in a specifically designed top chamber with a movable penstock and carefully removed and placed into a bath of 30 – 40 g l^{-1} solution of benzocaine solution. Once anesthetised all salmon were measured (fork length (mm)), weighed (g), sexed and tagged. A clip from the adipose fin was taken to mark the fish as tagged. A scale was removed for genetic and ageing analysis from those salmon caught in 2010 (Chapter 4; see Appendix 1 for the origins of salmon captured in 2010). Salmon caught in 2011 were not aged or genotyped. The tags used were V13 acoustic transmitters with dimensions 36 mm x 13 mm and weigh 6 g in water (manufactured by VEMCO Ltd; www.vemco.com). Each transmitter had an individual code, a transmitting frequency of 69 kHz and a transmitting rate of 10 – 30 seconds. Tags had an estimated battery life of 239 days and each was confirmed to be working before fish were released. The tags used in this study were below the well documented maximum transmitter weight to fish weight ratio of 2% (Winter, 1983).

The tags were inserted into the stomach of the salmon as described by McLeave *et al*. (1978) and Smith *et al*. (2009) using a plastic tube and plunger to release the tag. After insertion of a tag salmon were placed into a large well-oxygenated bath of fresh river water and once fully recovered released 10 m upstream of the tagging site and held until the fish swam off naturally. All tags were tested and confirmed to be transmitting using a hand held receiver (VR100) after insertion into the salmon whilst the salmon was recovering in the bath of freshwater. The work was carried out under the Home Office project licence number PPL 80/2471. Water temperature ranged from 12.3 to 14.7° C and 12.3 to 14.6 °C and dissolved oxygen saturation from 53.8 to 88.0% and 81.8 to 89.9% up- and downstream of the weir and fish trap, respectively. Tagged salmon are denoted by the tag serial number.

Tagged salmon were detected using an array of 13 (August 2010 – April 2011) and 14 (August 2011 – April 2012) fixed automatic receivers (VR2W, Vemco Ltd) positioned at strategic locations, including both up- and downstream of the tagging site, or in locations where receiver security was optimal (Figure 5.1). Receivers are herein denoted with an R and the relevant receiver number, e.g. receiver 8 as R8. Receivers were placed in deep slow moving water and had a clear line of site up, down and across stream to ensure acoustic transmission from the tags was recorded. Note, R14 was deployed in year 2 only.

Receivers were either secured with rope and zip-ties to a fixed point such as jetty (R8, R14), a fish pass exit (R10, R11) a shipping marker (R4, R6, R7), a post dug into the river bed (R9, R12), attached to a scaffolding bar bolted to a canalised bank (R13) or secured midstream using an buoy suspended form an anchor with a rope and attaching the receiver to the rope (all other receivers). A small float on light rope was then attached to aid in location and retrieval of receivers and the grid reference and a photo of the site taken. No range testing was carried out of the VRW2 receivers. Some 90 –

100% VEMCO tag pings are recorded within a range of 150 – 200 m of a VRW2 (Webber, 2009). The widest point of the Ship Canal and the furthest a salmon could get from a receiver whilst passing is 130 m, and as such range was considered not to be an issue.

Fish tracking data were recorded between 01/09/2010 and 07/032011 and between 01/09/2011 and 24/03/2012. Tracking data were gathered monthly by retrieving and inspecting the receivers one at a time from a boat (Receivers 1 - 8) or by wading (Receivers 9 - 13) and using a blue tooth enabled laptop to download the tracking data onto VEMCO User Environment (VUE) software (version 2.2.1). Receivers were then re-configured, data deleted and the receivers secured back in their locations.

Environmental data

Dissolved oxygen (% saturation) and temperature measurements were recorded upstream and downstream of Woolston weir sporadically during tagging year 1 only owing to equipment availability. The measurements were gathered 8 m downstream of the fish pass entrance and 2 m upstream of the fish pass exit using handheld water quality meters (www.YSI.com) on the morning of trapping days.

Dissolved oxygen and ammonia concentrations, temperature and pH were all recorded from 01/08/2010 – 01/04/2012 using a stationary multi parameter SONDE (www.ysi.com) stationed in the Ship canal (NGR SJ7213692418). The SONDE was recovered monthly, the data downloaded and the SONDE cleaned, calibrated at an EA laboratory and then redeployed a few days later.

River flow data were collected from 2010 – 2012 by the EA for the Rivers Bollin, Glaze and Upper Mersey (section 3.3.2). No flow data were available for the Lower River Mersey and the Ship Canal. As a result the flow of the Lower River Mersey was estimated by combining the flows from all upstream rivers. Flow data were converted into daily means (Cumecs (Q) (m^3 s^{-1})).

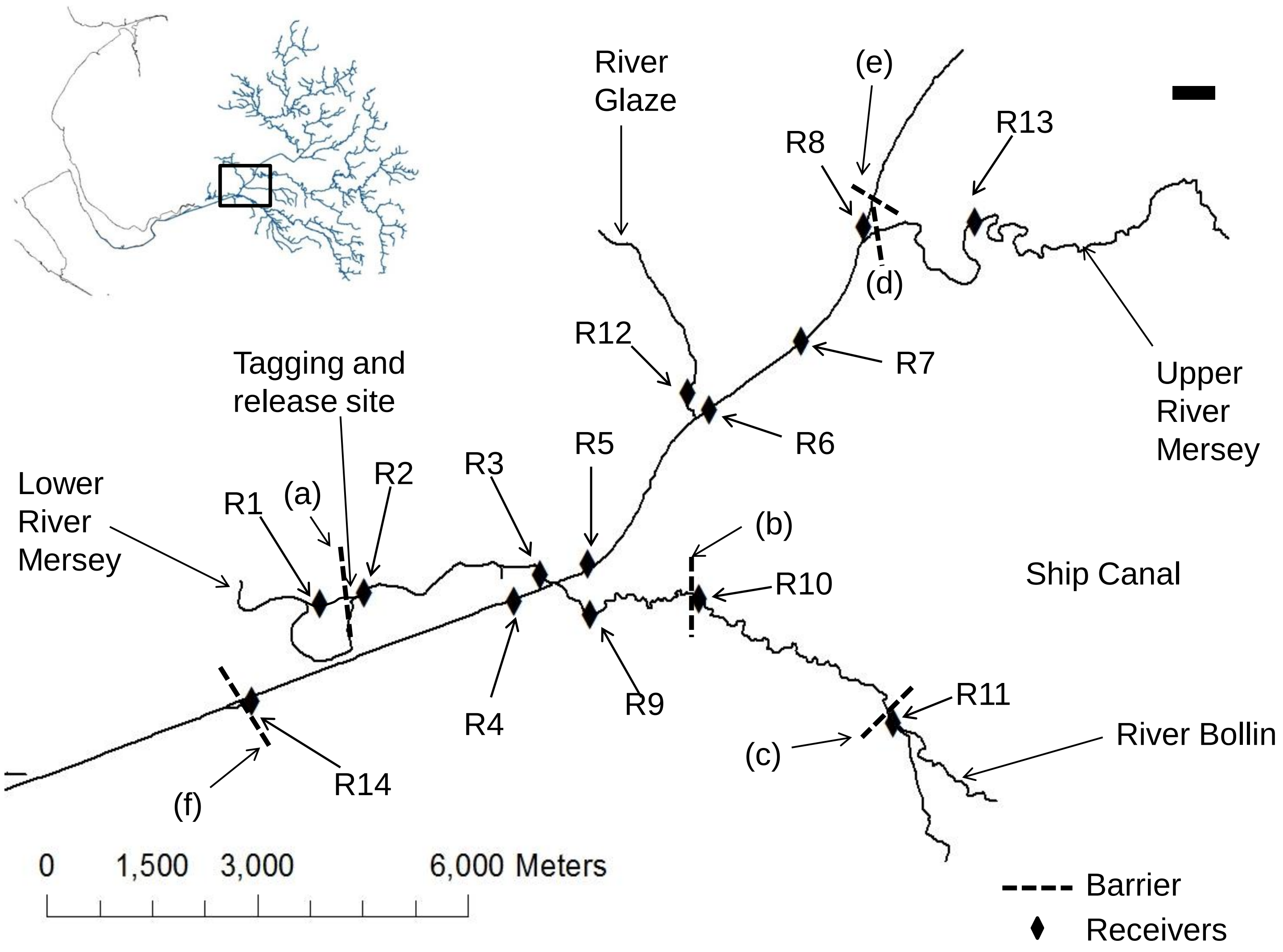


Figure 5.1 Simplified map of the receiver network including the barriers (a) Woolston weir, (b) Heatley weir, (c) Little Bollington, weir, (d) Irlam weir, (e) Irlam Locks and (f) Latchford Locks (Figure 5.2). Note R14 only deployed in tracking year 2.

Figure 5.2 Photographs of (a) Woolston weir, (b) Heatly weir and (c) Little Bollington weir and fish passes (marked with an arrow), (d) the Upper Mersey confluence with the Ship Canal and Irlam weir and downstream views of (e) Irlam Locks and (f) Latchford Locks.

5.2.2 Interpretation and analysis

Management of tagging data

All raw tracking data were downloaded from VUE into Microsoft Excel for analysis using the column headings tag I.D., date/time and station (receiver) name. Tag I.D. codes where used to sort the tracking data by salmon, which were then ordered chronologically using date/time of detection. The data were then cleaned; for each continual period of uninterrupted detections at the same receiver the first and last detections were identified and kept, the remaining data or 'hits' at that receiver were deleted. These data were converted into movements represented by the first and last or last and first detections at a single receiver or adjoining receivers, respectively, to represent a movement. For example, after cleaning the data of repeated hits a tag that recorded at the receivers R2, R3, R2, then R1 would be ascribed the movements R2-R3, R3-R2, R2-R1.

For each movement the time taken (minutes, hours and days) between the first and last detections at a receiver (R2 – R2), representing no actual movement between receivers, or the last detection at a receiver and the first detection at the next receiver (R2 – R3) was calculated. The direction of movement (downstream (d/s), upstream (u/s) or stationary (0)) was also calculated.

Distance (m) between receivers and from the tagging site and each receiver was estimated using Arc Geographic Information System (GIS) mapping programme. It was not possible to determine the exact pathway selected by the fish; therefore, distance was based on the assumption that fish took a direct route. Fine resolution movements, those which occurred within range of only one receiver, are not considered here as exact distance moved was unknown. As a result, all analyses consider salmon as either displaying reduced movement, i.e. movement within range of one receiver, a distance of <1 km based on a maximum 500 m receiver range (picking up 50 – 90% of tag pings (Webber, 2009)), or active movement between two receivers.

Fate and route choice of tagged salmon

When calculating the fate of tagged salmon the following assumptions were made. Firstly, those tags not recorded by either R1 or R3 after the tag was confirmed to be working and the released salmon displayed natural swimming behaviours were classed as failed, having been regurgitated or the salmon having perished. These fish were removed from any further analysis. Secondly no suitable spawning habitat exists in the receiver network (section 3.4.2) and salmon have to move upstream of the receiver network to have an opportunity to spawn. Thirdly, based on the sighting of spawning salmon and the presence of redds in the Mersey catchment (Environment Agency, personal communication) and the known spawning periods of salmon in the rivers Dee and Ribble (Environment Agency, personal communication), the spawning window for salmon in the Mersey catchment was assumed to be between December – February. Lastly, if a salmon progressed upstream of the receiver network and into the rivers Bollin or Mersey it was thought to have had opportunity to spawn as juvenile salmon have been captured in these rivers (Chapter 3).

Behaviour of tagged salmon

As routinely undertaken when reporting tracking studies, temporal and spatial plots of movement for each salmon were made (Cooke *et al.,* 2012). Using these plots and reviewing the 'cleansed data', the behaviour of salmon was then categorized as erratic, wherever considerable up and down stream movement was evident, or non-erratic, whenever upstream or downstream directional migration was evident, similar to Kennedy *et al.* (2013).

The distance between receivers and time taken to complete a movement was used to generate a ground speed, or progress speed, for each upstream and downstream movement made by each salmon (m / min $^{-1}$). Individual value plots were used to describe progress speeds between pairs of receivers.

Each receiver has a range of 500 m (picking up 50 – 90% of tag pings) (Webber, 2009) and therefore the distance between receivers will not represent actual distance a salmon has moved. In addition a salmon may have made several up and downstream movements between receivers without coming into range of either receiver. As such, progress speed is a measure of progress through the receiver network and not actual swimming a speed. Progress speeds between the receivers R6–R7, R7–R6, R3–R5, R5–R3, R3–R4 and R4–R3 were removed as these receivers were close together (700 – 1650 m) and were in direct line of site of each other owning to the straight channel of the Ship Canal, meaning the time recorded to complete a movement was thought to be unrepresentative of actual progress speed.

Distribution and residency of tagged salmon

The total time (hours) that each salmon spent within range of a receiver (e.g. movement R2 – R2) or approaching a receiver having left an adjacent receiver (i.e. the time taken to move from one receiver to the next, e.g. R2 – R3) was calculated and plotted on an individual value plot. This did not include time spent upstream of R11, R12 or R13 or movement between R4 to R1 or R14 to R1. For each individual salmon the % of total time in the network each salmon spent within range of a receiver or approaching a receiver was also calculated and plotted on an interval plot with 95% confidence intervals. Data from receivers R4 and R14 were combined in year 2 so as to be comparable with year 1. As salmon could move downstream out of range of R1 the R1-R1 movement was a recording of the time between first and last detections.

River entry and weir passage

The behaviour of salmon entering the Ship Canal and the rivers Bollin, Glaze and Lower River Mersey was described. River entry was plotted on hydrographs for all rivers and on flow duration curves for the Rivers Bollin and Upper River Mersey. Woolston weir passage (R1-R2) was also plotted on a flow duration curves. Flow duration curves were generated using flow data from 01/09/2010 – 30/03/2012 and was taken from gauging stations identified in section 3.3.2 on the respective rivers. Condition factor of salmon was calculated using the equation proposed by Fulton (1911):

$$K = 100 \times M/L^3 \qquad \text{(Eq. 1)}$$

where K = condition factor, M = body mass, L = body length. Unpaired t-test was used to test if there was significant difference in condition factor of salmon moving upstream of weirs and those that had opportunity to do so but did not.

5.4 RESULTS

5.4.1 Capture and tagging of salmon and tagging response

Section 3.4.2 and Table 3.4 describe the trapping and catch rate of salmon in each tagging year. Thirty two and 16 salmon were captured between 01/09/2010 – 06/10/2010 (Year 1) and 16/08/2011 – 03/10/2011 (Year 2), respectively (Table 5.1). In Year 1, one salmon (captured 28/09/2010) caught was found to have had its adipose fin clipped with a ‘V’ notch and a second salmon (captured 29/09/2010) was tagged with a ribbon like tag under the dorsal fin with an address and reference number on.

Neither fish was tagged in case the fish already contained a tag and had undergone a tagging procedure. Both hatchery reared and wild salmon smolts from the River Dee, 11 km south of the Mersey estuary, have their adipose fin clipped with a 'V' (Ian Davidson, EA, personal communication) which may account for the first of these fish. The second was found to have been tagged and released at Chester Weir fish trap on the River Dee on the 19/08/2010 attempting to move upstream (Ian Davidson, EA, personal communication). All other (n = 30) salmon captured were tagged. Two salmon were found to have been fin clipped ('V' notch in their adipose fin) in year 2 (caught on 16 and 30/08/2011); neither fish was tagged (Table 5.1). Two salmon captured, tagged and released on 2/09/2011 and 5/09/2011 were found dead the following day. The tags were removed and re-used. All other (n = 14) salmon captured were tagged (Table 5.1).

Table 5.1 Salmon captured at Woolston weir fish trap.

	Successfully tagged	Fin clipped or already tagged	Perished and tag retrieved	Total
Year 1	30	2	0	32
Year 2	14	2	2	18
Total	44	2	4	50

The 50 captured salmon (Table 5.1) ranged from 528 – 852 mm (mean = 649) fork length, 1150 – 6100 g (mean = 2965) weight, condition factors of 0.74 – 1.41 (mean = 1.04) and 22 were identified as female and 28 male. Thirty salmon from year 1 were aged and all salmon were found to have spent two years in fresh water apart from one salmon that had spent one year and another salmon three years in fresh water. Scales from four salmon were replacement scales and freshwater age could not be estimated. Two salmon had spent two winters at sea and the other salmon one winter at sea. Only three of the 50 released salmon moved off immediately and several salmon took long periods of time (>15 minutes) to swim off from the release site after displaying normal breathing and balance in the recovery tank.

Of the 44 tagged salmon (Table 5.1), 10 were considered to have either regurgitated their tags, the tags failed or the fish perished as three tags were never recorded by any receivers and seven tags recorded by R2 only; these tags were discounted from further analysis. 18 tagged salmon resumed upstream movement and 16 did not progress to R3 and moved downstream of the tagging site and Woolston Weir to R1 post tagging, five of which later moved back upstream. Of the 16 salmon that did not move upstream to R3 only three did not move in range of R2.

In tagging year 1, dissolved oxygen saturation ranged from 53.0 – 79.0 % (mean = 66.7) upstream and 67.4 – 96.0 % (mean = 82.2) downstream of Woolston Weir. Temperature ranged from 12.2 – 14.7 °C (mean = 13.3) and 12.3 – 16.4 °C (mean = 14.6) up and downstream, respectively. Due to SONDE equipment failure no environmental data were collected for the Ship Canal.

No receivers were lost during either tagging year, but R5 ceased recording in October 2010 and September in 2011 during tracking years 1 and 2, respectively, for unknown reasons. R5 tracking data were not included in the analysis for either year owing to its close proximity to R3, R4 and R6 and this area being suitably represented by receivers.

5.4.2 Overview of route and fate of salmon

Salmon are referred to by tag serial number (Appendix 2). Movement flow charts describing the numbers of salmon recorded moving between pairs of receiver were produced to illustrate route choice (Figure 5.3).

Of the 34 salmon with functioning tags in both Year 1 and 2, three salmon moved downstream of Woolston weir and in range of R1 post tagging without coming into range of R2. Two of the three salmon (fish 38945 and 3173) remained in range of R1 for 14 and 55 days, the third (fish 38943) was in range of R1 for only five minutes before moving out of range and did not return to R1. Thirteen salmon moved downstream of Woolston Weir after release and after coming in range of R2, but did not progress upstream to R3, and were recorded by R1. Eleven of the 16 salmon that moved downstream of Woolston weir without making it to R2 and/or R3 did not move back upstream of Woolston weir and in range of R2.

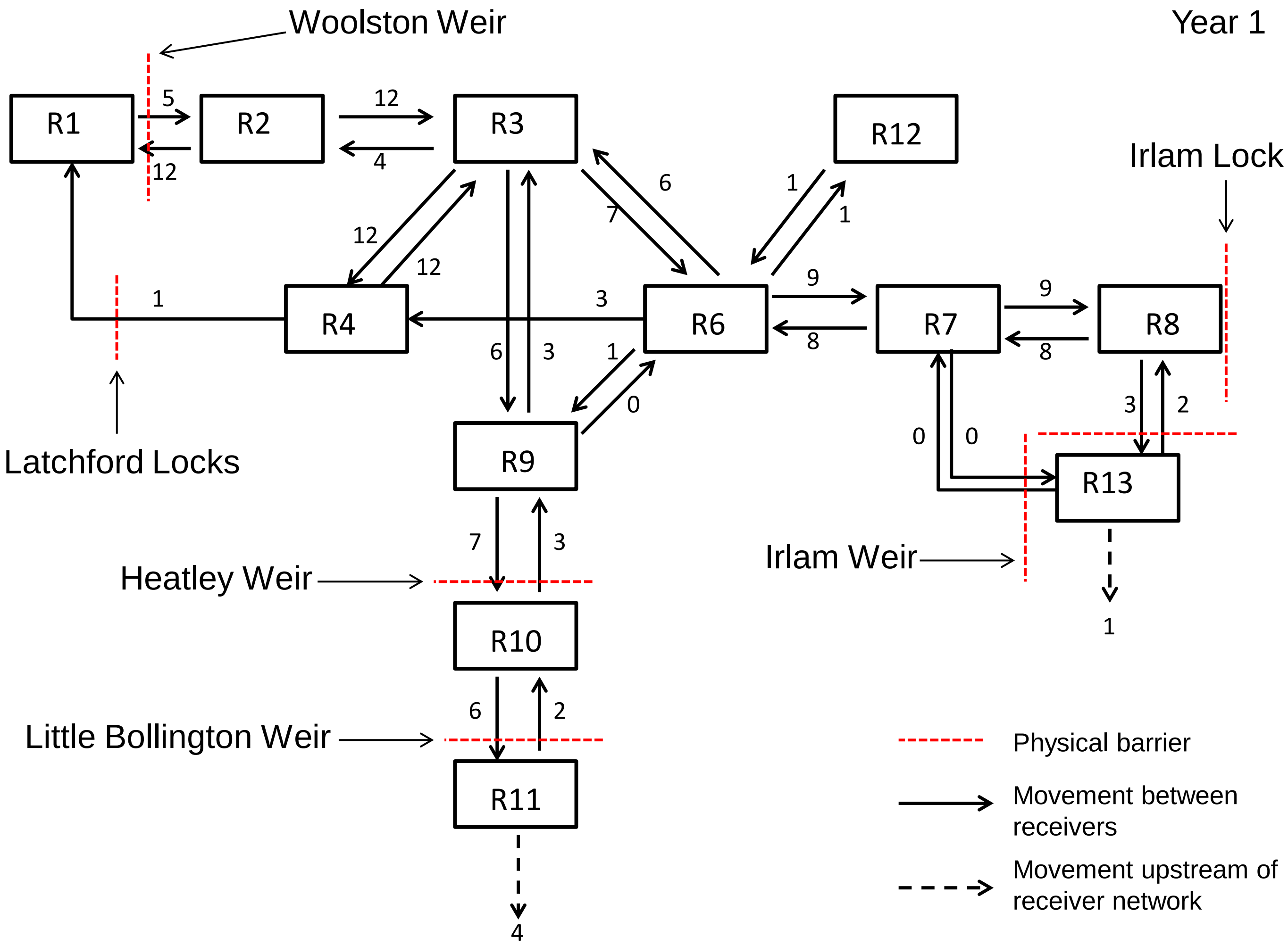


Figure 5.3 The numbers of individual salmon that moved between receivers. Numbers next to the movement arrows denote the number of salmon moving. Note receiver 5 has been discounted in both years due to failure.

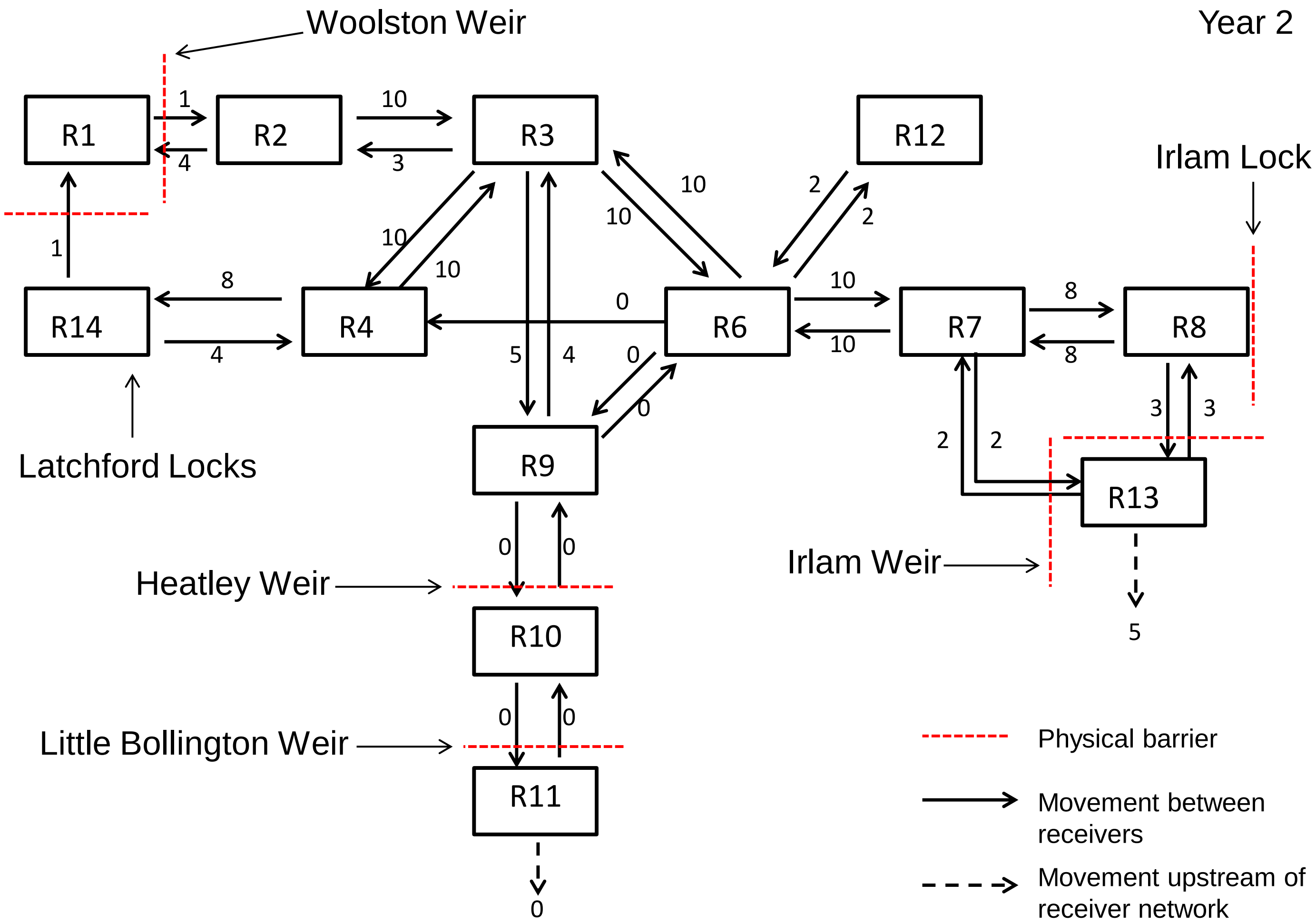


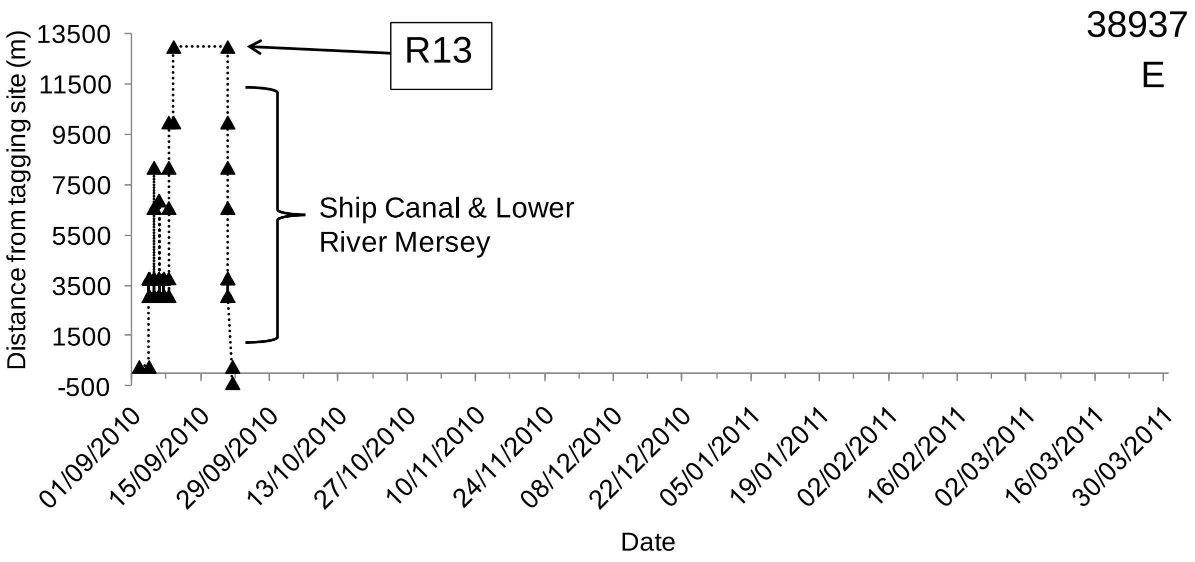
Figure 5.3 (continued) The numbers of individual salmon that moved between receivers. Numbers next to the movement arrows denote the number of salmon moving. Note receiver 5 has been discounted in both years due to failure.

Five salmon did move back upstream of Woolston weir having moved downstream and in range of R1; fish 3169 progressed no further than R2 (recorded by R2 on 16/09/2010, having dropped downstream of Woolston weir and in range of R1, four hours after tagging on 11/09/2010) and was not detected again. Temporal and spatial plots using receiver distance from tagging site were produced for the 22 salmon that had moved into the receiver network (Figure 5.4).

Of the other four salmon that moved back upstream of Woolston Weir, fish 3175 moved upstream in the Ship Canal and moved between R7 and R8 until it was last recorded at R8 and the tag became undetectable; three salmon moved upstream of the receiver network: fish 38941 moved from R3 to R9 and into the River Bollin where it progressed to R11 and remained upstream of the receiver network and fish 3179 moved into the River Bollin but after extensive up and downstream movement in the Ship Canal. Once in the River Bollin fish 3179 quickly progressed to and upstream of R11 where it remained until moving back downstream into range of R11 where the tag became undetectable. Fish 38941 and 3179 are thought to have had opportunity to spawn, having met the assumptions set out in 5.2.2 (i.e. moved upstream of the receiver network into either the River Bollin or Mersey within a spawning window of December – February). Fish 3178 moved directly to R8 and then to and upstream of R13 where it remained until 14/11/2010 moving back downstream into the Ship Canal and last recorded by R4 (Figure 5.4).

Eighteen salmon moved upstream and in range of R3 post tagging and release. Three of these salmon did not move into either the River Bollin or Mersey, fish 1507 and 3181 moved up and down the Ship Canal between R3 - R8 and R6 - R8 until they were last recorded at R4 before the tags became undetectable. The other salmon, fish 41814 first moved into the Ship Canal to R6 then R14 and then was recorded again downstream of Woolston Weir in range of R1, returned to the Ship Canal and made similar movements to fish 1507 and 3181 between R6 – R8 and moved back downstream of R1 on 11/02/2012. Fish 41814 then later returned to R1 on 24/04/2012 when it was last detected.

Eight salmon entered the River Bollin only. Three salmon (fish 1512, 1508 and 41815) moved up and downstream in the Ship Canal between receivers R14 and R8 before entering the River Bollin. These fish did not progress to R10 and moved back into the Ship Canal after entering the River Bollin and moved downstream to R14 where they remained until their tags became undetectable. Fish 3177 moved directly from R3 to R9 and into the River Bollin and after progressing to R10 fish 3177 returned to the Ship Canal and quickly moved downstream of Woolston Weir at in range of R1.



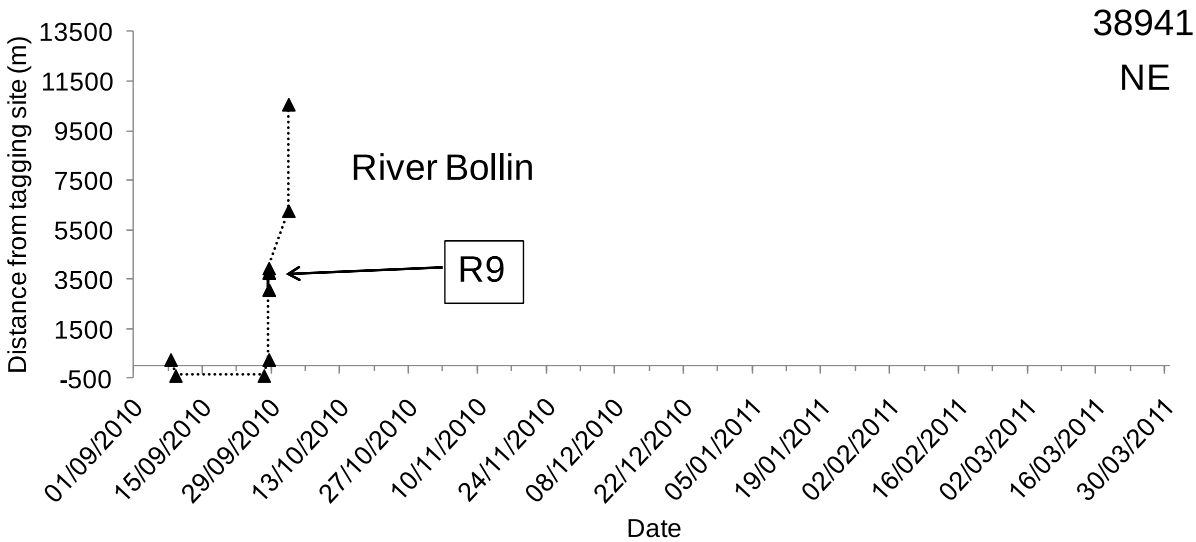
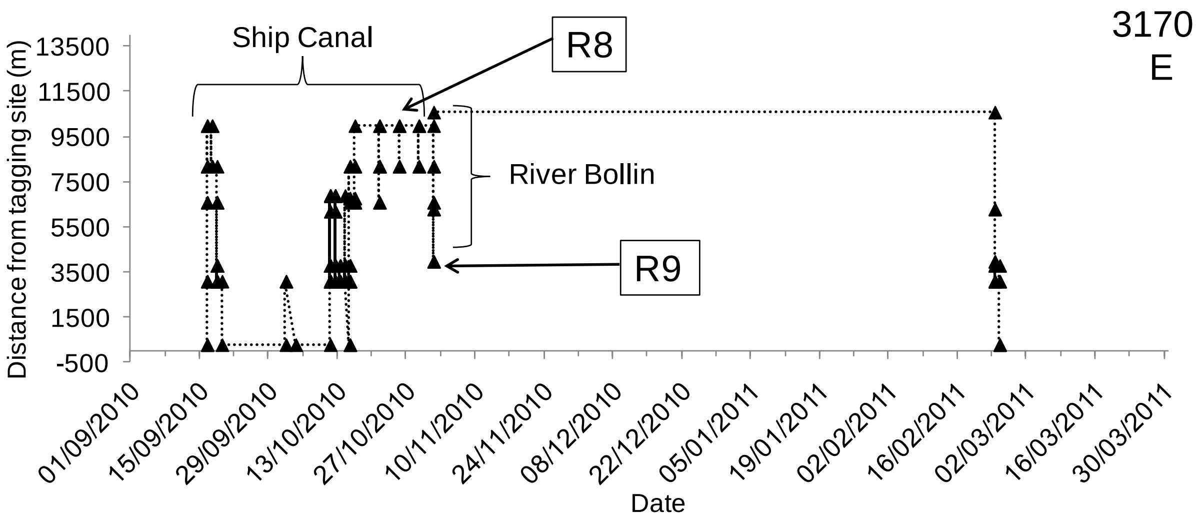
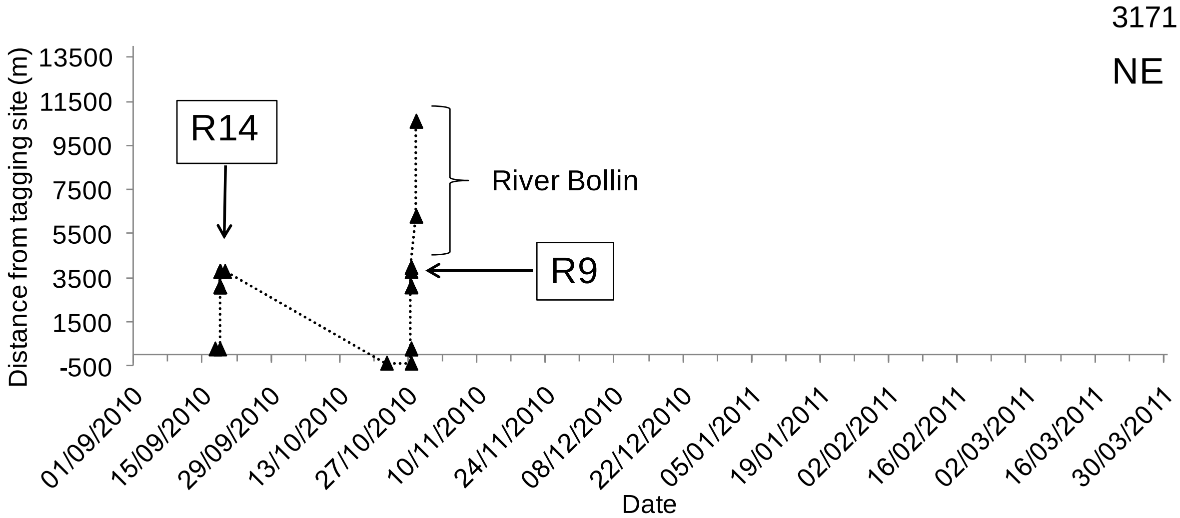


Figure 5.4 Temporal spatial plots for tagged salmon. Note, when interpreting temporal spatial plots: ▲indicates a fish being first recorded by a receiver at the end of a movement, the dotted lines connect ▲ for ease of interpretation. Key receivers (i.e. R8, R9 and R13) are denoted by a box with an R number in and an arrow; notes are provided on the graph to help in understanding where in the network a fish is (Figure 5.1). The ▲ below the x axis represents R1 (360 m downstream of the tagging site) and the X axis represents the tagging site (0 m). Plots are presented in tagging order. NE of E is used to denote non-erratic or erratic behaviour classification, respectively. The scale date axis for fish 41814 is extended to include April, all other date scales are the same for each tracking year.





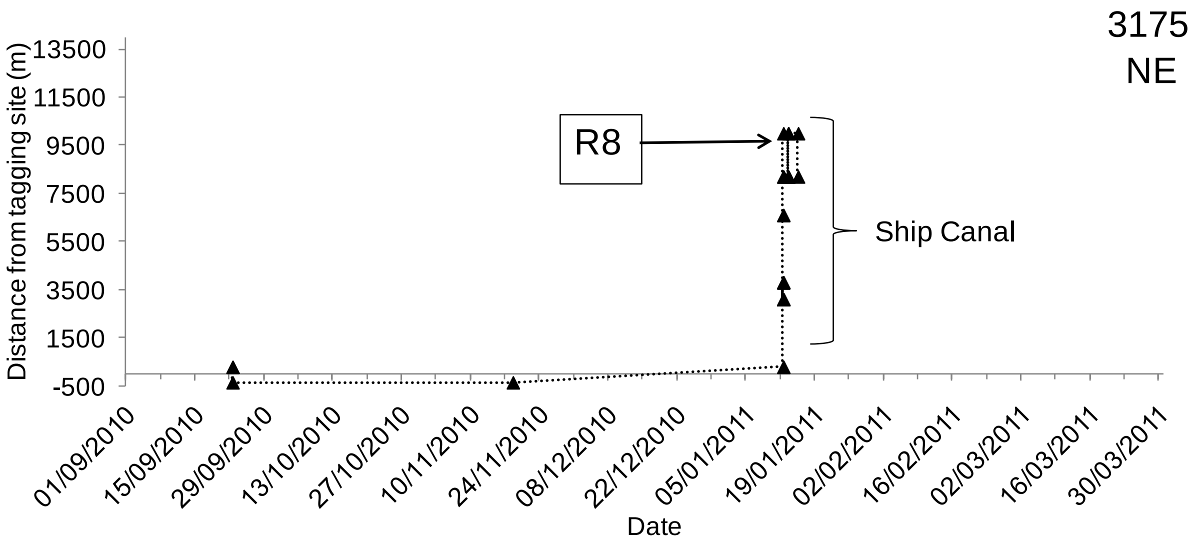


Figure 5.4 (continued) Temporal spatial plots for tagged salmon

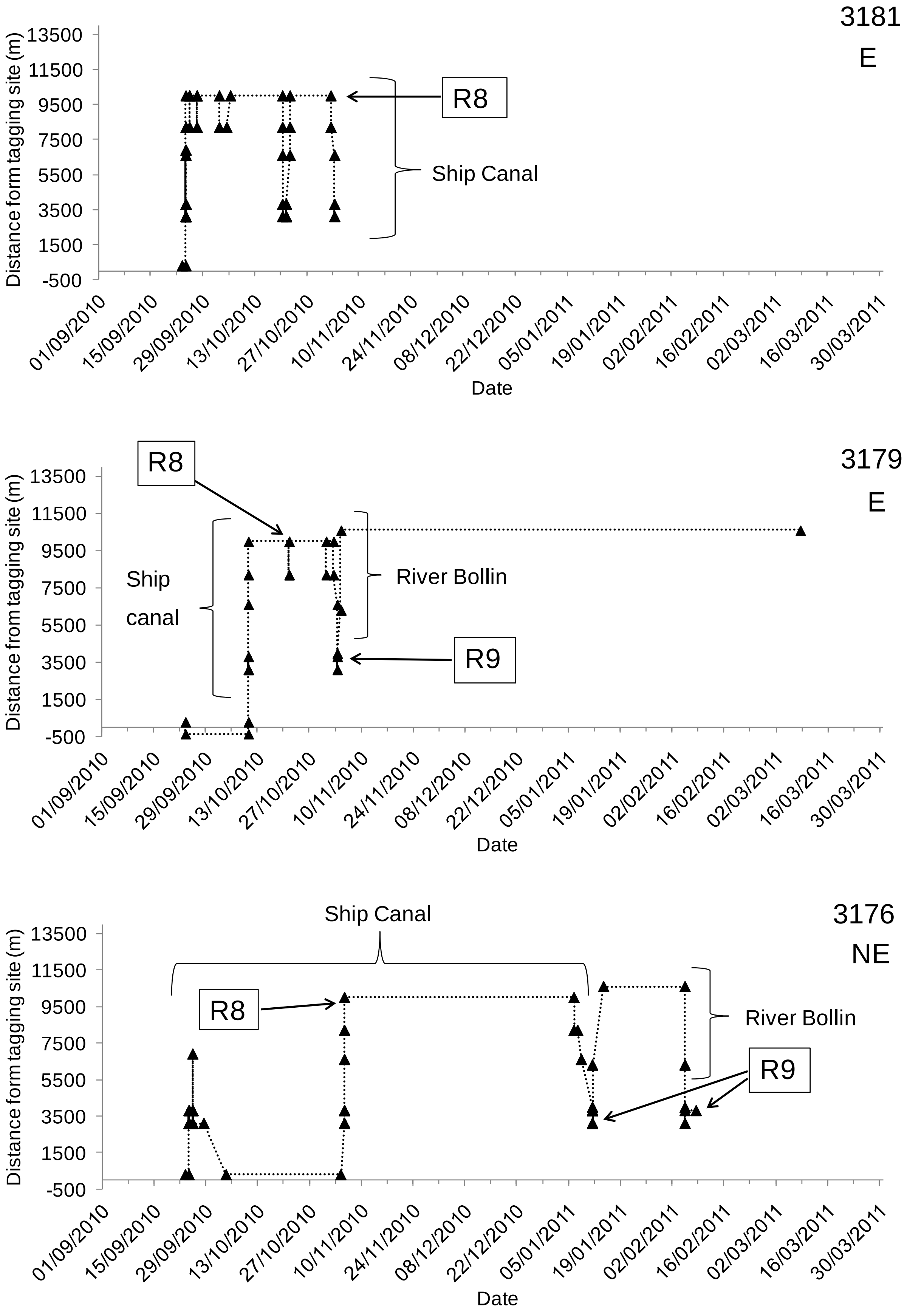


Figure 5.4 (continued) Temporal spatial plots for tagged salmon

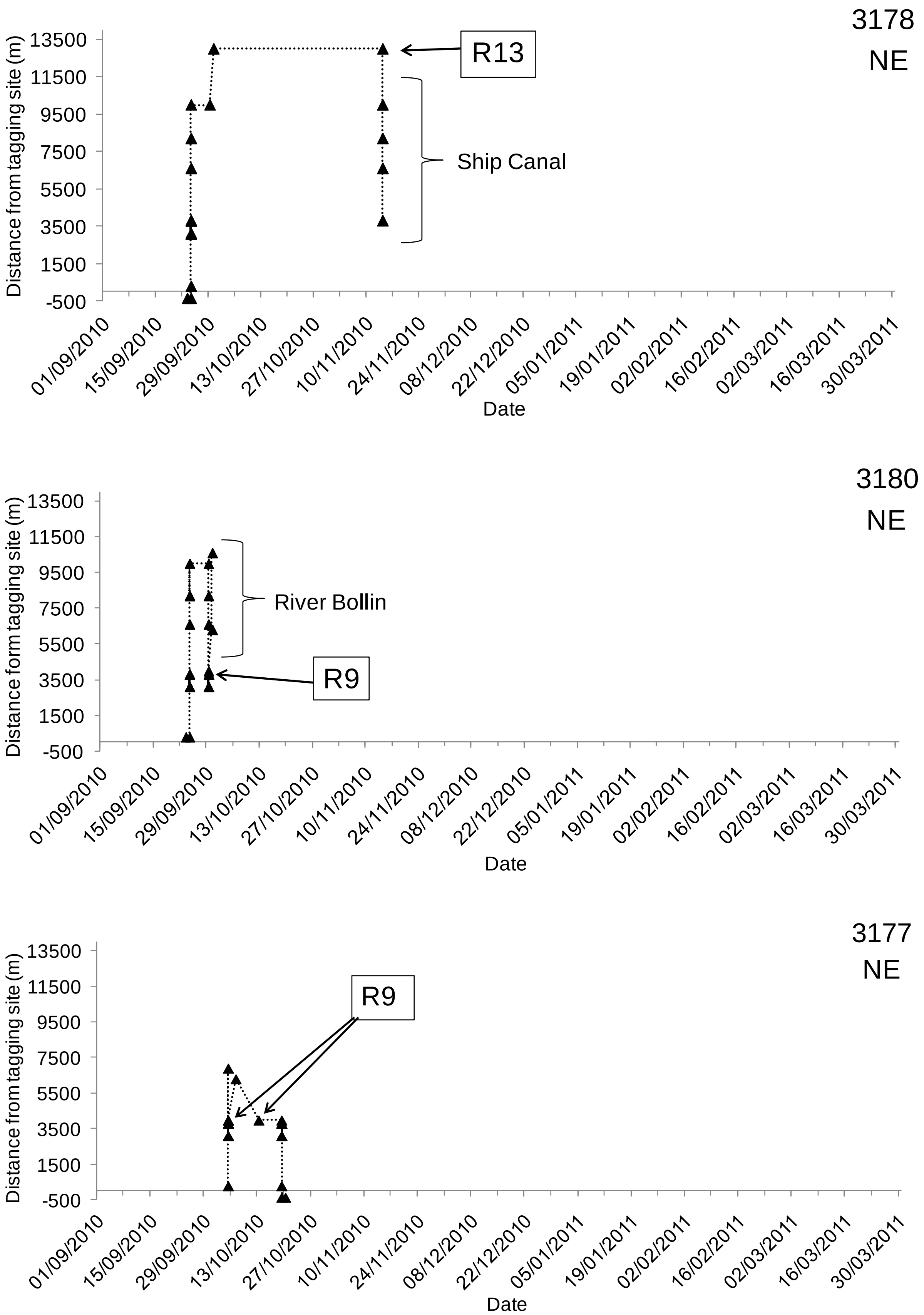
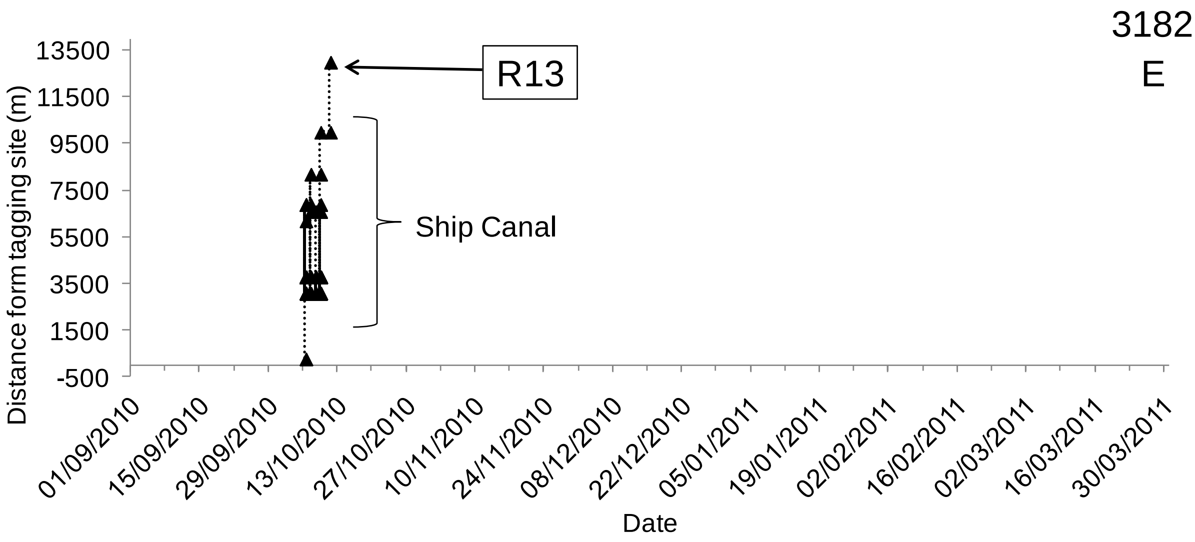
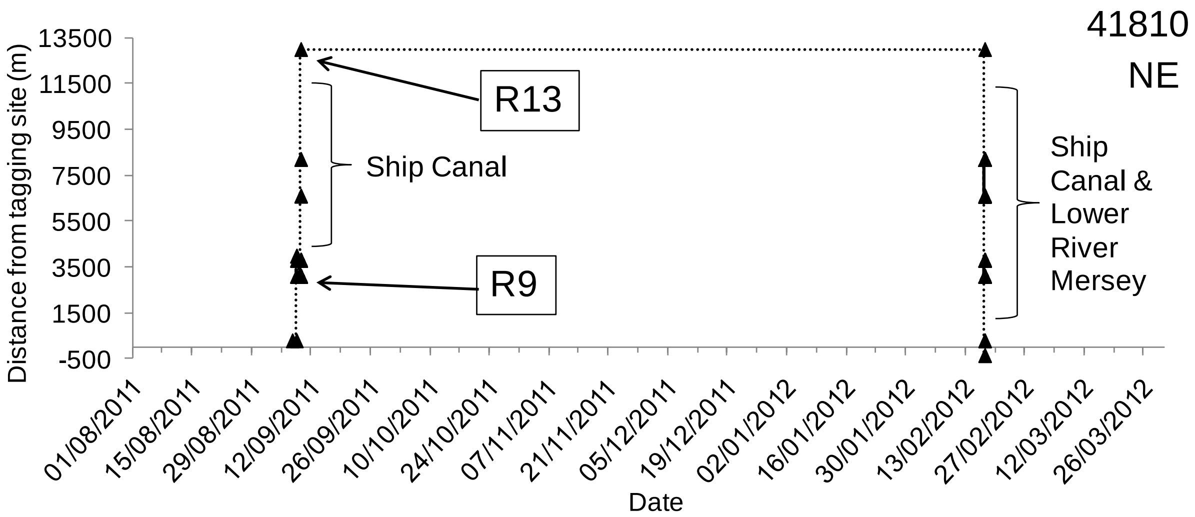


Figure 5.4 (continued) Temporal spatial plots for tagged salmon.





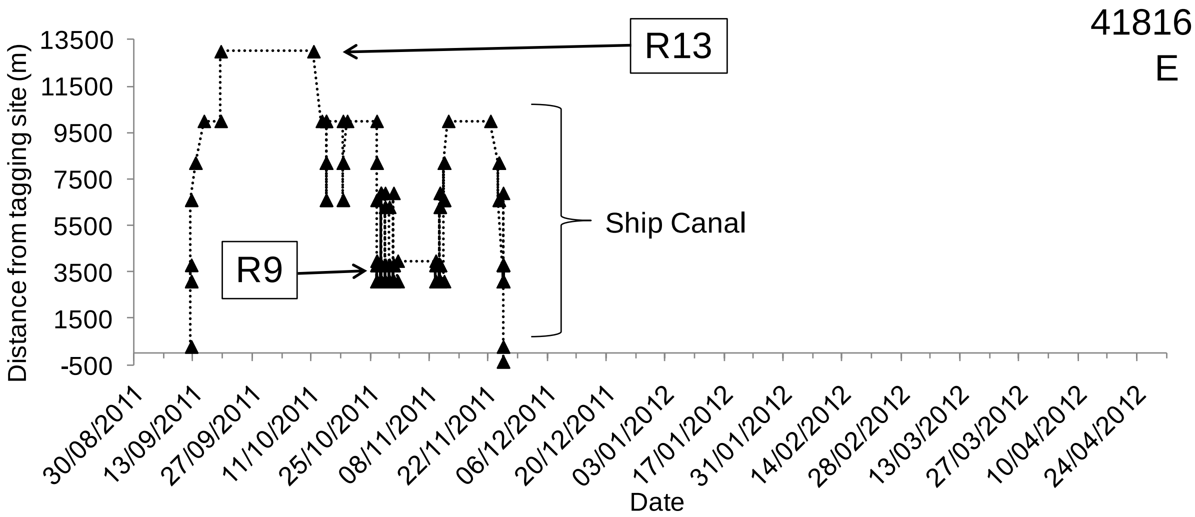
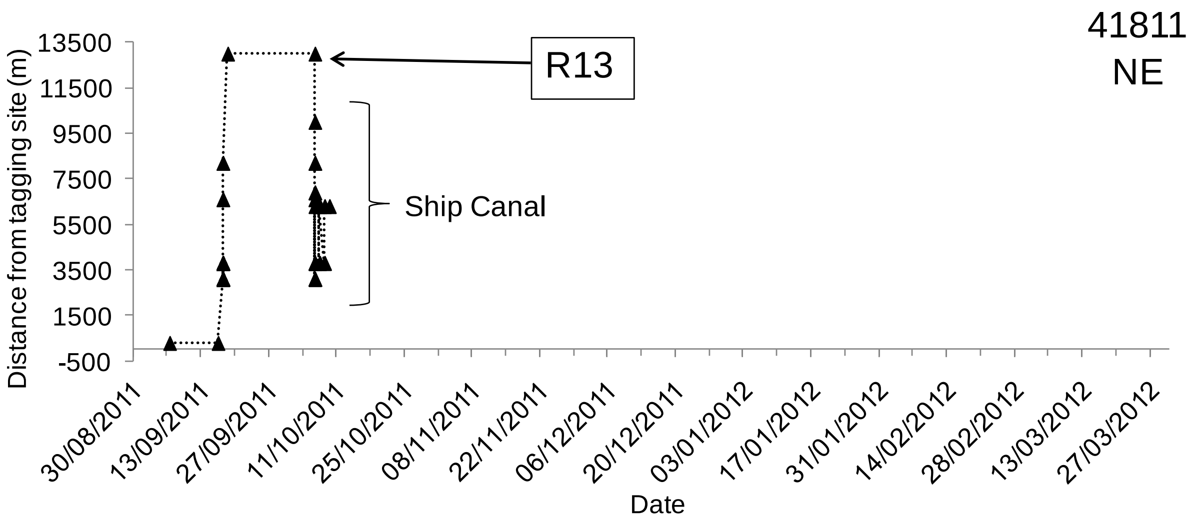
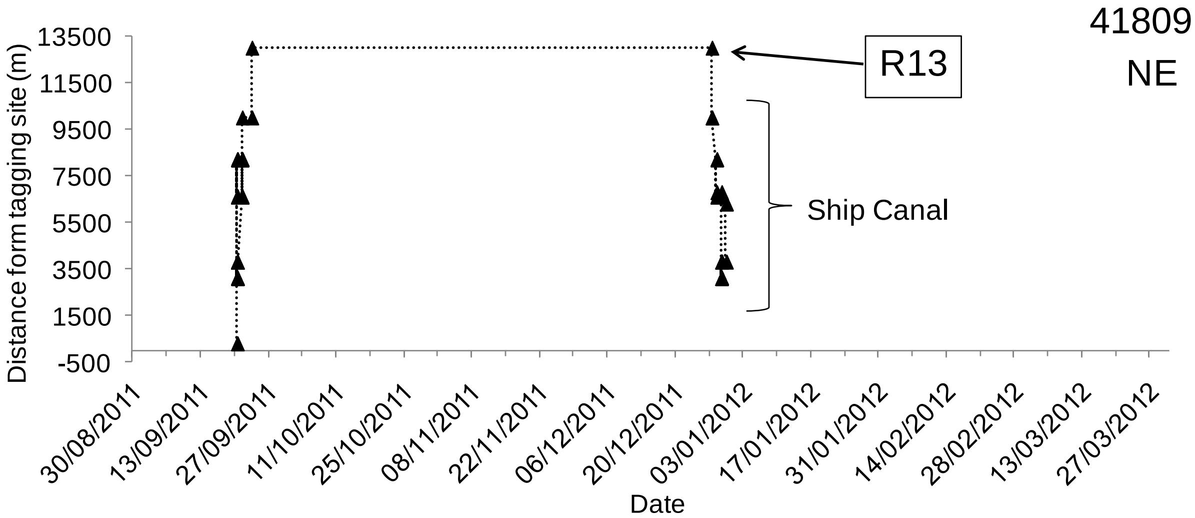


Figure 5.4 (continued) Temporal spatial plots for tagged salmon





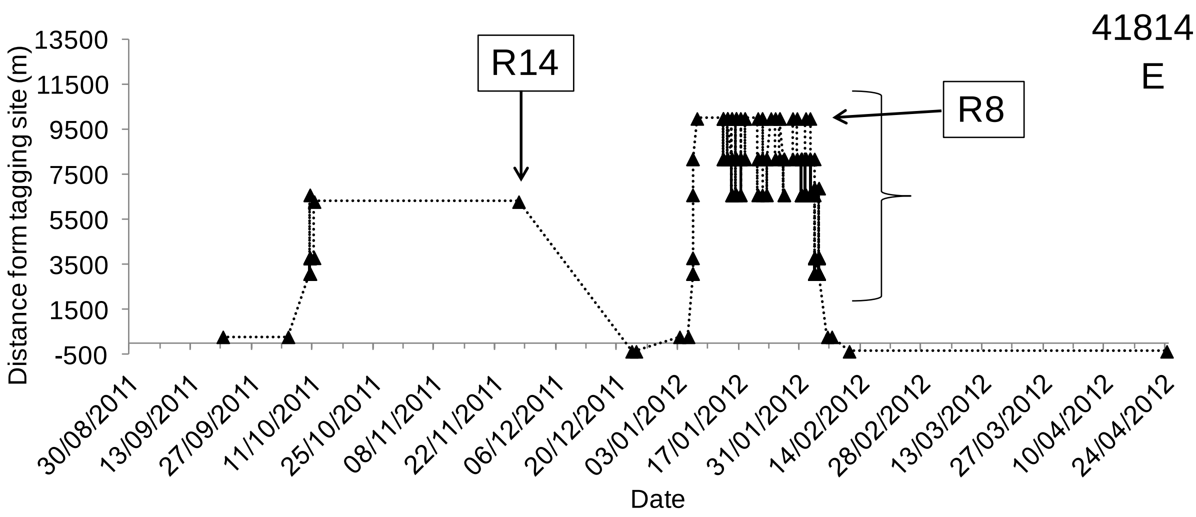
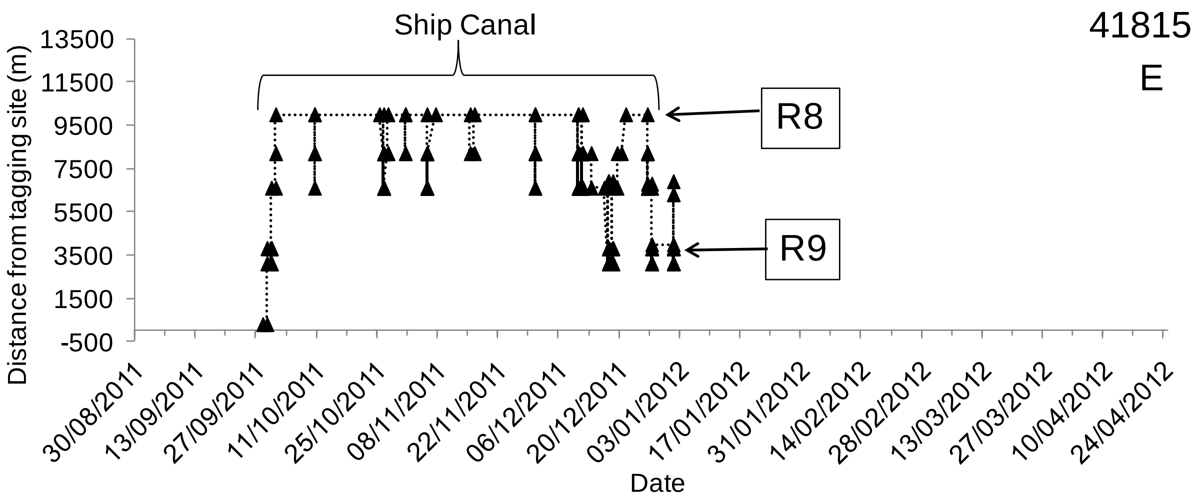
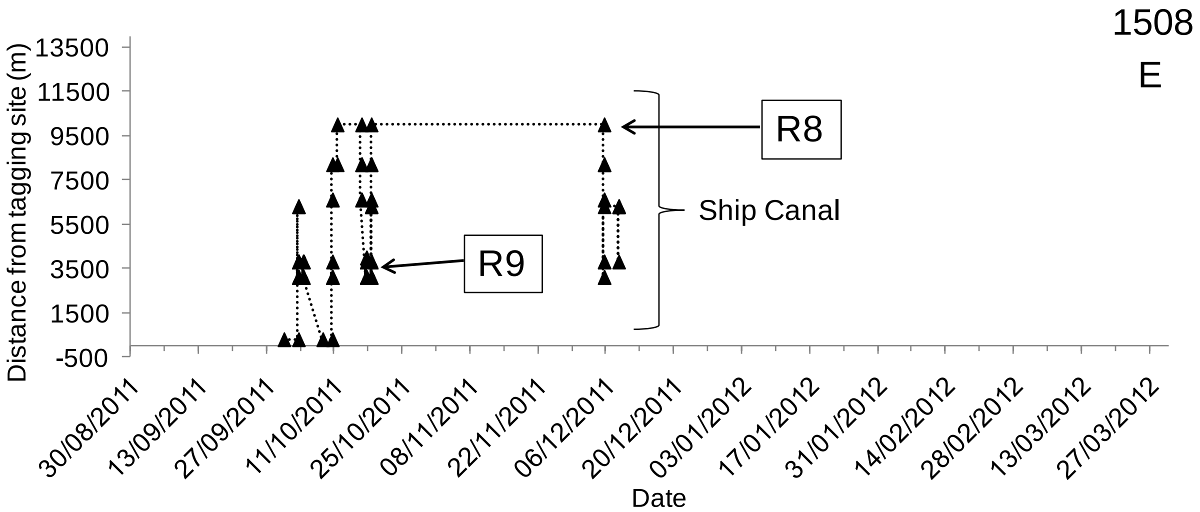


Figure 5.4 (continued) Temporal spatial plots for tagged salmon





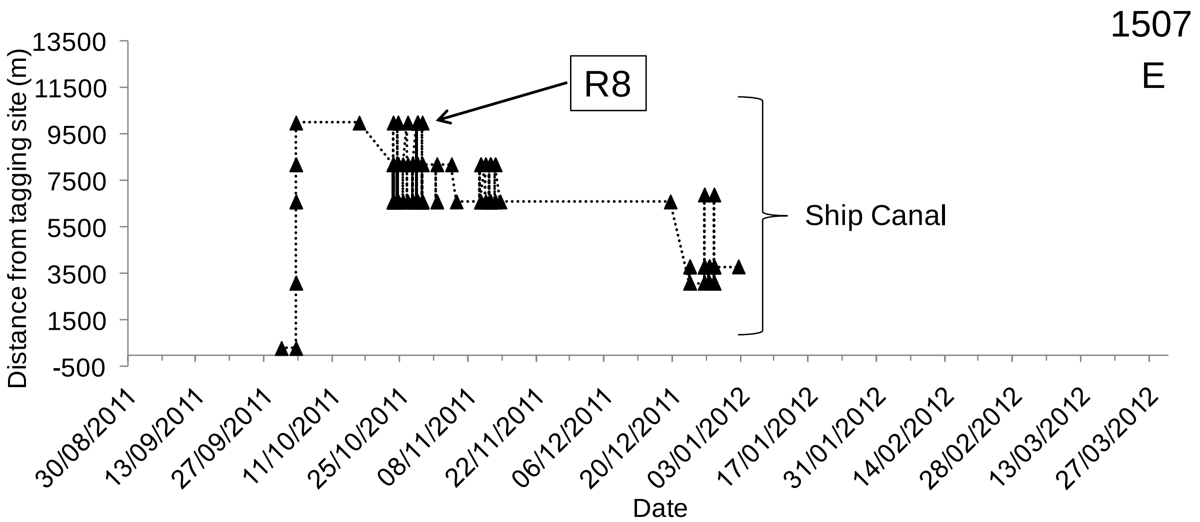
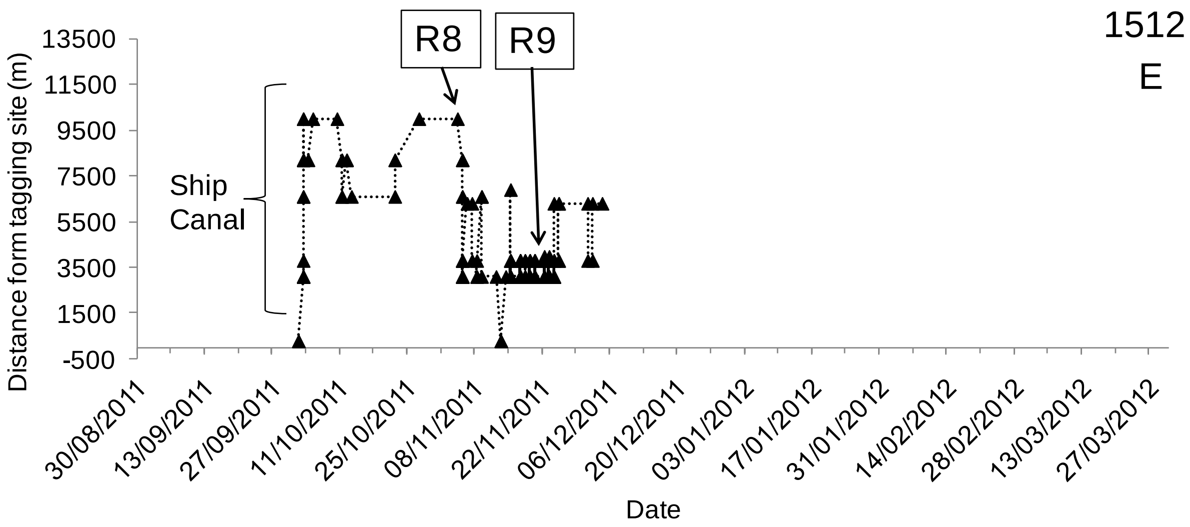


Figure 5.4 (continued) Temporal spatial plots for tagged salmon



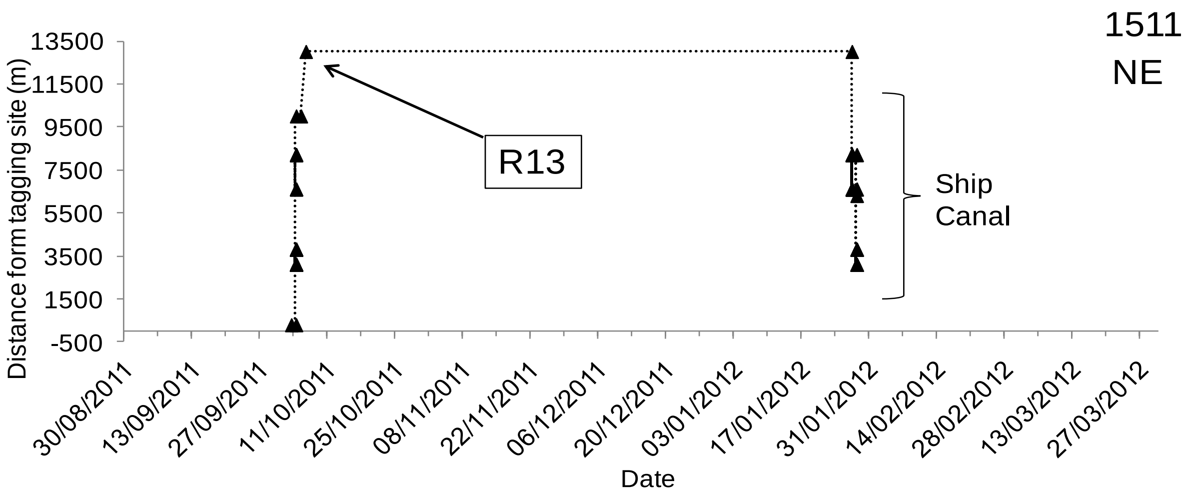


Figure 5.4 (continued) Temporal spatial plots for tagged salmon

Four salmon entered the River Bollin and progressed to and upstream of R11: After first entering the Ship Canal, fish 3171 moved downstream from R3 and after moving downstream of R4 was next recorded by R1. Fish 3171 then progressed quickly to R11 (taking 31 hours) where it remained upstream and fish 3180 moved upstream and downstream in the Ship Canal to R8 before moving into the River Bollin and progressing quickly (21 hours) to and upstream of R11 where it remained. Fish 3176 and 3170 both made extensive upstream and downstream movement in the Ship Canal, each spending a high proportion of time at R8, and the Lower River Mersey (R2) before moving into the River Bollin. Fish 3170 spent 114 days upstream of R11 before returning downstream of R11 to R2 where the tag became undetectable, and fish 3176 spent 22 days upstream of R11 before moving downstream to R9 where it became undetectable. All four salmon are thought to have had opportunity to spawn (Figure 5.4).

Two fish moved into both the River Bollin and Upper River Mersey. Fish 41810 moved directly from R3 / R4 to R9 into the Bollin where after 12 hours it returned to the Ship Canal and moved quickly (34 hours) to and upstream of R13 where it remained for 161 days after which it moved quickly (15 hours) and directly from R13 – R1 and out of the receiver network. Fish 41816 moved quickly (7 days) and directly from tagging site to and upstream of R13 where it remained upstream for 22 days after which it made extensive upstream and downstream movements in the Ship Canal (R14 – R8), including entering the River Bollin for 9 days but not progressing to R10. Fish 41810 is thought to have had opportunity to spawn in the Upper Mersey.

Five salmon progressed upstream of R13 and into the Upper River Mersey only. Fish 38937 made extensive up and downstream movements in the Ship Canal before moving upstream of R13 but returned to the Ship Canal 11 days later where it quickly (25 hours) moved downstream of R1. Fish 41811 made quick (11 days) and direct movement upstream of R13 where it remained for 18 days after which it returned to the Ship Canal where it made upstream and downstream movements between R3 and R14 and was last detected at R14. Fish 41809 and 1511 both moved upstream of R13 after moving upstream to R8, downstream to R3/4 and R6, respectively, and finally back upstream to R13; both fish then returned into the Ship Canal after 95 and 113 days where they made up and downstream movement between R6/R4 and R14 where they were both last detected. Fish 3182 made extensive movements up and downstream in the Ship Canal until moving upstream of R13 where it remained. Fish 3182 and 1511 are thought to have had opportunity to spawn. It is unlikely fish 41809 had opportunity to spawn as was only upstream of R13 from 23/09/2011 to 27/12/2011 and is unlikely to have been able to move upstream to spawning grounds during this time period.

In total across both tracking years 14 salmon moved upstream of the receiver network and into the River Bollin or Upper River Mersey. Nine salmon are thought to have had the opportunity to spawn (fish 1511, 3170, 3171, 3176, 3179, 3180, 3182, 38941 and 41810), six were identified as female and three as male. Seven of these fish had been genotyped; four fish were assigned to the Solway and Northwest England, two the Scotland and one the Southwest England Reporting Regions in both genetic tests (Chapter 4).

5.2.3 Salmon behaviour

Eleven salmon were classed as showing erratic behaviour (Figure 5.4; an E under the tag number denotes erratic). Five of these fish (45%) moved upstream of the receiver network (two into the Upper River Mersey and three in the River Bollin, one of which having already moved upstream of R13 and back into the Ship Canal again, of which fish 3170, 3179 and 3182 had opportunity to spawn (27% of 11).

Eleven salmon were classed as showing non erratic behaviour (Figure 5.4; NE under the tag number denotes non erratic). Nine of the fish (81%) progressed upstream of the receiver network. Five fish (45% of 11), fish 38941, 3171, 3180, 1511, and 41810, had the opportunity to spawn (two in the upper River Mersey and three in the River Bollin). However, although classed as non-erratic:

- fish 3171 moved from R4 to R1,
- fish 3180 moved up and down the Ship Canal twice before entering the River Bollin and moving upstream of R11,
- fish 41810 entered the River Bollin before moving upstream of R13 and into the Upper River Mersey,
- fish 3176 spent 31 days in range of R2, 62 days in range of R8 and although entered the Bollin and moved upstream of R11 moved downstream into the Ship Canal 25 days later,
- fish 3178 became undetectable after last being recorded at R4 on 14/11/2010 (49 days after tagging) as did fish 41811 last recorded by R14 on 9/10/2011 (33 days after tagging) both after moving upstream of R13. Fish 41811 displayed erratic behaviour after entering the Upper River Mersey (Figure 5.4)
- fish 3175 remained downstream of Woolston Weir moving in and out of range of R1 from initially moving downstream post tagging for 112 days before moving back upstream of Woolston weir and into the receiver network, and
- fish 3177 moved into the River Bollin and in range of R10 but then moved downstream and out of receiver network via R1.

Progress speeds

A total of 171 upstream movements were recorded during the study, ranging from 0.001 – 139.40 m/min (mean = 27.60) and 149 downstream movements were recorded ranging from 0.04 – 212.10 m/min (mean = 32.70). Downstream progress speeds, means and maximums, were faster at 8 of the 11 pairs of adjacent receivers (Figure

5.5). Mean upstream speeds were faster than the downstream speeds between R14 - R4, R3 - R6 and R3 - R9 only.

The ground speed of salmon between R1-R2 had the lowest mean, maximum and minimum upstream speed (0.001 – 8.85, mean 1.94 m / min). Salmon displayed slower progress speeds moving over barriers, R9 - R10 (range 0.45 – 18.41, mean = 5.91 m / min), R10 - R11 (range 1.14 – 19.16, mean = 11.69 m / min), R7 - R13 (range 3.36 – 9.69, mean = 6.53 m / min) and R8 - R13 (range 2.31 – 23.41, mean = 9.16 m / min).

Salmon displayed faster and a greater range of upstream progress speeds in the Lower River Mersey, Ship Canal and moving into the River Bollin than other sections with mean speeds in these sections ranging from 28.70 – 44.98 m / min and maximum speeds ranging from 54.37 – 139.45 m / min (Figure 5.5). Upstream speeds of salmon in the Ship Canal ranged from 0.28 – 139.46 (mean = 34.08) compared with downstream speed in the Ship canal 0.18 – 212.14 m / min (mean = 212.14).

Downstream movements out of the Rivers Bollin (R11 - R10 and R10 - R9) and Glaze (R12 - R6) into the Ship Canal and salmon moving downstream over Woolston Weir (R2 - R1) were much faster than upstream equivalents; 2.7, 2.9, 3.4 and 6.6 times faster, respectively (Figure 5.5). Movement out of the River Glaze was particularly fast (25.67, 80.90 and 88.74 m / min). Downstream progress speed in the River Bollin (including movement to R10, R9 and R3) ranged from 0.27 – 54.91 m / min (mean = 24.280). Movement downstream from R13 into the Ship Canal was slower than that of the River Bollin ranging from 1.13 – 35.77 m / min (mean = 14.55) only 0.5 times faster than upstream progress into the Upper River Mersey (Figure 5.5).

Distribution and residency of tagged salmon

Analysis of distribution includes only 32 of the 34 salmon with working tags. Of the 16 salmon that dropped downstream of Woolston weir post tagging, which did not make it back upstream of Woolston weir:

- fish 38943, 38945 and 3173 moved downstream without first coming into range of R2. Only fish 38943 showed active downstream movement remaining in range of R1 for 5 minutes, with the other two remaining in range of R1 for 14 and 55 days, presumably attempting to move back upstream of Woolston weir (see below).

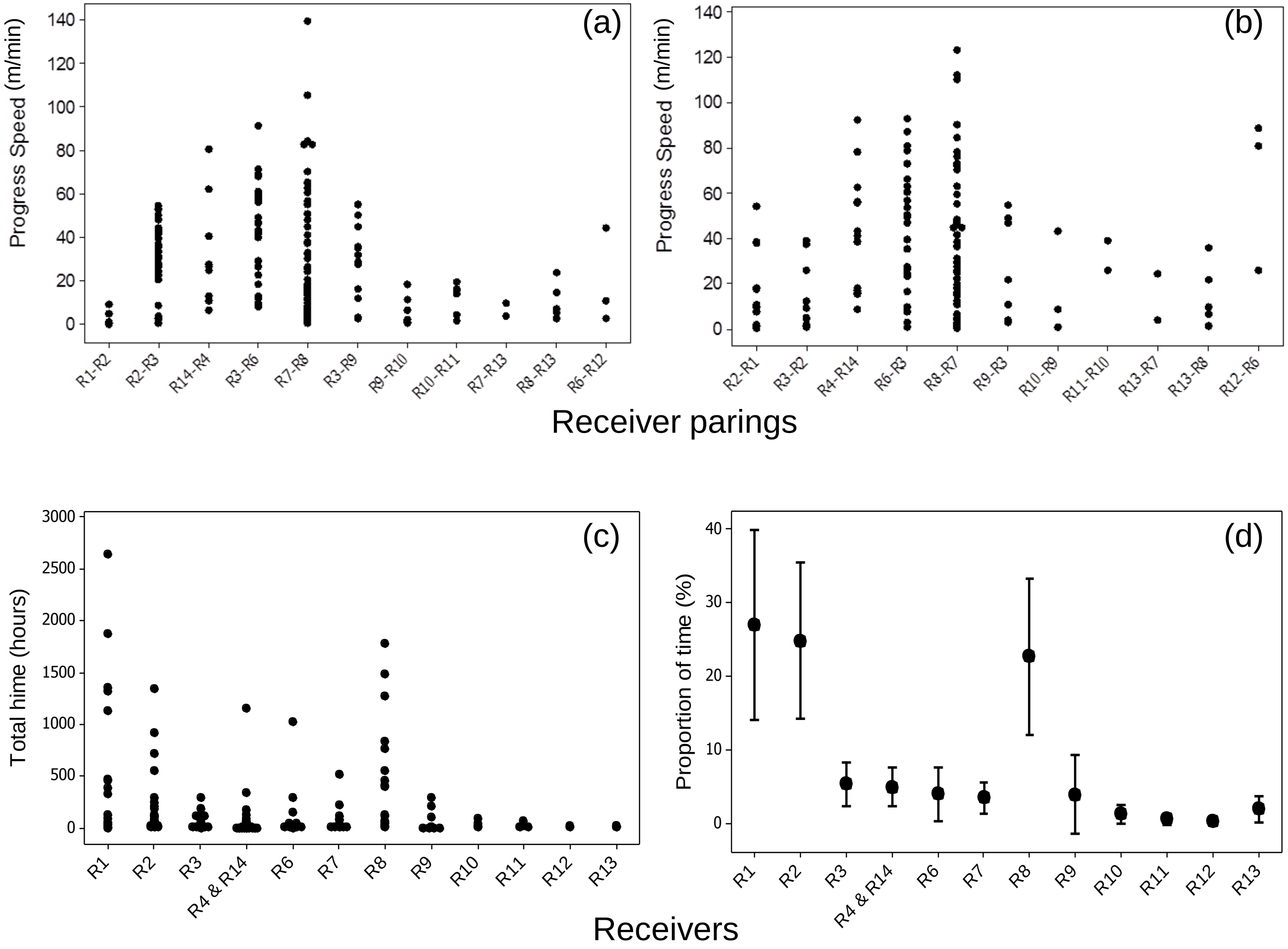


Figure 5.5 Individual value plots of ground speed between (a) upstream and (b) downstream pairs of receivers and (c) individual value plot of total time and (d) an interval plot of % of time spent approaching or in range of a receiver.

- Of the fish that did move in range of R2 before moving downstream of Woolston weir six salmon (fish 3172, 3183, 38936, 38942, 38944 and 41812) spent between 3 – 12 days in range of R2, presumably holding position in the Lower River Mersey but not moving upstream in range of R3. Fish 3174 spent 36 hours and fish 38935 20 minutes in range of R2.
- Once downstream of Woolston weir fish 3174 spent 48 days in range of R1, presumably attempting to move upstream of Woolston weir (see below). Fish 38935 spent 7 hours in range of and moving to R1 form R2, presumably making active downstream movement.

As such, fish 38943 and 38935 are considered to have made active downstream movement out of the receiver network post tagging not to return and were not included in analysis of distribution and residency. Fish 38943 spent 100% and fish 38935 88.9% in range of or moving to R1.

Salmon spent between 74 and 4597 hours (3 – 191 days) (mean = 985 hours or 41 days) in the receiver network post tagging before leaving the network or tags became undetectable (Figure 5.6). Salmon spent a greater amount of time in range (i.e. between first and last detections) of or approaching R1 (mean = 516 hours), R2 (mean = 180 hours) and R8 (mean = 466 hours) and significantly greater proportion of their time in range of or approaching R1 (mean = 27%), R2 (mean = 52%) and R8 (mean = 23%) than at other receivers (Figure 5.5). Salmon spent < 6% of their total time in the receiver network in range of or moving towards any of the other receivers.

On average salmon spent 97.8 hours (5.6% of total time) in range of or moving towards the receivers in the River Bollin (R9, R10 and R11). After R1, R2 and R8, R9 had the greatest range of the proportion of time salmon spent in range or moving towards a receiver; 0 - 82% (mean = 3.8%). Excluding R8, salmon spent an average of 17.5% of their time in the receiver network in range of or moving towards the receivers in the Ship Canal (R4 & 14, R6 and R7) and R3. Two salmon spent long periods in range of or moving towards the receivers R4 & R14 (1150 hours) and R6 (1022 hours), noticeably more than all other salmon (Figure 5.5).

Salmon that did not progress upstream into either the River Bollin or Upper River Mersey tended to spend longer in the receiver network than those that did (Figure 5.6). Salmon spent significantly longer (unpaired t-test, $t = 2.5722$, $p = <0.05$) in the receiver network before moving into the River Bollin than salmon that moved into the Upper River Mersey (Figure 5.6).

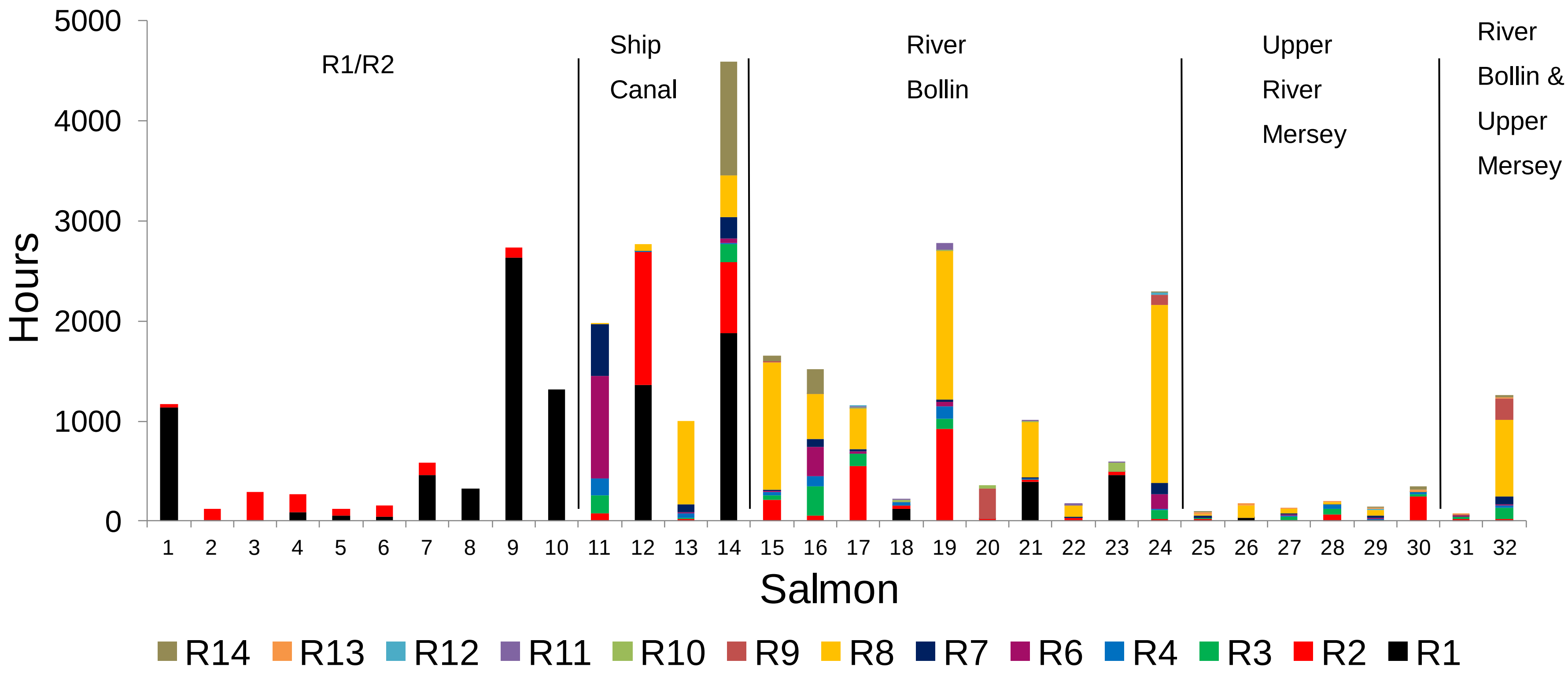


Figure 5.6 Total number of hours spent within range of or approaching receivers by the 32 individual salmon with working tags and made active upstream movement post tagging. The graph has been split into five groups with labels describe the furthest upstream point / section salmon reached.

5.4.4 River entry and weir passage

Woolston Weir

Twenty two salmon came into range of R1 during years 1 and 2 of the study (n = 18 in year 1, n = 6 in year 2). As mentioned in section 5.2.3, fish 38943 and 38935 were considered to have made active downstream movement post tagging. Seven other fish were considered to have passed R1 making active downstream movement: fish 38937, 41810, 41816 and 3177 moved downstream of R1 after entering the receiver network post tagging and making either extensive movements in the network or entering the River Bollin or Mersey, then making direct movement downstream passed R1, < 12 hours between first and last detection at R1. Fish 38936, 38942 and 3172 moved within range of R2 but then moved downstream post tagging for just eight minutes, 11 minutes and four hours between first and last detections at R1.

The remaining 13 salmon were considered to have attempted to move back upstream of Woolston weir. Six salmon were successful and six were unsuccessful, one fish (41814) attempted to move back upstream of Woolston weir twice, once successfully and the other not. There were between 4 and 1358 hours (mean = 338 hours or 14 days) between first and last detections at R1 for successful salmon (before they moved back upstream of Woolston weir). When the time taken for these fish to progress from R1 – R2 was included, i.e. the time between first detection at R1 and first detection at R2, successful salmon spent 28 – 2680 hours (mean = 583 hours or 25 days) moving upstream of R1 to R2. The seven successful attempts of passage by salmon were made in a range of flows and between flow exceedence probabilities of 0.5 - 60% (Figure 5.7). Condition factor was found not to be a predictor of success (unpaired *t*-test, t = 1.1758, p = 0.2645). The unsuccessful salmon spent 88 – 2337 hours (mean = 1058 hours or 44 days) between first and last detection at R1. This time includes multiple attempts to move upstream of Woolston weir where a salmon drops downstream of R1 to then moves back in range and upstream out of range or R1. Salmon were in range of R1 between flow exceedence probabilities of 0.5 - 94% (Figure 5.7).

The Ship Canal

Twenty two salmon moved from R2 – R3 and out of the Lower River Mersey 30 times (R2 - R3 movement was used to ensure fish were moving out of the Lower Mersey and not just in range of R3 in the Ship canal).

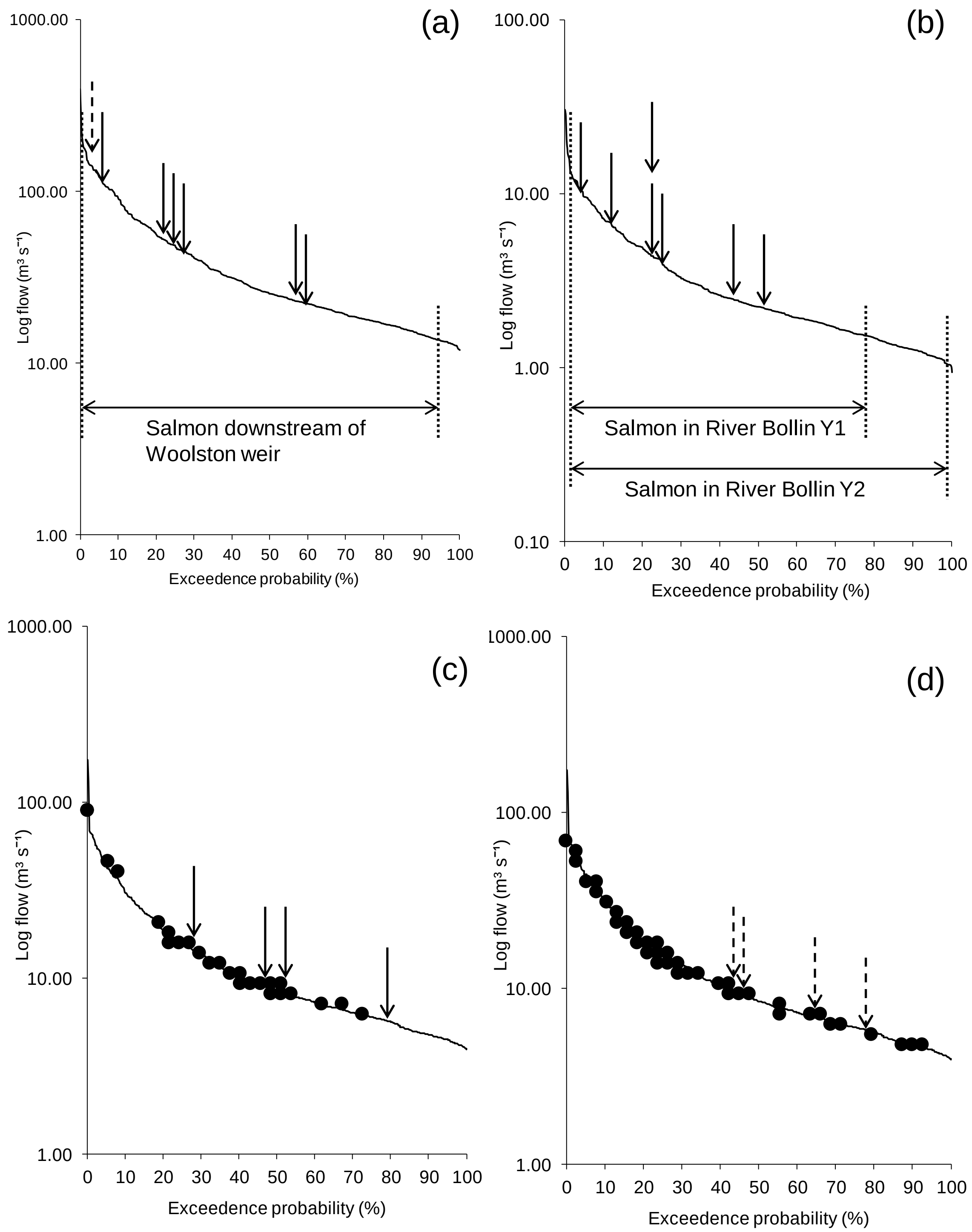


Figure 5.7 Flow duration curves for Rivers (a) Lower Mersey, (b) Bollin, (c) upper Mersey (Year 1) and (d) upper Mersey (Year 2). ↓ denotes Year 1 and ⇣ denotes Year 2 salmon (a) passage of Woolston weir or (b) passage of Heatley weir. Stacked arrows indicate multiple salmon. ● denotes movement between R7 – R8 and R8 – R7.

Three of these initial salmon movements were directly into the River Bollin (see below), twenty one in an upstream direction to R6 and four downstream; one moved to R14 (fish 1508), one downstream of R4 which was later recorded by R1 (fish 3171) and two back downstream to R2. The two fish that moved downstream to R2 (fish 3170 and 3176) later returned to R3 and moved upstream to R6 as did fish 1508 after initially moving downstream to R14. On its second movement into the Ship canal fish 3171 moved directly into the River Bollin (R9) from R3 resulting in five of the 30 movements out of the Lower River Mersey being directly into the River Bollin.

There were 1 – 74 hours (mean = 9) between first and last detection at R3 and R4. This may represent movement back downstream towards R2 from R3 but not coming in range of R2, or holding behaviour in and around the Lower Mersey confluence with the Ship Canal, before then moving in range of R4.

River Bollin

Over the two tracking years, 12 salmon entered the River Bollin (R9), seven in year 1 and five in year 2. Only one salmon entered the River Bollin from an upstream direction (from R4), five directly from the Lower River Mersey (R3) and six moving downstream in the Ship Canal (R6).

Ten salmon entered the River Bollin only once and two each entered twice; one salmon 4 hours between each entry and the other 5 days. Eight of the salmon that entered the River Bollin did so after initially entering the Ship Canal and moving upstream and/or downstream, a number of which made considerable movements in the Ship Canal first. Salmon moved into the River Bollin after 1 and 2638 hours (mean = 730 hours or 30 days) in the receiver network. Salmon entered the River Bollin during a range of flows and appeared not to respond to elevated flows (Figure 5.8) and between flow exceedence probabilities of 5 - 52% (Figure 5.7).

Heatley weir

Seven of the 12 salmon that entered the River Bollin moved upstream of Heatley weir (Figure 5.3) (all year 1 fish) taking between 2 and 86 hours (mean 25) to move the 2320 m from R9 to R10. One of the successful salmon had previously entered the River Bollin but had been in range of R9 for <2 hrs before moving downstream so was unlikely to have had a chance to attempt to move upstream of Heatley weir. As such, all salmon that moved into the River Bollin in year 1 moved upstream of Heatley weir and in range of R10.

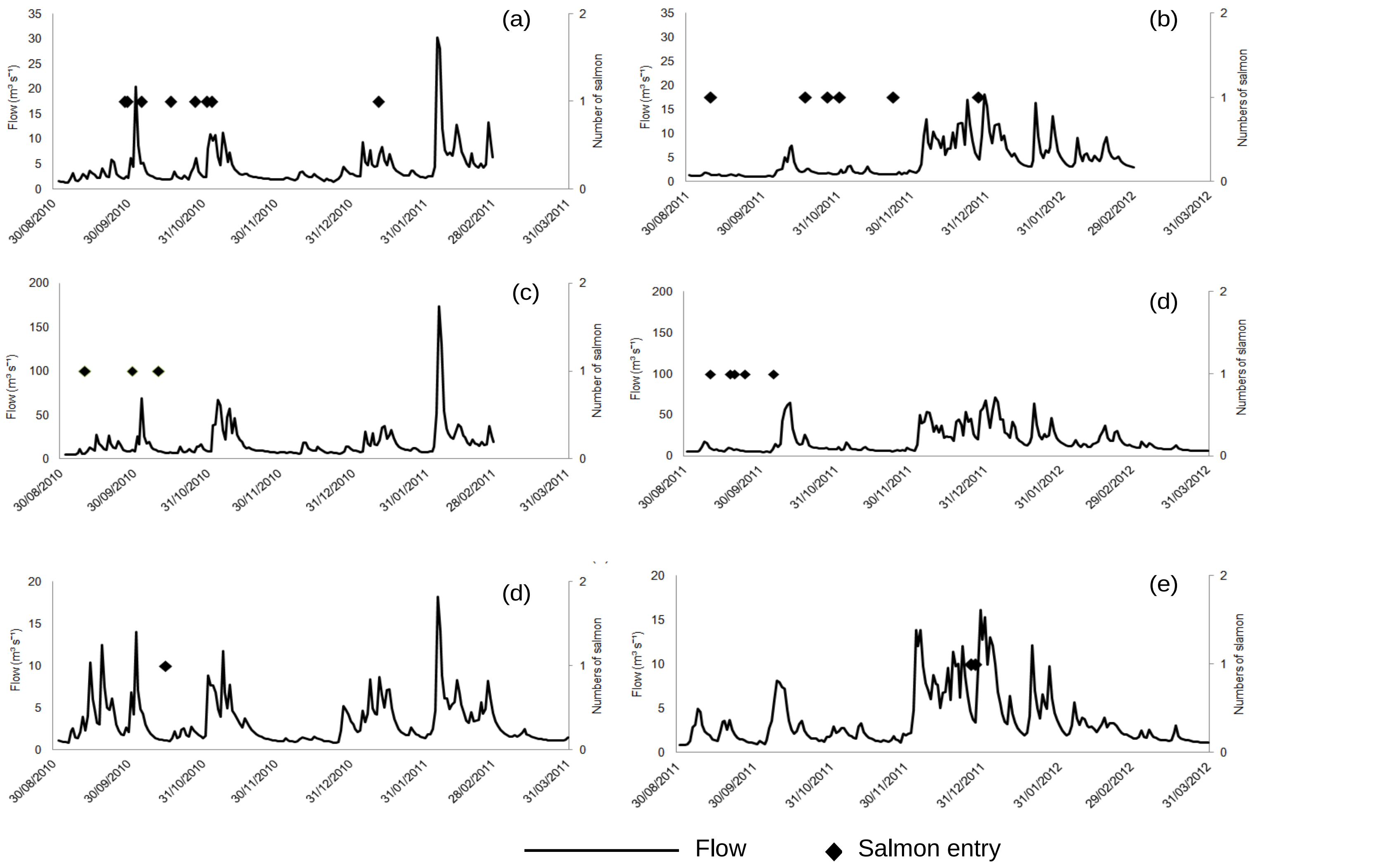


Figure 5.8. Hydrograph and salmon entry in the River (a) Bollin year 1, (b) Bollin year 2, (c) Mersey year 1, (d) Mersey year 2, (e) Glaze year 1 and (f) Glaze year 2.

Owing to the short time between leaving R9 and being recorded by R10 salmon are thought to have used the Heatley fish pass in a range of flows (Figure 5.7 and Figure 5.8).

None of the five fish from year 2 that entered the River Bollin moved upstream of Heatley weir. Of these salmon one spent < 1 minute in range of R9 (time between first and last detection) before moving downstream so did not have the opportunity to attempt using Heatley weir fish pass. Of the other four salmon, three were upstream of R9 for 4, 12, and 104 hours and one entered the River Bollin twice and was upstream of R9 for 7 and 201 hours. These fish were considered to have had the opportunity to attempt to use Heatley weir fish pass.

Condition factor was found not to predict success (unpaired *t*-test, $t = 0.7336$, $p = 0.4800$). Successful fish had been in the receiver network for 9 – 2638 hours (mean = 871 hours or 36 days) and unsuccessful fish had been in the receiver network 5 – 2174 hours (mean = 872 hours or 36 days) before reaching R9.

Little Bollington weir

Of the seven fish in year 1 that moved upstream of Heatley Weir (Figure 5.3), six salmon successfully moved upstream of Little Bollington and in range of R11. The single fish that was not recorded by R11 was in range of R10 for just one 'ping' of the tag (in range of R10 for ~30 seconds). R10 was positioned so the fish only became detectable once the fish had exited the fish pass, the fish would remain in range once upstream of the pass unless it immediately moved downstream of the fish pass exit via the weir or the fish pass. It is assumed that this salmon upon successfully using and exiting Heatley fish pass then immediately moved downstream over the weir.

Salmon took between 4 – 62 hours (mean = 16) to move the 4269 m from R10 to R11. As four salmon took < 5hr to move from R10 to R11, one 18 hours and another 62 hours, salmon are considered to have used the pass in a range of flows (Figure 5.7 and Figure 5.8).

River Mersey

The Upper River Mersey flows over Irlam weir at the point of joining the Ship Canal (Figure 5.1). As such River entry and weir passage are considered as one.

Eight salmon moved upstream of Irlam weir, into the Upper River Mersey and were recorded by R13. Three salmon from year 1 and three salmon from year 2 moved from

R8 to R13 and two salmon (both from year 2) moved from R7 to R13. Salmon took between 5 - 15 hours to move the 3177 m from R7 – R13 and between 2 – 24 hours to move the 3353 m from R8 to R13. Salmon moved into range of R13 after 58 – 283 hours (mean = 141 hours or 5 day) in the receiver network. Salmon entered in a range of flows (Figure 5.8) and between flow exceedence probabilities of 30 - 80% (Figure 5.7).

Sixty movements were made between R7 – R8 by 17 fish; nine fish made 24 movements taking between 13 minutes and 7 hours (mean = 2 hours) in year 1 and eight fish made 36 movements taking between 26 minutes and 114 hours (mean 11 hours) in year 2. Fifty-eight movements were made between R8 and R7 by 16 fish; eight fish made 22 movements taking between 15 minutes and 16 hours (mean = 2 hours) hours in year 1 and eight fish made 36 movements taking between 25 minutes – 169 hours (mean = 11 hours) in year 2. These movements were made between flow exceedence probabilities of 0.5 and 93% (Figure 5.7).

Of the salmon that moved between R7-R8 and R8-R7, condition factor was not found to predict success of moving upstream of Irlam weir and into the Upper River Mersey (unpaired *t*-test, t = 0.1284, p = 0.8993). Although, it should be noted some salmon may have moved upstream of Irlam weir and into the Upper River Mersey but not as far as R13.

River Glaze

Three salmon entered the River Glaze, one in year 1 and two in year 2. Salmon entered the River Glaze <2 days after large flow events (Figure 5.8). However, salmon spent only 2, 18 and 29 hours in the River Glaze (leaving and arriving back in range of R6).

5.5 DISCUSSION

5.5.1 Overview

The hypothesis under examination is that the lower Mersey catchment does not inhibit salmon migration to spawning areas upstream of the Ship Canal. In an attempt to identify what factors may impede or prevent a potential movement upstream and so recolonisation in the lower Mersey catchment key behaviours in the catchment will be reviewed in an upstream order.

The receiver network included 3.5 km of the Lower River Mersey (R1 – R3) (13% of the total 26.8 km receiver network length) and Woolston weir. All 44 tagged salmon had initially successfully located and used Woolston weir fish pass in order to be tagged. Twenty two salmon moved downstream of Woolston weir during the tracking study, 13 of which were considered to have attempted to move back upstream, of which only six (46%) successfully did so. Successful upstream passage of Woolston weir was completed by salmon in a range of flows and the condition factor of salmon was not a significant predictor of passage success. Improvements made to the Woolston weir fish pass in 2004 (section 3.4.2) are known to have reduced the flow through the pass and the attraction flow at the fish pass entrance, which itself is at a 90° angle to the pass, further reduces the attraction flow (EA national fish pass panel, unpublished data & personal communication). Fish passes that are the most effective provide sufficient attraction flows (Trussart *et al*., 2002) and fish passes can become ineffective as a result of reduced flows unable to attract and ensure successful upstream migration (Bjorn & Peery, 1992). The Woolston weir fish pass entrance is 20 m from the cascade over Woolston weir, which may mask the attraction flow or attract fish away from the pass. Banks (1969) reported that salmon will inevitably be influenced by the greater volume and higher velocity of water when travelling upstream. Conversely, Clay (1995) highlighted the importance of the entrances to fish passes being positioned close to the obstruction as possible, stimulating and enabling fish to use the fish pass. The results of this study suggest that not all salmon tagged were able to locate and use Woolston weir fish pass. This was further reflected in the slow progress speed of salmon between R1-R2 and the time spent downstream of Woolston weir, in range of R1 and a significantly higher proportion of time spent approaching or within range of R1 and R2 than other receivers; the latter presumably resulting from salmon being upstream of R1 and attempting to pass Woolston weir.

Salmon (n = 22) appeared to move through the Lower River Mersey (R2 - R3) freely with similar progress speeds to those in the Ship Canal, indeed salmon travelled faster moving upstream from R2 - R3 than downstream. Eight tagged salmon came into range of R2 before moving downstream of Woolston weir. Although the downstream movement was assumed to be in response to the capture and tagging process (see below), this response could be a deliberate movement out of the section of the Lower River Mersey immediately upstream of Woolston weir. The time between the first and last detections at R2 ranged between 30 minutes – 289 hrs (mean = 115 hrs or 5 days) before these salmon dropped downstream of Woolston weir, suggesting at least some of the salmon had sufficient time to recover from tagging and therefore may have actively chosen to leave this section of the Lower River Mersey. Dissolved oxygen saturation was lower upstream than downstream of Woolston weir with mean saturation levels over the year 1 tagging period of 66.7 % (range = 53 – 79%) and 82.2% (range = 67 – 96%) respectively. This might be a factor affecting salmon motivation to migrate upstream or stay in this section of the Lower River Mersey, especially as salmon are known to require suitable dissolved oxygen concentrations to recover from the exhaustive efforts of fish pass use (Tufts *et al.*1990; Katopdis, 1994; Colavecchia, 1998). Furthermore, low concentrations of dissolved oxygen have been documented as a barrier to salmon migration (Alabaster, 1990; Alabaster *et al*., 1991; Elliott & Elliott, 2010; Jonsson & Jonsson, 2011). Priede *et al*. (1988) found salmon avoided certain areas of the River Ribble estuary with less than 55% dissolved oxygen and salmon stopped migrating if they moved into areas below 40% dissolved oxygen and concluded dissolved oxygen levels can influence the probability of salmon straying into rivers. As such dissolved oxygen levels of 53 – 79% saturation may not prevent salmon moving upstream in the Lower River Mersey but may reduce motivation and delay upstream migration.

Salmon passed freely into the Ship Canal during the study; there were five movements directly into River Bollin, 21 upstream and four downstream in the Ship Canal from the Lower River Mersey. Salmon appear to orientate themselves in the directions of flow in the Ship Canal or the flow from the River Bollin and use it as a cue to movement direction. Salmon did not hold in the area surrounding the confluence of the River Bollin, Lower Mersey and Ship Canal (known locally as Bollin point) or spend significantly more time in range of R3 or R4 than any other areas in the receiver network.

Salmon had faster progress speeds in the Ship Canal than any other sections of the receiver network and were able to move freely upstream and downstream and displayed some holding behaviours. The middle section of the Ship Canal was used almost exclusively as a transition area although two fish displayed holding behaviours in this section. There were frequent upstream and downstream movements in the Ship Canal and it was here salmon accrued time spent in the receiver network and displayed erratic behaviours. It is unknown if erratic behaviour resulted from salmon being unable to progress upstream of the Ship Canal or the ability of salmon to progress upstream was decreased by increased erratic behaviours. Studies have documented salmon displaying erratic behaviours in response to barriers to migration (Thorstad *et al*., 2005; Kennedy *et al*., 2013).

Salmon spent significantly more time approaching or in range of R8, representing the upstream limit in the Ship Canal, than any of the other receivers, except R1 and R2.

Salmon have been documented displaying holding behaviours for up to several months during upstream migration (Solomon *et al.*, 1995; Milner *et al.*, 2012) and salmon may have been using this area as a holding area. Avoidance behaviour and refuge seeking and use in salmon in response to unfavourable environmental conditions is well documented (Spoor, 1990; Ytrestoyl *et al.,* 2001; Thorstad *et al.*, 2008; Elliott & Elliott, 2010; Broadmeadow, *et al*., 2010; Moore *et al*., 2012). The confluence with the Upper River Mersey is likely to be better oxygenated than the Ship Canal resulting from the better water quality of the Upper River Mersey (section 3.3.3) and aeration caused by the weir (Figure 5.2). Salmon may have being using this area as a refuge from low dissolved oxygen in the Ship Canal. Salmon may be involuntarily holding in this area as Irlam weir and Irlam locks may prevent salmon moving further upstream. Salmon may have progressed over Irlam weir from R8 but not made it in range of R13, resulting in time spent at R8 being over represented.

Two salmon moved from the Ship Canal (R4 or R14) to R1 without moving downstream in the Lower River Mersey. This is assumed to be salmon moving downstream past Latchford Locks back to the Mersey estuary and back into the receiver networking via R1. There is no evidence this was due to tag failure as no other salmon had a period of being undetected and both salmon could be accounted for within the receiver network for the rest of the time. Latchford locks are operated once a week for commercial reasons and occasionally for a tourist ferry (no dates of operation available; Manchester Ship Canal company, personal communication) and after passing downstream of Latchford locks these salmon would have had to negotiate at least two sets of locks which are operated infrequently and travelled 25 km downstream in the Ship Canal to reach the Mersey estuary and over 25 km up the Mersey estuary and Lower River Mersey to re-enter the receiver network.

Nine fish were last recorded at R4 (year 1, n = 3) or R14 (year 2, n = 6), or 40% of the 22 salmon that moved into the Ship Canal, between 3/11/2010 – 28/12/2010 and 9/10/2011 – 01/01/2012, respectively. The ultimate fate of these salmon were unknown and it was assumed these fish had perished in the downstream section of the Ship Canal. However, the R4/R14 – R1 movement suggested salmon were able to move downstream of Latchford locks and back into the Mersey estuary. The nine salmon may not have perished in the receiver network but have moved downstream out of the Ship Canal and potentially back into the Mersey estuary. This, however, seems unlikely owing to the infrequent operation of Latchford and other locks on the Ship Canal. This has implications for downstream migration of smolts (Chapter 7).

Only three salmon entered the River Glaze and moved in range of R12, all moving back downstream quickly. The River Glaze is a typical lowland river with slow flows, low dissolved oxygen and poor salmonid habitat (Chapter 3; Environment Agency, personal communication). Salmon have specific habitat and flow requirements (Armstrong *et al*., 2003; Chapter 2) and were not expected to enter or use the River Glaze for this reason, and the tracking findings confirmed this prediction.

Seven of the 12 salmon that entered the River Bollin did so only after moving upstream in the Ship Canal and were recorded as approaching and/or in range of R8 for extended periods of time (> 1 week). Only three salmon made direct movements into the River Bollin, one of which moved to R10 and R11. Salmon entered the River Bollin in a range of flows and appeared not to respond to high flow events. Salmon that entered the River Bollin did so after a greater amount of time in the receiver network than those that entered the River Mersey. This may suggest that the River Bollin was difficult to locate by salmon, was less attractive than moving upstream in the Ship Canal or possibly a second choice to the River Mersey or moving upstream in the Ship Canal. Salmon have been reported displaying searching behaviours (Okland *et al*., 2001; Thorstad *et* al., 2008; Kennedy *et al.*, 2013) and salmon may be exhibiting searching and holding behaviours in other areas of the receiver network, specifically the Ship Canal before, moving into the River Bollin.

Keefer *et al*. (2008) reported bypass movements (movement past a river or tributary a salmon ultimately returned to and entered) were more common in lower basin rivers (lower catchments) and went on to suggest homing behaviour was less precise in impounded reaches and large migratory corridors. The lower basin conditions reported by Keefer *et al*. (2008) are similar to those found in the Ship Canal. The authors also suggested bypass movements may be associated with salmon travelling on the opposite side of the river from the tributary and missing olfactory cues. Eiler *et al.* (2015) found salmon bypassed tributaries when in large main stem rivers and suggested that discharge had been obscured by mainstream flow and that salmon were unable to recognise and respond. Flow is an important cue for upstream migration in salmon (Jonsson & Jonsson, 2011; Milner *et al*., 2012), especially to straying salmon lacking olfactory cues (Quinn *et al.*, 1991; Unwin & Quinn, 1993). Salmon may move upstream from the Lower River Mersey in the Ship Canal on the right hand bank (facing downstream) and so not sense the River Bollin flow and only when displaying searching behaviours in the Ship Canal do they later locate and move into the River Bollin. Eiler *et al.* (2015) suggested bypass movements are inadvertent (i.e. the salmon failing to detect environmental cues) since the distance travelled represents an energetic cost that would presumably have negative impact on individual salmon. However, owing to the small distances moved in the lower Mersey catchment this may not be a factor in spawning success of salmon and searching behaviours may be an advantage allowing salmon to eventually locate the River Bollin.

All seven of the salmon that entered the River Bollin in year 1 progressed to R10 and six of these to R11, all of which are thought to have had an opportunity to spawn; three of the six remained upstream, two were upstream from late October / early November until February / March and a single salmon spent 22 days from the 05/02/2011 upstream of R11; interestingly, prior to this, this last salmon recorded 62 days between first and last detection at R8 before moving into the Bollin. This salmon was in and out of range of R8 during this period and may have entered the Upper River Mersey and not progressed to R13, or at least made several attempts to move upstream into the Upper River Mersey. In addition, February is late in the salmon spawning window for North West England (Environment Agency, personal communication) and this fish exhibited some limited searching behaviour after leaving the River Bollin and as such may not have actually spawned. The upstream limit in the River Bollin at the time of this study was Styal weir, 18.9 km upstream of Little Bollington. A fish pass was constructed on Styal weir in 2014 (Chapter 3) and prior to this, salmon moving upstream of Little Bollington would have had access to only limited sub-optimal spawning habitat (Chapter 6).

By contrast, of the five salmon that entered the River Bollin in year 2 none progressed upstream of Heatley weir. The extended periods of time between the first and last detection at R9 before moving into range of another receiver suggest the salmon had moved upstream of R9 and are thought to have had opportunity to use Heatley weir fish pass. Flows and/or condition factor does not appear to influence Heatley fish pass use. Following this result, visual examinations of the passes were made in April 2012 (Heatley and Little Bollington fish passes were constructed in 2009). The passes were found to contain branches and other debris. Both the Heatley and Little Bollington fish pass exits use a floating surface boom to block debris entering the pass. On both fish passes this had become fouled and stuck on its runners, debris and silt had built up over the fish pass exit to such an extent that both fish pass exits were effectively blocked. As a result, flow into the fish passes was reduced and came into the pass over the build up of debris and silt. Reduced flows in fish passes are known to make them ineffective in attracting and ensuring successful upstream migration (Bjorn & Peery, 1992). It is assumed this will have lowered the attraction flow at the fish pass entrance and also rendered the fish pass impassable.

Eighteen of the 22 salmon that moved upstream of R3 moved within range of R8 (19 in range of R7); eight entered the Upper River Mersey, five of which were thought not to have had the opportunity to spawn, either leaving quickly and/or resuming searching behaviour afterwards and three having had opportunity to spawn. Salmon that entered the Upper River Mersey did so after spending relatively little time in the receiver network and after displaying non-erratic behaviour suggesting some salmon are able to locate and move into the Upper River Mersey quickly and directly. Eiler *et al*. (2015) and Hinch & Rand (2000) noted the advantages of energy-efficient optimal behaviour such as these direct movements upstream. However, 10 of the 18 salmon that reached R8 passed within at least 60 m of the Upper River Mersey confluence (the furthest distance from the confluence when moving up or downstream in the Ship Canal) and did not progress to R13. As previously mentioned and similar to the River Bollin, this may be due to the discharge being obscured by mainstream flow and that salmon were unable to recognise and respond (Eiler *et al.*, 2015).

Olfactory cues are widely considered to be the most important cues influencing upstream passage of salmon (Bertmar & Toft, 1969; Troft, 1975; Candy & Beacham, 2000; Keefer *et al.*, 2008; Kennedy *et al*., 2013), and as salmon in the Mersey are strays they may not have moved into the Upper River Mersey in the absence of olfactory cues. Irlam weir may act as a barrier to upstream migration. Several fish showed slow progress speed from R7 and R8 to R13 and the high proportion of time spent approaching or in range of R8 suggest salmon cannot move freely between R7 and R8 to R13. Fish moved in a range of flows and salmon condition factor was not found to predict success of moving into the upper River Mersey. It is also worth noting five of the eight salmon that did enter the Upper River Mersey moved back downstream suggesting the river may not be attractive to straying salmon or barriers to upstream migration exist further upstream. The number of potential obstructions to migration in the Upper River Mersey (section 3.3.3) and the cumulative effect of barriers probably reduce motivation to migrate in salmon (Thorstad *et al*., 2008). Studies have documented salmonids exhibiting short exploratory incursions into rivers before moving back downstream and upstream in another tributary or the main stem river (Okland *et al.*, 2001; Kennedy *et al*., 2013; Eiler *et al*., 2015), and it may be that salmon entering the Upper River Mersey are exploring.

Of the twenty two salmon that moved into the Ship canal six eventually moved back downstream into the Lower River Mersey (five of which moved out of the receiver network) and five salmon stayed upstream of the receiver network; the 11 salmon that remained in the Ship Canal were last picked up by R4 (n = 3), R14 (n = 7) and R7 (n =

1). The 11 salmon last detected in the Ship Canal displayed both up and downstream movement passed the confluence with the Lower Mersey and may have been unable to locate the Lower River Mersey and move downstream. This may have been due to salmon moving downstream in the Ship Canal on the opposite side to the confluence and not sensing the Lower River Mersey, similarly to salmon missing the River Bollin confluence when moving into the Ship Canal. If this was the case this it has implications for the downstream migration of smolts (Chapter 7). Two of the salmon (fish 41810 and 38937) that did move downstream of the Ship Canal into the Lower River Mersey made quick direct movement into the Lower Mersey suggesting salmon are able to locate the Lower Mersey (Figure 5.4). However, the other four salmon (fish 41814, 41816, 3170 and 3177) made up and downstream movements passed the Lower Mersey confluence before moving downstream into the Lower Mersey, again potentially as a result of moving downstream in the Ship Canal on the opposite side to the confluence.

5.5.2 Conclusions

An assumption of tagging studies is that the capture, handling and tagging procedure does not adversely affect the fish or its subsequent movement (i.e. tagged fish behave the same as untagged fish) or any effect is limited and has negligible impact (Eiler *et al*., 2014). During this tagging study ten salmon were considered to have either regurgitated their tags, the tag failed or the fish perished and two salmon made active downstream movements soon after tagging. In addition, one salmon either regurgitated its tag, the tag failed or the fish perished after moving back upstream of Woolston weir after initially moving downstream post tagging. It is unknown if the tagging procedure resulted in these behaviours and/or fates of these salmon. Capture, handling and tagging methods can have a variety of effects on fish from minimal impacts on behaviour through to impaired behaviour or death (Eiler *et al*., 2014). Studies have documented salmon dropping downstream or temporarily delaying their upriver movements and increased mortality rates immediately after tagging (Burger *et al*., 1985; Bernard *et al*., 1999; Bromaghin *et al*., 2007; Eiler *et al.,* 2014).

Eiler *et al.* (2014) indicated that tagged fish that stop moving or die soon after release are easy to identify, whereas impaired movements upriver are more difficult to identify, impaired behaviour therefore resulting from tagging can inaccurately reflect natural behaviour. Similarly, Klimley *et al*. (2013) found that premature electronic tag failure can cause a negative bias in fish survival estimates because tag failure is interpreted as mortality. Regurgitation of tags can also be interpreted as fish loss and regurgitation rates can range from 0.2 – 15% in salmonids (Smith *et al*., 1998; Ramstad & Woody, 2003; Keefer *et al.*, 2004). Eiler *et al*., (2014) noted it is therefore important to assess if and how tagged fish have been affected by tagging, as tagging may affect upriver movement and final destination of salmon. However, it is extremely difficult to compare tagged to non-tagged fish as fine scale movement data can often only be collected from tagging and tracking. In the case of this tracking study no other salmon movement data exist. After reviewing different telemetry techniques, Rivinoja *et al*. (2006) concluded gastric tags were suitable for behavioural studies even in challenging environments like regulated rivers. As such the tagged salmon in this study are assumed to represent movement accurately enough so conclusions can be made.

The hypothesis established for this study has been disproved and it has been found salmon cannot move freely within and upstream of the lower Mersey catchment, with Woolston and Irlam weir and poorly maintained fish passes on the River Bollin all preventing or delaying upstream migration. Barriers to migration have been documented delaying upstream passage (Ovidio & Philippart, 2002; Thorstad *et al*., 2005), causing erratic movement patterns downstream of the obstacle (Thorstad *et al*., 2005; Kennedy *et al*., 2013), reducing motivation to migrate (Thorstad *et al*., 2003) and causing salmon to abandon upstream migration altogether (Croze, 2005). Barriers to upstream migration can lead to exposure to environmental stressors (Thorstad *et al.*, 2008). Environmental stressors, such as low dissolved oxygen and elevated ammonia levels, were found in the Ship Canal, the Lower River Mersey and to an extent the lower Mersey catchment (Chapter 3), the impact of which on salmon have been described in Chapter 2. The results of the tracking study suggest salmon spend long periods of time in the Lower River Mersey and the Ship Canal and if unable to quickly progress upstream salmon display erratic behaviours in the Ship Canal and as a result exposing themselves to environmental stressors. As described in Chapter 2 environmental stressors reduce the fitness, reproductive potential and motivation of salmon. Salmonids will deploy behavioural responses to short term or episodic stress events (Spoor, 1990; Crisp, 1996; Elliott & Elliott, 2010); however, the chronic nature of the issues in the Ship Canal and lack of easily accessible refugia will limit a salmon’s ability to mitigate the impact.

Salmon were found to progress more quickly through the Ship Canal than between R2 - R3 (a stretch of the receiver network free from barriers) and displayed quicker progress speeds moving downstream than upstream. It is not known if the increased progress speeds may be in response to poor conditions and an attempt to seek refuge or to exit the Ship canal. The effects of temperature and dissolved oxygen on swimming speed has been documented (Beamish, 1978; Erkinaro *et al.*, 1999; Karppinen *et al.*, 2004; Solomon and Lightfoot, 2008: Chapter 2), but there is little documented evidence of salmon increasing swimming speeds in response to stressors. Research on swimming speeds in the Ship Canal in conjunction with environmental data would be an interesting subject for further study.

Upstream mean net ground speeds of salmon in rivers range from 0.1 to 45 km d^{-1} (Thorstad *et al*., 1998; Gerlier & Roche, 1998; Okland *et al*., 2001; Karppinen *et al*., 2002; Thorstad *et al*., 2008). Mean upstream progress speeds in this study ranged from 2.8 to 93 km d^{-1} across the two tracking years. The high progress speeds have been skewed by movements between receivers in close proximity of each other, where salmon movement was recorded when moving in / out of range at the limits of a receivers range but the distance a salmon travelled recorded as the actual distance between the receivers, thus giving a false and much exaggerated swimming speed. As such, swimming speed is not been considered further. Further, migration speeds are difficult to compare among studies because of the different methods and techniques employed (Thorstad *et al*., 2008) and fish may not have followed the shortest route or swam with a consistent speed or in consistent water velocity between receivers, over time, within sections of study areas or between studies.

Delays also cause the over-ripening of gonads (Thorstad *et al.*, 2008), and Kennedy *et al*. (2013) suggested a salmon's physiological capability will decrease over time as energy is invested in reproductive development, which may also counteract any increase in motivation to migrate upstream. This is likely an issue in the Mersey when trying to pass complex obstacles such as those in the lower catchment. Successfully passing an obstacle is energetically costly and can cause stress in salmon; Gowans *et al.* (2003) identified rates of metabolism in salmon remained high for prolonged periods of time after passing through a fish ladder and suggested this would reduce the amount of energy available for further migration, spawning activity and gonad production. Mathers *et al*. (2002) reported negotiating a barrier could increase stress in fish. Both acute and chronic stress has been documented causing sub-optimal behaviour, reduction in fitness and immunosuppresion in salmonids (Jacobson *et al*., 2003; Quigley & Hinch, 2006; Cooke *et al*., 2006; McConnachie *et al*., 2012). Budy *et al*., (2002) speculated that the cumulative effects of stress may be delayed for some time. The findings of this study suggest the lower Mersey catchment will potentially serve to elevate levels of stress in salmon and so potentially reduce spawning potential, ultimately impeding recolonisation processes.

Thirty two salmon had active tags and displayed active or attempted movements upstream. Only nine were thought to have had opportunity to spawn. It has been demonstrated that barriers to migration have prevented many salmon moving upstream and a reduction in the fitness and/or motivation resulting from cumulative stress may have compounded this and also prevented those salmon that did progress upstream reaching spawning grounds. The capture and tagging process may have also increased stress and so the eventual success of the salmon used in this study. Eiler *et al.* (2014) suggested that fish may experience latent or sub-lethal tagging effects and presumably exhibit impaired movements and reduced vitality as they move upriver. It may be that this, combined with the complex nature of the catchment and environmental stressors, could reduce optimal behaviour and ultimately reproductive success of the tagged salmon.

Flow is known to play an influential role in the upstream movement of salmon and movement past physical barriers (Chapter 2). However, no flow requirements or flow-related responses to specific flows when entering the River Bollin, Glaze and Upper River Mersey, or when passing upstream of a barrier were found in this study. However, this is based on very few fish and it worthy of further investigation, especially behaviour downstream of and in response to flow around key barriers such as Woolston and Irlam weirs.

The distribution of receivers during this tracking study allowed key behaviours and route choice in and out of the lower Mersey catchment to be discerned. However, receivers were too close together to estimate distance travelled by each salmon accurately nor were they focussed around key points such as Woolston, Irlam, Heatley or Little Bollington weirs to distinguish unsuccessful and successful attempts to move upstream. A future tracking study focussing on these issues would be better able to identify optimal and sub-optimal behaviours of salmon and better suggest management actions to improve passage upstream of these barriers. Further to this, a wider array of receivers extending into the upper catchment would identify behaviours, potential barriers and better identify the success and fate of salmon and is recommended for further study.

5.5.3 Summary

1. Weirs in the lower Mersey catchment inhibit upstream movement of salmon with <50 % of salmon that attempted to move upstream of Woolston weir able to do so: no salmon were able to move upstream in the River Bollin in year 2 because of poor fish pass maintenance and potentially <40% of salmon that had opportunity to

do so moved upstream of Irlam weir. However, 100% of salmon could locate and use the River Bollin fish passes in year 1 demonstrating the potential for fish passes to mitigate the barrier effect of weirs.

2. Salmon spend significantly more of their time in the Lower River Mersey as a result of the barrier effect of Woolston weir and/or in the upstream section of the Ship Canal. Salmon are more exposed to environmental stressors in the Lower River Mersey and the Ship Canal and display erratic behaviours in the Ship Canal in response to not being able to move upstream.

3. Salmon can locate and move upstream in both the River Bollin and Upper River Mersey. However, only nine salmon are thought to have had an opportunity to spawn, with barriers, sub-optimal behaviours and cumulative effects of stress all thought to affect salmon fitness, motivation and their likelihood of moving upstream and spawning successfully.

4. Of the salmon that moved upstream of the receiver network, those that entered the River Bollin were more likely to have an opportunity to spawn, if they are able to locate spawning grounds, than those entering the Upper River Mersey. Salmon appear to locate the River Bollin after a period of searching behaviour in the Ship Canal.

Chapter 6 will build on the findings of the tracking study and identify and describe the location, quality and accessibility of juvenile habitats and spawning habitats to migrating adult salmon.

6 JUVENILE SALMON HABITAT QUALITY AND ACCESSIBILITY IN THE MERSEY CATCHMENT

6.1 INTRODUCTION

The habitat requirements of salmon are well documented (Chapter 2) with suitable river depth, current, substrate and cover the features most important to the distribution and abundance of salmonids (Armstrong *et al*., 2003). Adult salmon spawn in areas with specific sedimentary and hydraulic conditions, selecting sites for spawning where depths and velocities can ease the process of redd cutting (Moir *et al.,* 2012). The survival of salmon eggs is in turn dependent on the substrate composition (Chapman,

1988) and a sufficient supply of dissolved oxygen percolating through the redds (Chapman, 1988; Solbé, 1997). The total area and distribution of suitable spawning gravel is of fundamental importance in determining the productivity of a river and may limit salmon productivity in many streams (Kondolf & Wolman, 1993; Armstrong *et al.*, 2003).

Spawning and juvenile salmon habitats are commonly found in landscapes with a high degree of anthropogenic impact, putting the specific habitat requirements under stress (Parrish *et al*., 1998; Owens *et al*., 2005; Finstad *et al*., 2007). Fine sediment impacts negatively on salmonid reproductive success and result from deforestation, agriculture, construction and mining (Kondolf, 2000; Ferreira *et al*., 2010). Sedimentation can result in clogging of gravels, which can affect salmonid spawning habitat by reducing the flow of oxygenated water to fish eggs and therefore can reduce the survival of salmonid eggs (Chapman, 1988; Kondolf, 2000; Pawson, 2008). Other potential anthropogenic impacts include: reduction in riparian shade negatively affecting stream water temperatures (Broadmeadow *et al.,* 2010); low summer flow conditions resulting in reduced habitat availability, especially in regulated rivers (Riley *et al.,* 2009; Clews *et al.,* 2010); impoundments and physical alterations within channel and to whole river systems (Williams & Wolman, 1984; Vericat *et al*., 2006; Malcolm *et al.*, 2012); alteration to flow regime and floodplain connectivity (Cowx, 2002); poor livestock management practices resulting in loss of bank habitat and sedimentation (Couper & Maddock, 2001); poor water quality and pollution (Bendall *et al*., 2012); and deforestation leading to sedimentation (Eros, 2012). Many of these factors have already been shown to be impacting the Mersey catchment (Chapters 3 and 5). However, despite these anthropogenic disturbances, adult salmon are able to enter the upper reaches of the Mersey catchment and spawn (Chapters 3 and 5). It is unknown if habitat accessibility, availability and quality are functioning as limiting factors, which could hinder or prevent a successful recolonisation in the Mersey catchment.

This chapter identifies and describe the location, quality and accessibility of juvenile habitats and spawning habitats to migrating adult salmon and potential factors affecting juvenile salmonid habitat quality. The following hypothesis was tested to investigate if access to and the quality of spawning and juvenile habitats are acting as limiting factors: habitat availability, accessibility and quality is not a limiting factor in the Mersey catchment and would not inhibit the survival or growth of juvenile salmon.

6.2 METHODS

6.2.1 Study area

This investigation focused on the rivers Goyt, Tame, Etherow, Bollin and Dean and some of their tributaries, as these rivers are thought to be the most suitable for and also most accessible or partially accessible to salmon (Figure 3.1) (Chapter 3 and 5). The rivers above Irlam locks were not reviewed as these are and are likely to remain inaccessible to adult salmon due to locks in the Ship Canal (Chapter 3 and 5). No assessment of habitat in the upper or lower River Mersey, the River Glaze and the Manchester Ship Canal was made as these are typical lowland rivers with no suitable spawning and very limited fry habitat (personal communication, Environment Agency; Chapter 3).

6.2.2 Habitat type, distribution, and quality

HABSCORE

HABSCORE is a system for measuring and evaluating stream salmonid habitat features based on empirical statistical models relating the population size of five salmonid species and age combinations (0+ salmon, >0+ salmon, 0+ trout, >0+ trout (<20cm), >0+ trout (>20cm)) (Wyatt *et al*., 1995). HABSCORE uses habitat data, river catchment information and fisheries information, which are entered into the HABSCORE for Windows program. The software produces estimates of the expected population and degree of habitat utilization for each site surveyed for each species and age combination, specifically (definitions from Wyatt *et al.*, (1995)):

Habitat Quality Score (HQS)

The HQS is derived from habitat and catchment features and is a measure of the habitat quality, expressed as the expected long-term average density of fish (in no./100 m^2) and assumes that neither water quality nor recruitment limit the populations. The HQS is used as an indicator of the potential of the site, against which the observed size of populations may be compared.

HQS lower and upper confidence limits

These are the lower and upper 90% confidence limits for the HQS, in no./100 m^2. The confidence limits given should enclose the average observed density for a site on 90% of occasions.

Habitat Utilisation Index (HUI)

HUI is a measure of the extent to which the habitat is utilized by salmonids based on the observed density measured during fisheries surveys and that which would be expected under 'pristine' conditions (where water quality and other environmental conditions or recruitment is not limiting population density) predicted by HQS. When the 'observed' density and the HQS are identical, the HUI takes the value of one; HUI values less than one will occur when the observed densities are less than expected.

HUI lower and upper confidence limits

These are the upper and lower 90% confidence limits for the HUI, expressed as a proportion. An upper HUI confidence interval <1 indicates that the observed population was significantly less than would be expected under pristine conditions. Conversely, a lower HUI confidence interval >1 indicates that the observed population was significantly higher than would normally be expected under pristine conditions.

The salmonid population estimates produced by HABSCORE are based on habitat and catchment information only; HABSCORE presumes recruitment and water quality and other environmental factors are not limiting. HABSCORE habitat surveys were undertaken in 2007 (n = 16), 2008 (n = 5), and 2014 (n = 10) across 20 sites (Figure 6.1). Annual fish survey data over a number of years for each site were used where possible; this improves the HABSCORE outputs by taking into account some of the observed temporal variability of the trout populations at each site.

Fisheries information for each site included the estimated population size calculated using the catch removal method (Carle & Strub, 1979) (observed) and a variance (standard error^2) for each of the five salmonid species / age combinations. The EA's National Fisheries Population Database (NFPD) was interrogated to provide the observed data and the variance was generated using the EA's 'Hab-score calculator' model which uses the numbers of salmon, or brown trout, caught on each run of a catch depletion survey to produce a variance (Environment Agency, unpublished). When entering the catchment data into the HABSCORE for Windows program 'always accessible' was selected as the 'migratory access' option for salmon. This was done so the estimates of the expected population were based on habitat only and not affected by the accessibility of sites, which has already been shown to potentially prevent adult salmon migration in the Mersey catchment (Chapter 3 and 5).

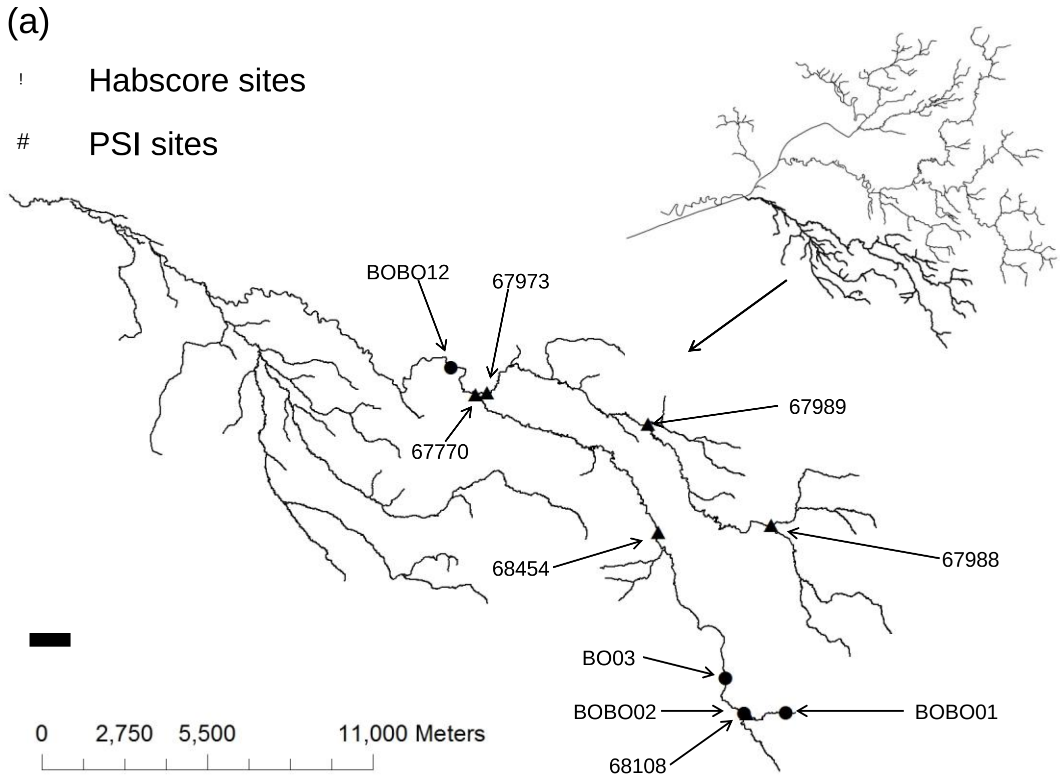


Figure 6.1 HABSCORE and PSI sites in the rivers (a) Bollin and Dean and (b) the Goyt, Tame, Etherow, Sett and Chew and Black Brooks.

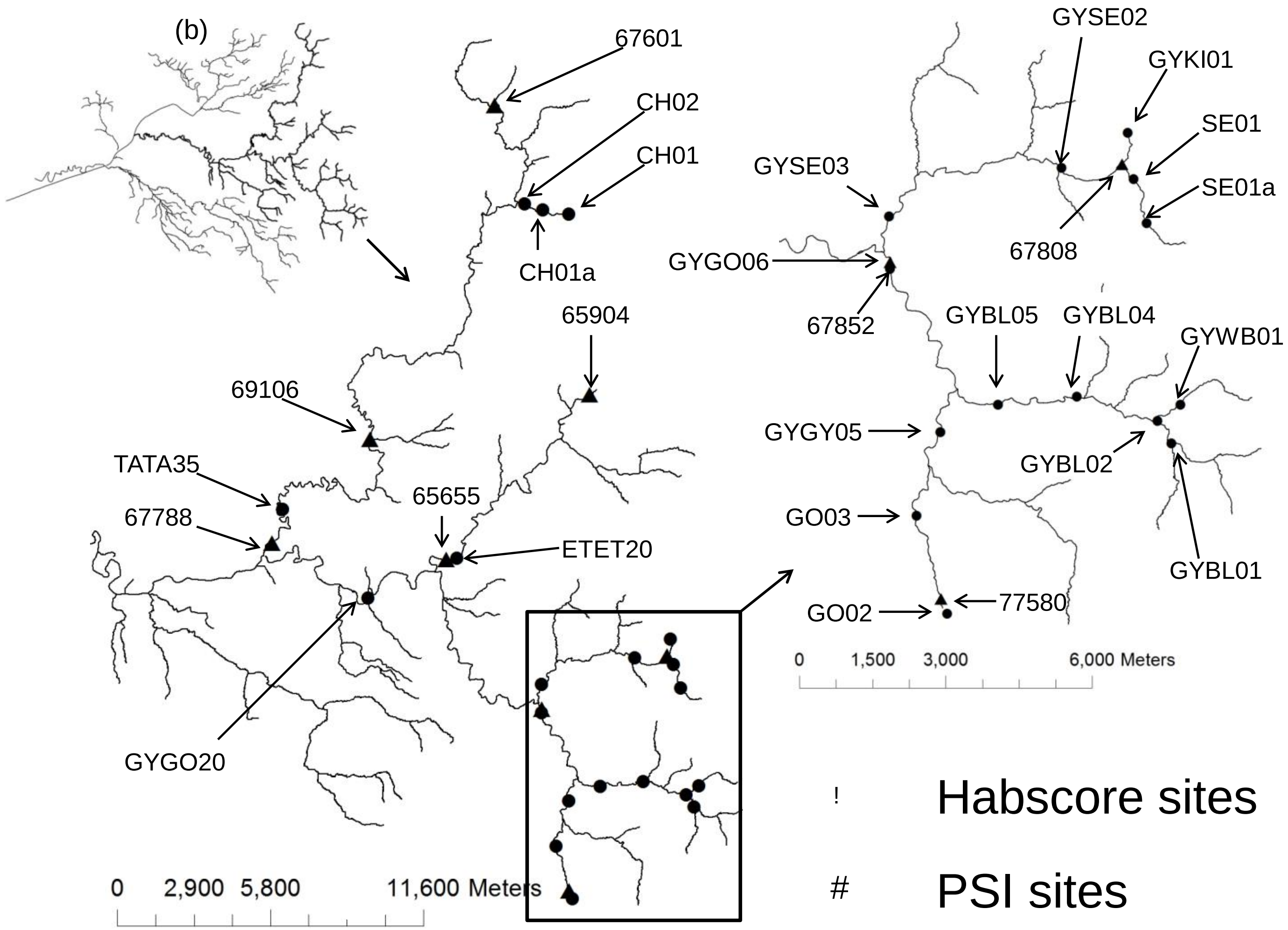


Figure 6.1 (continued) HABSCORE and PSI sites in rivers (a) Bollin and Dean and (b) the Goyt, Tame, Etherow, Sett and Chew and Black Brooks.

Walkover Surveys

The walkover surveys undertaken by APEM Ltd (section 3.3.2) identified type, distribution and relative proportions of different salmonid habitats in the rivers Bollin, Goyt and Tame and their main tributaries in 2004, 2006 and 2008, respectively. All walkover surveys were undertaken under Q90 flow conditions. The methodology for the walkover survey followed that outlined in the EA's Fisheries Technical Manual 4 "Restoration of Riverine Salmon Habitats" (Hendry & Cragg-Hine, 1997). Habitat was classed as one of six types: spawning, fry (0+), parr (>1+), riffles, glides or pools and recorded in GIS. Spawning, fry and parr habitat data (Table 6.1) were collated, tabulated and mapped. Walkover surveys of the rivers Bollin and Dean also recorded spawning habitat as sub-optimal spawning habitat where the surveyor deemed significant sedimentation had occurred.

Proportion of sediment-sensitive invertebrates

Several practical issues exist in assessing fine sediment deposition (Extence *et al*., 2011). The proportion of sediment-sensitive invertebrates (PSI) metric, which describes the degree to which river beds are composed of, or covered by fine sediments (< 2mm in size) (Extence *et al*., 2011; Glendell *et al.*, 2013), was used to describe river bed sedimentation. PSI quantifies the proportion of fine sediment-sensitive macro-invertebrates versus sediment insensitive taxa in an invertebrate survey sample (Extence *et al*., 2011). PSI does not describe how impacted the river bed is by anthropogenic sediment inputs, only its current sediment condition, which may be its natural state.

Table 6.1 Habitat classification system used by to describe salmon habitat type (after Dennis & Campbell, 2008).

Habitat Type	Description
Spawning Gravel	Ideally stable but not compacted, with a mean grain size 25 mm or less for trout, but up to 80 mm for salmon. 'Fines' (< 2 mm grain size) to be less than 20% by weight.
Fry (0+) habitat	Shallow, < 20 cm deep, fast flowing (> 30 cm s^{-1}), with surface turbulence and a gravel and cobble substrate.
Parr (>1+) habitat	20 - 30 cm deep, fast flowing (>30 cm/s), surface turbulent, with gravel/cobble/boulder substrate.

Since 1990 the EA has delivered an annual invertebrate sampling programme across all rivers in the study area, however, due to weather conditions, changes in EA policy and resource constraints survey location and sampling frequency have been inconsistent. After each survey invertebrates were identified to family or species level, and their numbers estimated and recorded on the EA's biological data database BIOSYS (see Anon 2009a and 2009b for survey and data management methodology). BIOSYS generates the indices Biological Monitoring Working Party score (BMWP) to assess organic enrichment (Armitage *et al*., 1983) and a Lotic Invertebrate Stress Evaluation score (LIFE) to assess flow pressure (Anon, 2012c) impacts on invertebrates. These scores, along with the abundance scores of 302 invertebrate families, are used to generate a PSI score using the EA's 'PSI calculator' (Environment Agency, unpublished), which uses a matrix and formula described by Extence *et al*.(2011). The matrix assigns one of four Fine Sediment Sensitivity Ratings (A-D) to each of the 302 invertebrate families present in a sample. The PSI index is calculated as the ratio of the sum of ratings allocated to the most sensitive groups A+B to the total sum of ratings (Extence et *al*., 2011). PSI scores range from 0 (entirely silted river bed) to 100 (entirely silt-free river bed) (Table 6.2). BIOSYS was interrogated and a PSI scores generated for a selection of invertebrate surveys providing representative spatial and temporal cover for each of the rivers in this study (Figure 6.1).

Table 6.2 Interpretation of PSI scores (taken from Extence *et al*., 2011; Anon, 2012c).

PSI Score	River bed condition
81 - 100	Minimally Sedimented / unsedimented
61 - 80	Slightly sedimented
41 - 60	Moderately sedimented
21 - 40	Sedimented
0 - 20	Heavily sedimented

6.2.3 Fisheries data

Brown trout densities

Between 1993 and 2013, the EA delivered an annual electro-fishing survey programme throughout the study area but due to weather conditions, changing policy and resource constraints coverage was inconsistent. Electro-fishing involves a survey team fishing in an upstream direction and a bank supervisor operating the fishing equipment, which consists of a 2kVA generator with an Electrocatch control box producing a 220 v PDC output (www.electrocatch.com). All sites were isolated by upstream and downstream stop-nets to ensure no fish escaped from, or migrated into, the sample area to allow an estimate of numbers of fish present. Fish were identified to species and the fork length measured (mm). Sites were either quantitative survey sites involving multiple independent fishing runs within the netted off area or semi-quantitative surveys involving a single fishing run. Quantitative surveys were used to generate estimates of absolute abundance (density (no./100 m²)) based on a three-catch removal method (Carle & Strub, 1979).

Density estimates for brown trout derived from the removal method (Carle & Strub, 1979) were generated using the EA's National Fish Population Database (NFPD) for fish survey sites on the Rivers Bollin, Goyt, Etherow and Tame and some of their tributaries (Figure 6.2). Actual brown trout density was used for semi-quantitative surveys as a minimum density estimate. The status of brown trout fish populations was assed using the EA's Fisheries Classification Scheme matrix (EA-FCS) (Table 6.3). The EA-FCS was developed to allow comparison of juvenile salmonid monitoring data with a juvenile database derived from over 600 survey sites in England and Wales (Mainstone *et al.,* 1994). The EA-FCS grading scheme is translated as follows: Grade A (excellent), Grade B (good), Grade C (fair or average), Grade D (fair/poor), Grade E (poor) and Grade F (fishless). Fish were assigned to either 0+ and ≥1+ age group (see section below for methodology).

Table 6.3 Salmonid abundance (n 100 m²). classification used in the EA Fisheries Classification Scheme (EA-FCS). Colours are assigned for clarity in subsequent data analysis.

	Abundance classification					
Species group	A	B	C	D	E	F
0+ brown trout	>38.0	17.0-37.9	8.0-16.9	3.0-7.9	0.1-2.9	0
≥1+ brown trout	>21.0	12.0-20.9	5.0-11.9	2.0-4.9	0.1-1.9	0
0+ salmon	>86.0	45.0-85.9	23.0-44.9	9.0-22.9	0.1-8.9	0
≥1+ salmon	>19.0	10.0-18.9	5.0-9.9	3.0-4.9	0.1-2.9	0

Brown trout growth rates and length frequency distributions

Salmonid growth is sensitive to environmental perturbations and measurements of growth rate can often be used to provide an index of population performance (Elliott & Hurley, 1997).

(a)

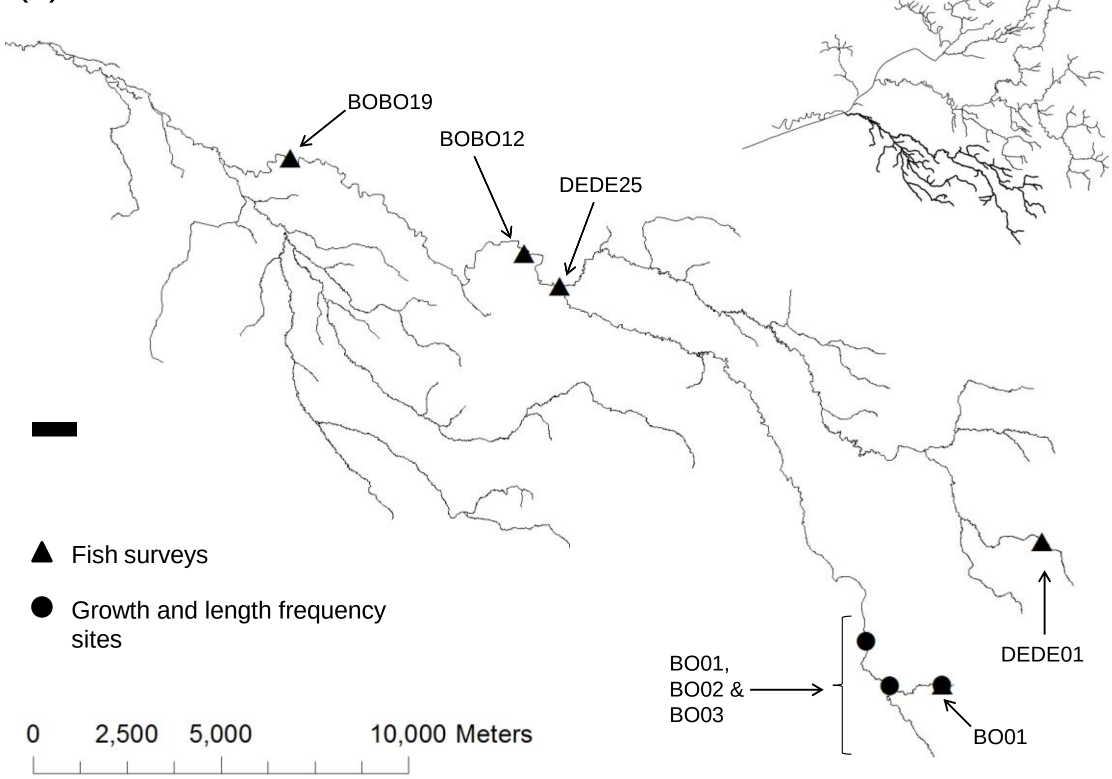


Figure 6.2 Fish survey sites and sites from which growth and length frequency data was generated from the rivers (a) Bollin and Dean and (b) the Goyt, Etherow, Tame, Sett and Chew and Black Brooks. Note the fish survey site BO01 is the same site as HABSCORE site BOBO01.

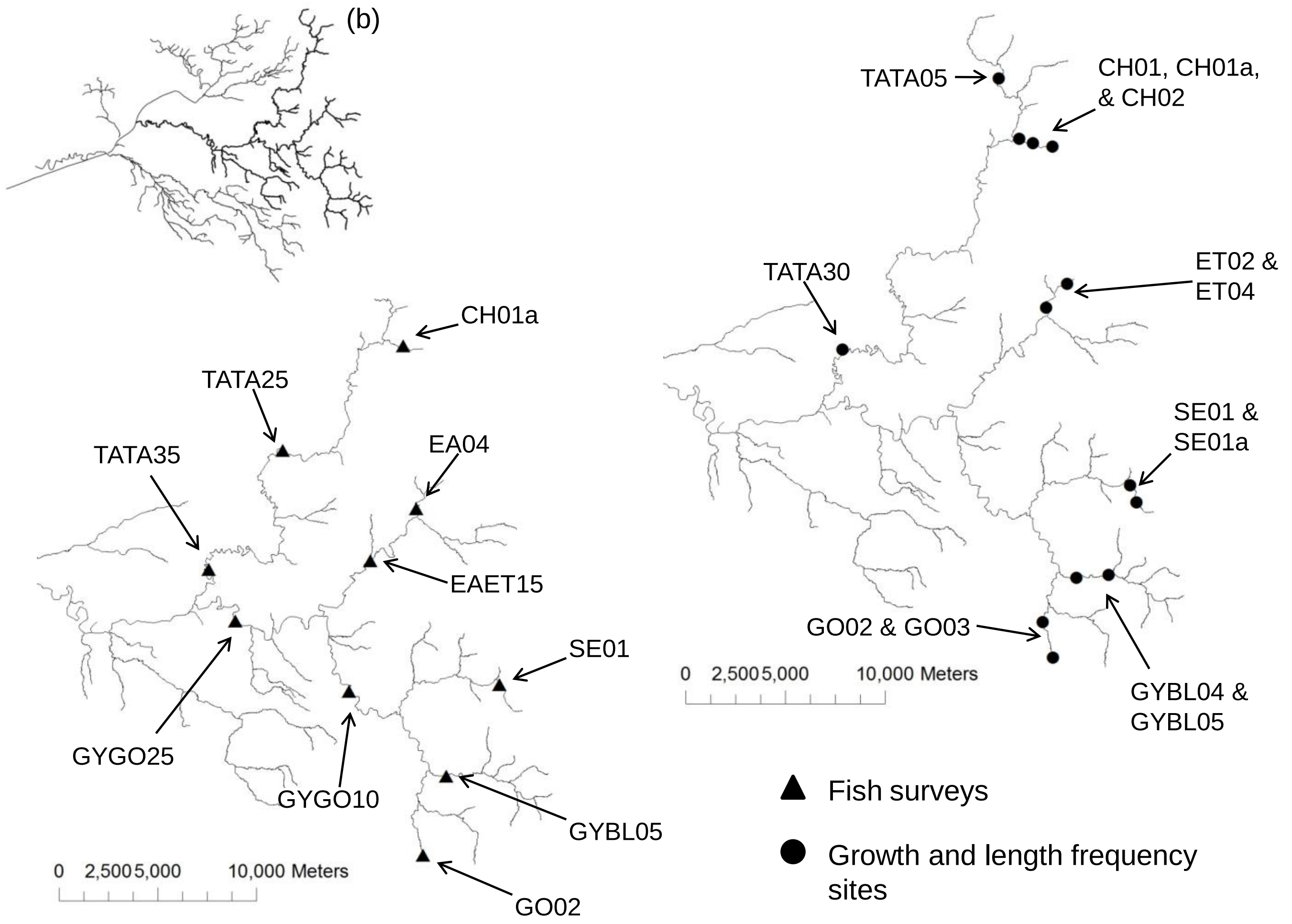


Figure 6.2 (continued) Fish survey sites and sites from which growth and length frequency data was generated from the rivers (a) Bollin and Dean and (b) the Goyt, Etherow, Tame, Sett and Chew and Black Brooks.

As such, in the absence of juvenile salmon populations (section 3.4.2) and as brown trout and salmon share similar habitats and have similar physiochemical requirements (section 2.2.8), brown trout catch data were reviewed to illustrate potential juvenile salmon performance.

The age and growth of brown trout at a number of sites on the rivers Bollin, Goyt, Etherow and Tame were determined by the interpretation and counting of annual growth checks (annuli) that appear on the scales of the fish (Bagenal & Tesch, 1978). Annuli are formed during periods of little or no growth generally occurring during the winter months in temperate regions. The EA has delivered an annual electrofishing programme which includes the aging of individual fish caught during electrofishing surveys since 1993. Several scales were carefully removed from each individual fish for ageing analysis during a survey; sub-sampling a representative size range of fish was carried out if large numbers of scale samples were collected during a survey (as described in Britton, 2003). Scales were then sent to and examined by the EA national fisheries laboratory fish aging team under a microfiche projector and the fish aged by counting the number of annuli. The length at age was calculated from the scale radius to each annuli at each age using the Dahl-Lea method, Francis (1990) (equation 2).

$$Li = (Si/Sc) \times Lc \qquad \text{(Eq. 2)}$$

where, *Li* is the length (mm) at year 1, *Si* is scale radius at length *Li*, *Lc* the length at capture and *Sc* the scale radius at capture. This calculation was repeated for each fish and the mean length for each age from all the fish was calculated and plotted as a growth rate. Age and growth rate determination of brown trout were undertaken at the request of the EA North West fisheries survey team at a limited number of sites for a range of local interest reasons across the study area since 1993. All available age and growth rate data were requested from the EA national fisheries laboratory and reviewed. Where appropriate, sites that were in close proximity that had age data over a number of years were grouped.

The last three years of age and length data available at each site/site grouping were used to generate growth plots and a percentage standard growth (PSG) curve for brown trout at representative sites on the Rivers Bollin, Goyt, Tame and Sett and the Chew and Black Brook (Figure 6.2). PSG describes the growth rate as a percentage of the national average (Environment Agency, unpublished data), where the national average is 100% and were produced using the EA 'Ageing Workbook' excel worksheet (EA, unpublished data). Additionally length frequency distribution graphs were constructed for brown trout from these sites. This involved assigning fish into 10 mm fork length classes to determine the total number of fish in each size class.

6.3 RESULTS

The results section is divided into the sub-catchments 'Bollin' containing the rivers Bollin and Dean and the 'Upper Mersey' containing the rivers Goyt, Tame, Etherow Sett and Black and Chew Brooks. All survey sites use EA identifiers as recorded in their respective databases.

6.3.1 Bollin sub-catchment

HABSCORE surveys

Eight HABSCORE surveys were carried out at four sites in 2007, 2008 and 2014 (Figure 6.1). HABSCORE data indicated that 0+ and >0+ salmon densities were significantly lower (HUI upper C.L. <1) at all sites than predicted from the Habitat Quality Score (HQS) (Table 6.4). HQS predicted a range of 0+ salmon densities of 23.98 – 29.03 salmon/100 m² under pristine conditions (EA FCS class C) at sites BOBO01 and BO03 in all years surveyed. At the other upstream site, BOBO02, the HQS predicted potential densities of 7.9 – 13.5 0+ salmon/100 m², classes E - D, while at site BOBO12, just downstream of the River Dean confluence, the HQS predicted a potential density of 18.7 0+ salmon/100 m², class D (Table 6.4). The HQS at BOBO12 revealed potential densities of 2.77 >0+ salmon/100 m² (class E) and the other upstream sites ranged from 3.5 – 6.7 >0+ salmon/100 m² (classes D - C). No HABSCORE surveys were carried out on the River Dean due to resource limitations.

HABSCORE outputs revealed variations in the observed density, predicted density (HQS) and habitat utilization (HUI) in 0+. >0+ (<20 cm) and >0+ (>20 cm) brown trout across the Bollin sites (Table 6.5). The predicted densities of 0+ trout at the three upstream sites, BOBO01, BOBO02 and BO03 ranged from 6.73 – 16.53 0+ trout/100 m² (class D – C). Observed 0+ trout densities at site BO02 were higher than the predicted densities producing HUI vales of 1.22 in 2007 and 1.66 2014. All other surveys at all sites and the 2008 survey at BO02 found 0+ trout densities less than that predicted form the HQS, of which the 2007 survey at site BOBO01, the 2008 survey at site BO03 and the 2014 survey at site BOBO12 were significantly lower (HUI upper C.L. <1) (Table 6.5). Observed densities of >0+ (<20 cm) trout at five of the eight surveys on the Bollin were greater than that predicted by HQS, although none were significantly greater (Table 6.5).

Table 6.4 HABSCORE outputs for 0+ and >0+ salmon for HABSCORE surveys on the River Bollin (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
0+									
BOBO01	30/01/2007	0	0.00	28.97	8.71	96.38	0.02	0.00	0.13
BOBO01	09/09/2014	0	0.00	27.21	8.69	85.25	0.02	0.00	0.13
BOBO02	30/01/2007	0	0.00	7.97	2.65	23.97	0.03	0.00	0.23
BOBO02	26/11/2008	0	0.00	8.30	2.65	26.04	0.03	0.00	0.22
BOBO02	09/09/2014	0	0.00	13.45	4.15	43.62	0.02	0.00	0.16
BO03	26/11/2008	0	0.00	29.03	9.36	90.01	0.02	0.00	0.15
BO03	09/09/2014	0	0.00	23.98	7.29	78.84	0.02	0.00	0.16
BOBO12	09/09/2014	0	0.00	18.67	5.74	60.76	0.01	0.00	0.04
>0+									
BOBO01	30/01/2007	0	0.00	4.39	1.34	14.41	0.12	0.02	0.72
BOBO01	09/09/2014	0	0.00	6.49	2.03	20.69	0.08	0.01	0.45
BOBO02	30/01/2007	0	0.00	3.54	1.11	11.35	0.07	0.01	0.45
BOBO02	26/11/2008	0	0.00	3.65	1.10	12.12	0.07	0.01	0.44
BOBO02	09/09/2014	0	0.00	4.51	1.40	14.58	0.07	0.01	0.40
BO03	26/11/2008	0	0.00	4.19	1.28	13.66	0.15	0.02	0.91
BO03	09/09/2014	0	0.00	6.72	2.09	21.53	0.08	0.01	0.48
BOBO12	09/09/2014	1	0.10	2.77	0.81	9.40	0.04	0.01	0.25

Table 6.5 HABSCORE outputs for 0+, >0+ (<20 cm) and >0+ (>20 cm) brown trout for HABSCORE surveys on the River Bollin (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) and shaded cells (HUI lower C.L. column; green) represent sites where the observed population was significantly greater (HUI lower C.L. >1 than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
0+									
BOBO01	30/01/2007	4.3	2.22	16.56	4.47	61.40	0.13	0.02	0.90
BOBO01	09/09/2014	12.7	6.18	14.92	3.96	56.17	0.41	0.06	2.75
BOBO02	30/01/2007	44.7	11.71	9.59	2.58	35.63	1.22	0.19	8.03
BOBO02	26/11/2008	17.6	4.59	7.46	1.98	28.05	0.61	0.09	4.08
BOBO02	09/09/2014	37.5	11.18	6.73	1.77	25.54	1.66	0.25	11.10
BO03	26/11/2008	2.4	1.50	10.40	2.70	40.08	0.14	0.02	0.98
BO03	09/09/2014	6.9	3.68	8.53	2.26	32.24	0.43	0.06	2.89
BOBO12	09/09/2014	1.0	0.10	1.95	0.50	7.52	0.05	0.01	0.34
>0+ (<20 cm)									
BOBO01	30/01/2007	25.2	13.00	5.49	1.21	24.80	2.37	0.38	14.93
BOBO01	09/09/2014	27.8	16.57	9.40	2.20	40.13	1.40	0.24	8.71
BOBO02	30/01/2007	22.4	5.88	2.86	0.65	12.54	2.06	0.34	12.62
BOBO02	26/11/2008	29.5	7.68	8.13	1.95	33.93	0.95	0.16	5.60
BOBO02	09/09/2014	38.1	11.36	2.13	0.51	8.94	5.34	0.89	31.83
BO03	26/11/2008	8.4	5.23	10.23	2.42	43.32	0.51	0.09	3.04
BO03	09/09/2014	12.6	6.72	3.95	0.93	16.70	1.70	0.29	10.12
BOBO12	09/09/2014	1.4	0.14	0.77	0.18	3.37	0.18	0.03	1.11

Table 6.5 (continued) HABSCORE outputs for 0+, >0+ (<20 cm) and >0+ (>20 cm) brown trout for HABSCORE surveys on the River Bollin (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) and shaded cells (HUI lower C.L. column; green) represent sites where the observed population was significantly greater (HUI lower C.L. >1 than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
>0+ (>20 cm)									
BOBO01	30/01/2007	1.8	0.94	1.55	0.49	4.92	0.60	0.19	1.91
BOBO01	09/09/2014	2.3	1.12	0.74	0.23	2.34	1.52	0.48	4.83
BOBO02	30/01/2007	7.3	1.91	2.53	0.83	7.75	0.75	0.25	2.30
BOBO02	26/11/2008	7.0	1.82	2.19	0.73	6.63	0.83	0.26	2.71
BOBO02	09/09/2014	6.0	1.79	3.05	0.93	9.97	0.59	0.18	1.95
BO03	26/11/2008	3.9	2.44	2.48	0.82	7.45	0.99	0.33	2.96
BO03	09/09/2014	1.7	0.92	2.06	0.65	6.57	0.45	0.14	1.42
BOBO12	09/09/2014	2.8	0.28	1.51	0.47	4.83	0.19	0.06	0.59

One survey in 2014 at site BOBO01 revealed observed densities of 1.12 0+ (>20 cm) trout/100 m², which was greater than that predicted by HQS. All other surveys found observed densities to be less than that predicted by HQS with the 2014 survey at site BOBO10 significantly less with a HUI upper C.L. of 0.59.

Walkovers surveys

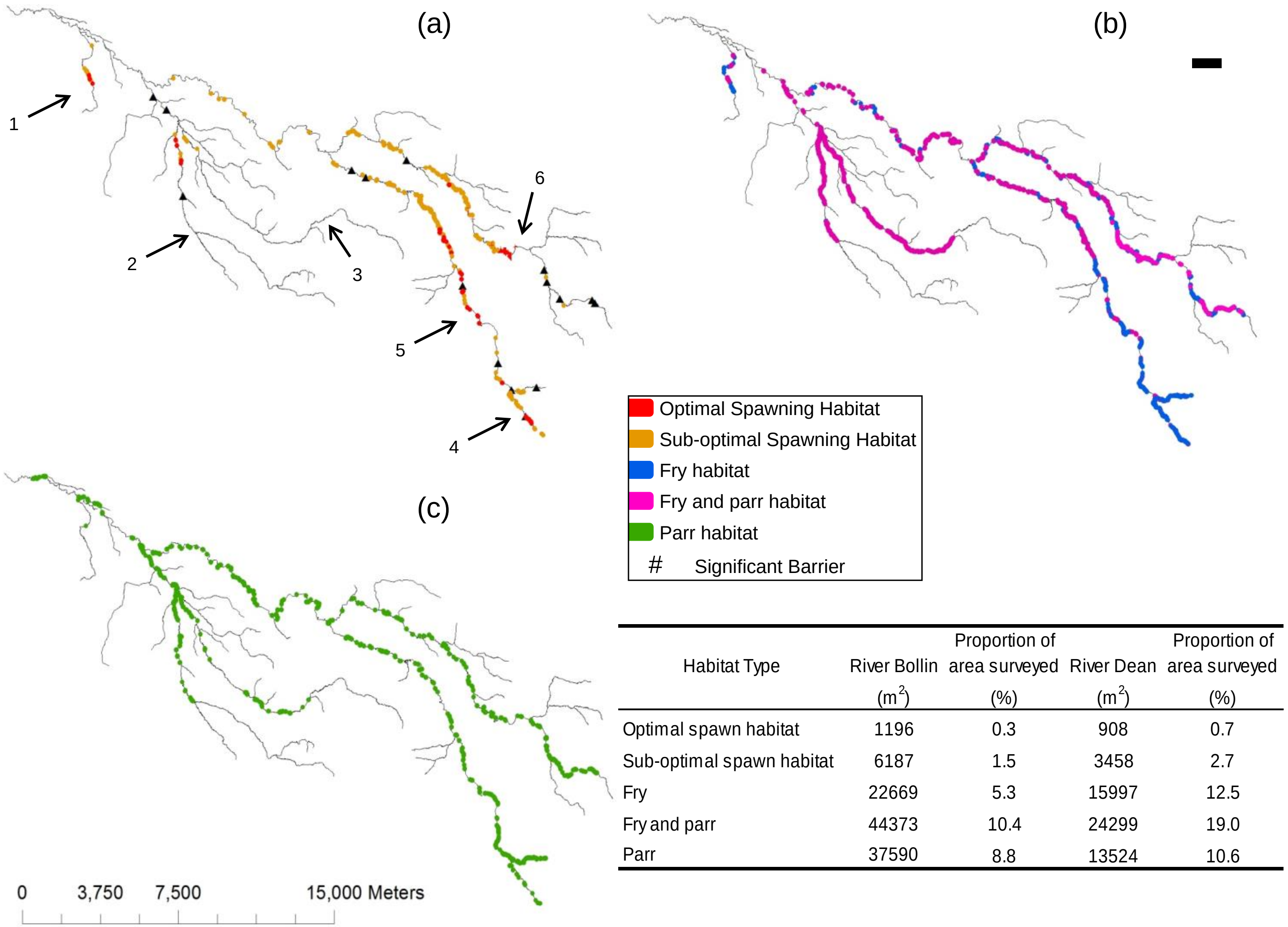
The entire length of the River Bollin and its tributaries the Rossendale, Birket, Mobberly and Agden brooks were surveyed. The entire length of the River Dean was surveyed. Habitat was recorded as either optimal spawning, sub-optimal spawning (were sedimentation of gravels was recorded) fry, parr or fry and parr (where the habitat was considered to be a combination of fry and parr with neither type dominating).

A total of 426,152 m² and 127,877 m² of habitat was recorded in the rivers Bollin and Dean, respectively, (Figure 6.3). No data on the area of habitat recorded was available for Agden, Birkin, Mobberly and Rossendale brooks. The Bollin sub-catchment contained 2104 m² of optimal spawning habitat and 9645 m² of sub-optimal spawning habitat totalling <2% and<3% of the entire area surveyed in the Rivers Bollin and Dean, respectively. The combined area of fry, fry and parr, and parr habitat accounted for 24.5% and 42.1%of the total area surveyed in the rivers Bollin and Dean, respectively. Fry habitat accounted for just 5.3% (22,669 m²) and 12.5% (15,997 m²) of the total area surveyed. Both the fry, fry and parr and parr habitats were distributed throughout the rivers and tributaries, extending into the lower reaches of the Bollin only a few kilometres upstream of the confluence with the Ship Canal (Figure 6.3).

Optimal spawning habitat was recorded in only the upper reaches of the rivers Bollin and Dean upstream of significant barriers (an impassable barrier during Q90 flows) (as identified in Chapter 3), Birkin Brook upstream of a significant barrier and Agden Brook. Sub-optimal spawning habitat was recorded in close proximity to optimal spawning habitat in all rivers and in Mobberly Brook and in the mid and lower reaches of the Bollin and Dean downstream of significant barriers (Figure 6.3).

Proportion of sediment-sensitive invertebrates (PSI)

Three sites representing up-, mid- and downstream sections on both the rivers Bollin and Dean were selected to generate a PSI scores (Figure 6.1). Where available, invertebrate data between 2000 – 2014 were selected for PSI analysis (Figure 6.4).



Habitat Type	River Bollin (m^2)	Proportion of area surveyed (%)	River Dean (m^2)	Proportion of area surveyed (%)
Optimal spawn habitat	1196	0.3	908	0.7
Sub-optimal spawn habitat	6187	1.5	3458	2.7
Fry	22669	5.3	15997	12.5
Fry and parr	44373	10.4	24299	19.0
Parr	37590	8.8	13524	10.6

Figure 6.3 Locations of (a) optimal and sub-optimal spawning habitat, (b) fry and fry and parr habitat and (c) parr habitat on the brooks (1) Agden, (2) Birkin, (3) Mobberly, (4) Rossendale and rivers (5) Bollin and (6) Dean and a table of areas (m^2) surveyed and habitat recorded.

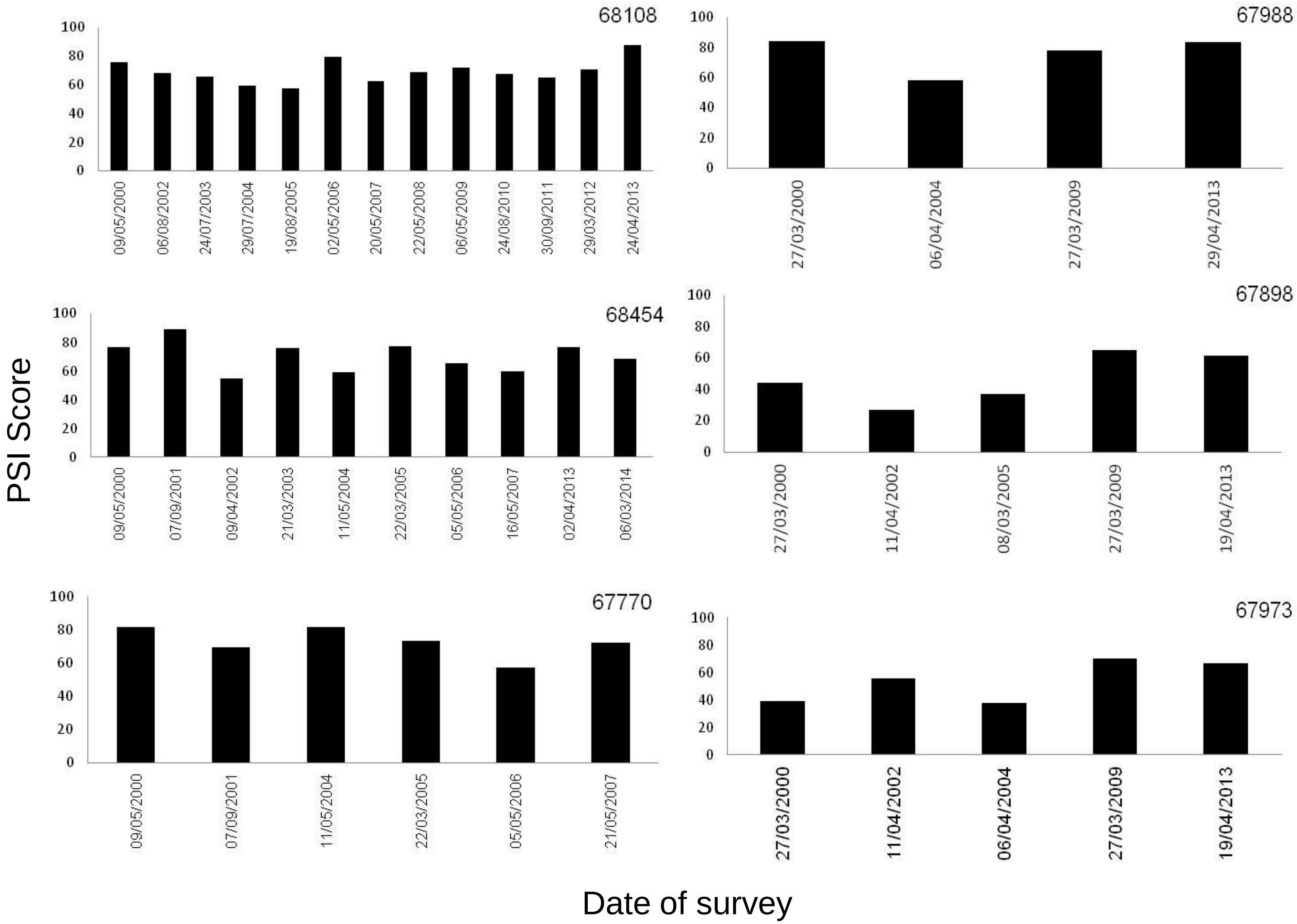


Figure 6.4 PSI scores of the River Bollin (68108, 68454, & 67770) and River Dean (67988, 67989, & 67973) invertebrate surveys.

Thirty one surveys over the Bollin sites were used to generate PSI scores which had similar mean PSI scores although mean PSI score increased moving upstream; with means of 60.0 (moderately sedimented) (range 30 – 81.8) at site 67770, 63.6 (slightly sedimented) (range 41.6 – 88.8) at site 68454 and 68.9 (slightly sedimented) (range 56.2 – 87.5) at site 68108 between 2000 – 2014. PSI scores were relatively consistent between years at each site and across sites, with 65% of all surveys resulting in a PSI score between 61 – 80, slightly sedimented, and only 5% of surveys resulting in a score >81, minimally or unsedimented (Figure 6.4). Twenty two surveys on the River Bollin from 2000 – 2014 across all years and sites had a PSI score <61 (30% of the total). Only 3 surveys resulted in PSI score <41 (sedimented) all of which were at the downstream site 67770.

The River Dean was represented by 14 surveys across 3 sites and showed a greater range of PSI scores across sites and years. The upstream site 67988 had a mean PSI score of 75 (range 58 - 84) (slightly sedimented); two surveys had PSI scores >81 minimally or unsedimented. Both the mid-stream site 67989 and the downstream site 67973 had mean PSI scores of a moderately sedimented bed condition with means of 47 (range 26 – 65) and 53 (range 37 - 70) for 2000 – 2013, respectively, each site had two surveys with PSI scores of <41, sedimented (Figure 6.4).

Fisheries data

There was a lack of data for many sites in Bollin sub-catchment and sites were poorly represented due to an inconsistent electrofishing survey programme and poor weather conditions, especially after 2010, when surveys were frequently cancelled due to poor weather and not rescheduled by the EA.

Density estimates and abundance classifications

A single juvenile salmon (151mm fork length = ≥1+) was captured at site BOBO12 in 2010 (0.145 salmon/100m² = class E for ≥1+ salmon). 0+ and ≥1+ salmon were absent from all other surveys (class F) in the Bollin sub-catchment.

The 0+ brown trout densities at site BO01 ranged from 0 - 42.9 0+ trout/100m² (class F – A) between 2000 – 2010 and a single run survey minimum density of 0.38 trout/100m² in 2013 (Table 6.6). There was little consistency between years in 0+ brown trout densities at site BO01; for example a density of 0.00 0+ trout/100 m² in 2009 was followed by a density of 29.50 0+ trout/100 m² in 2010. At the other two Bollin sites 0+ brown trout densities were low. At BOBO12 the density was 0.15 0+

trout/100 m² (class E) in 2010 and 0.00 0+ trout/100 m² (class F) in 2013, while at BOBO19 0+ brown trout densities were 0.00 0+ trout/100 m² (class F) between 2007 and 2013. 0+ brown trout were poorly represented in the River Dean with a single run survey minimum density of 0.80 0+ trout/100m² in 2013 at DEDE01 while at DEDE25 no trout were captured in any surveys (Table 6.6).

1+ brown trout densities were generally higher than those for 0+ brown trout at site BO01 which was classed A – C between 2000 and 2010 (7.34 – 31.3 ≥1+ trout/100 m²); single run survey minimum densities of 13.5 and 6.8 ≥1+ trout/100 m² were recorded in 2006 and 2013, respectively (Table 6.6). At the other two Bollin sites ≥1+ brown trout densities were 0.58 and 0.51 ≥1+ trout/100 m² (class E) in 2010 and 2013 at BOBO2, respectively, and 0.00 ≥1+ trout/100 m² (class F) in 2007, 2008, 2010 and 2013 and a single run survey minimum density of 0.23 ≥1+ trout/100 m² in 2011 at BOBO19. Again ≥1+ brown trout were poorly represented in the River Dean with a single run survey minimum densities of 3.20 ≥1+ trout/100 m² and 0.00 ≥1+ trout/100 m² in 2013 and 2002 at DEDE01, respectively, and 1.14 ≥1+ trout/100 m² and 0.23 ≥1+ trout/100 m² in 2008 and 2013, respectively, at site DEDE25 (Table 6.6).

Brown trout growth rates and length frequency distributions

Brown trout growth data were available for the sites BO01, BO02 & BO03 for the years 2008, 2009 & 2010. Brown trout growth rates at these combined River Bollin sites (Figure 6.2) were below the national average (Environment Agency, unpublished data) with PSGs of 84% (2008), 89% (2009) and 99% (2010), or slow, slow and average, respectively (Figure 6.5). There was a year on year increase in the growth rate of brown trout at the River Bollin sites for the three years sampled.

No growth data were available for the River Dean. Based on the growth rate graphs (0+ individuals were <99mm) there was an absence of 0+ individuals at the combined Bollin sites in 2008 – 2010 (Figure 6.6). The majority (87%) of the 165 trout captured over the 3 years at the combined River Bollin sites were between 100 – 200 mm.

6.3.2 Upper Mersey sub-catchment

HABSCORE surveys

Eighteen HABSCORE surveys were carried out at 15 sites in 2007, 2008 and 2014 on the River Goyt and the tributary rivers Sett, the Black, Kinder and Wash Brooks. One survey was carried out on the River Etherow and four surveys on the River Tame (Figure 6.1).

Table 6.6 0+ and ≥1+ brown trout densities (trout/100m²) at electrofishing surveys in the Bollin sub-catchment. Shading denotes EA FCS abundance classifications; cells with no colour are single run minimum density estimates.

A (excellent)	B (good)	C (average)	D (fair/poor)	E (poor)	F (fishless)

Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
0+ brown trout															
BO01	3.07	27.86	14.00	24.10	3.47	42.90	14.30	10.40	15.50	0.00	29.50			0.38	
BOBO12											0.15			0.00	
BOBO19								0.00	0.00		0.00	0.00		0.00	
DEDE01														0.80	
DEDE25			0.00						0.00					0.00	
≥1+ brown trout															
BO01	7.69	21.43	18.80	12.40	9.26	13.60	13.50	7.34	16.33	13.50	31.30			6.80	
BOBO12											0.58			0.51	
BOBO19								0.00	0.00		0.00	0.24		0.00	
DEDE01														3.20	
DEDE25			0.00						1.14					0.23	

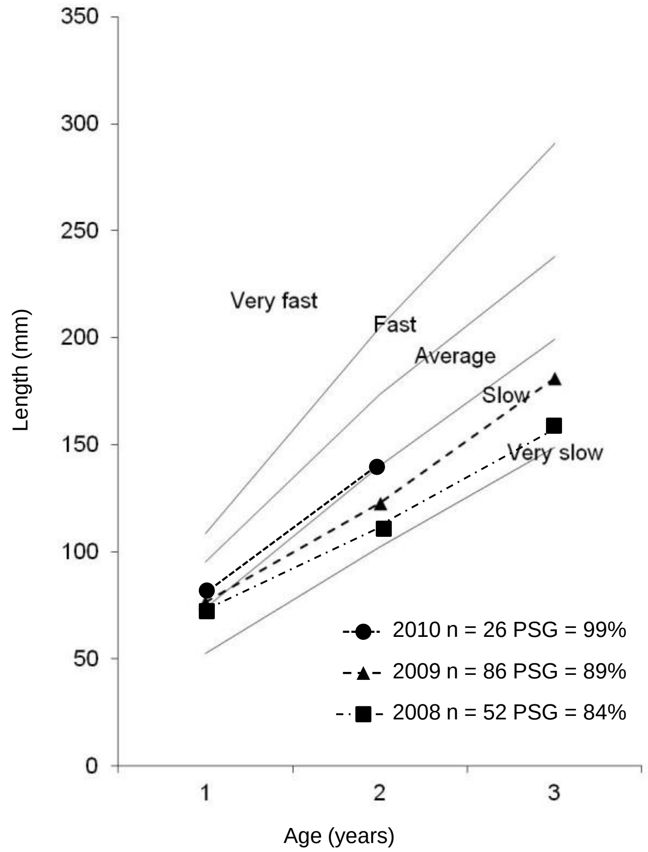


Figure 6.5 Growth rate plots for the combined River Bollin sites.

With the exception of 0+ salmon at site GYBL01 and 0+ and >0+ salmon at site SE01, HABSCORE data indicated that 0+ and >0+ salmon densities were significantly lower (HUI upper C.L. <1) at all sites than predicted from the Habitat Quality Score (HQS) (Table 6.7). Sites SE01 and GYBL01 had low predicted densities (HQS density) of 1.69 0+ and 3.27 >0+ salmon/100 m² and 4.05 0+ and 3.95 >0+ salmon/100 m², respectively.

HQS predicted the density of 0+ salmon would be >23 salmon/100 m² (class C) at 4 of the 6 sites on the main River Goyt and 68.95, 0+ salmon/100 m² at site GO02 under pristine conditions (class B). HQS predicted 0+ salmon densities at the Black brook site (GYBL01 – 05) of only 2.12 –9.9 salmon/100m² (class E-D) and 1.69 0+ salmon/100 m² (class E) at site SE01 on the River Sett (Table 6.7). HQS predicted densities of 12.51 – 68.74 0+ salmon/100m² (class D-B) at sites SE01a, SE02 and 03 on the River Sett and 116.21 0+ salmon/100 m² (class A) at site GYKI01 on Kinder Brook.

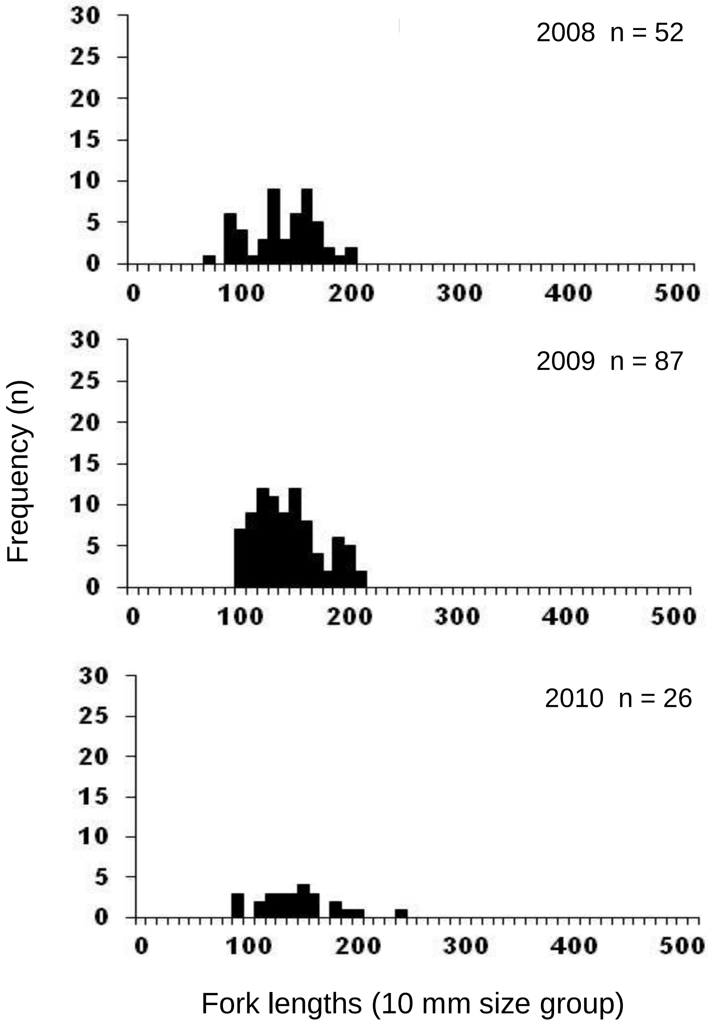


Figure 6.6 Length frequency plots for the combined River Bollin sites.

The HQS predicted densities ranged from 3.27 – 14.18 0+ salmon/100 m² (class E - D) at a number of sites in the Mersey sub-catchment and 10.75 – 14.18 >0+ salmon/100 m² (class D) at sites GO03, GYKIO1 and GYSE02 (Table 6.7). Sites on Black Brook had lower HQS predicted densities ranging between 2.12 – 9.21 0+ salmon/100 m² and 3.6 – 4.46 >0+ salmon/100 m². The HQS predicted salmon densities of 77.32 0+ salmon/100 m² (class B) and 7.7 >0+ salmon/100 m² (class C) at sites on River Etherow and 86.7 – 175.11 0+ salmon/100 m² (class A) and 7.27 – 11.29 >0+ salmon/100 m² (class C-B) at sites on Chew Brook (Table 6.7). The HQS predicted salmon densities of 5.65 0+ salmon/100 m² and 2.48 >0+ salmon/100 m², both class E, at site TATA35 on the River Tame.

Table 6.7 HABSCORE outputs for 0+ salmon for HABSCORE surveys on the rivers Goyt and Sett, Black Brook and their tributaries (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded calls (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
0+									
GO02	12/09/2007	0.0	0.00	68.95	20.79	228.70	0.00	0.00	0.04
GO03	12/09/2007	0.0	0.00	24.64	8.02	75.74	0.01	0.00	0.05
GYGO05	11/09/2007	0.0	0.00	12.63	3.91	40.73	0.02	0.00	0.17
GYGO05	08/09/2014	0.0	0.00	38.52	11.85	125.24	0.00	0.00	0.03
GYGO06	12/09/2007	0.0	0.00	44.98	12.62	160.35	0.00	0.00	0.03
GYGO20	08/09/2014	1.7	0.15	43.15	12.92	144.19	0.00	0.00	0.02
GYBL01	04/10/2007	0.0	0.00	4.05	1.18	13.83	0.14	0.02	1.02
GYBL02	04/10/2007	0.0	0.00	5.36	1.49	19.29	0.10	0.01	0.86
GYBL04	04/09/2007	0.0	0.00	2.12	0.57	7.87	0.12	0.01	0.91
GYBL05	10/09/2007	0.0	0.00	9.89	3.01	32.54	0.02	0.00	0.14
GYBL05	08/09/2014	0.0	0.00	9.21	2.55	33.27	0.02	0.00	0.15
GYKI01	10/09/2007	0.0	0.00	116.21	35.76	377.67	0.00	0.00	0.04
GYWB01	04/10/2007	0.0	0.00	10.26	3.06	34.46	0.05	0.01	0.33
SE01	29/09/2007	0.0	0.00	1.69	0.50	5.76	0.32	0.04	2.35
SE01a	30/09/2007	0.0	0.00	68.74	21.23	222.57	0.01	0.00	0.06
GYSE02	11/09/2007	0.0	0.00	28.16	9.39	84.43	0.01	0.00	0.07
GYSE03	11/09/2007	0.0	0.00	12.51	3.87	40.41	0.03	0.00	0.19
GYSE03	08/09/2014	0.0	0.00	38.48	9.01	164.32	0.01	0.00	0.06

Table 6.7 (continued) HABSCORE outputs for >0+ salmon for HABSCORE surveys on the rivers Goyt and Sett, Black Brook and their tributaries (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded calls (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
>0+									
GO02	12/09/2007	0	0	5.09	1.55	16.67	0.07	0.01	0.40
GO03	12/09/2007	0	0	10.75	3.39	34.05	0.01	0.00	0.09
GYGO05	12/09/2007	0	0	5.90	1.79	19.45	0.05	0.01	0.32
GYGO05	08/09/2014	0	0	5.93	1.81	19.47	0.03	0.00	0.18
GYGO06	12/09/2007	0	0	3.70	1.09	12.51	0.05	0.01	0.31
GYGO20	08/09/2014	0	0	6.24	1.17	22.84	0.01	0.00	0.09
GYBL01	04/10/2007	0	0	3.95	1.16	13.44	0.14	0.02	0.88
GYBL02	04/10/2007	0	0	4.46	1.35	14.77	0.13	0.02	0.83
GYBL04	04/09/2007	0	0	3.60	1.14	11.37	0.07	0.01	0.41
GYBL05	10/09/2007	0	0	3.74	1.14	12.22	0.05	0.01	0.30
GYBL05	08/09/2014	0	0	4.16	1.27	13.67	0.04	0.01	0.27
GYKI01	10/09/2007	0	0	13.12	4.21	40.92	0.00	0.00	0.04
GYWB01	04/10/2007	0	0	8.46	2.73	26.24	0.05	0.01	0.32
SE01	29/09/2007	0	0	3.27	1.01	10.62	0.17	0.03	1.01
SE01a	30/09/2007	0	0	5.44	1.59	18.59	0.11	0.02	0.69
GYSE02	11/09/2007	0	0	14.18	4.51	44.60	0.02	0.00	0.12
GYSE03	11/09/2007	0	0	6.10	1.89	19.69	0.06	0.01	0.33
GYSE03	08/09/2014	0	0	5.16	1.57	16.95	0.06	0.01	0.34

Table 6.7 (continued) HABSCORE outputs for 0+ salmon for HABSCORE surveys on the rivers Tame and Etherow and Chew Brook (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded calls (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
River Tame									
0+									
TATA35	12/11/2008	0	0	5.65	1.30	26.72	0.01	0.00	0.05
CH01a	13/11/2008	0	0	175.11	52.33	585.92	0.00	0.00	0.01
CH01	13/11/2008	0	0	95.30	28.98	313.35	0.00	0.00	0.02
CH02	08/09/2014	0	0	86.68	26.30	285.68	0.00	0.00	0.02
>0+		0	0						
TATA35	12/11/2008	0	0	2.48	0.70	8.76	0.01	0.00	0.09
CH01a	13/11/2008	0	0	7.27	2.25	23.52	0.04	0.01	0.25
CH01	13/11/2008	0	0	9.08	2.82	28.82	0.02	0.00	0.14
CH02	08/09/2014	0	0	11.29	3.40	37.47	0.02	0.00	0.14
River Etherow									
0+									
ETET20	08/09/2014	0	0	77.32	18.98	315.01	0.00	0.00	0.01
>0+									
ETET20	08/09/2014	0	0	7.70	2.28	26.05	0.01	0.00	0.08

Table 6.8 HABSCORE outputs for 0+, >0+ (<20 cm) and >0+ (>20 cm) brown trout for HABSCORE surveys in the Upper Mersey sub-catchment (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) and shaded cells (HUI lower C.L. column; green) represent sites where the observed population was significantly greater (HUI lower C.L. >1 than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
0+									
GO02	12/09/2007	5.4	1.79	12.42	3.23	47.84	0.14	0.02	0.99
GO03	12/09/2007	7.7	1.24	6.66	1.78	24.95	0.19	0.03	1.23
GYGO05	11/09/2007	11.0	3.37	5.96	1.58	22.57	0.56	0.08	3.76
GYGO05	08/09/2014	2.2	0.39	5.03	1.32	19.09	0.08	0.01	0.52
GYGO06	12/09/2007	0.0	0.00	4.10	1.05	15.96	0.04	0.01	0.30
GYGO20	08/09/2014	1.0	0.08	1.98	0.50	7.85	0.04	0.01	0.29
GYBL01	04/10/2007	70.0	38.90	14.10	3.71	53.66	2.76	0.41	18.45
GYBL02	04/10/2007	4.9	2.95	14.10	3.60	55.28	0.21	0.03	1.43
GYBL04	04/09/2007	13.3	3.27	1.56	0.42	5.88	2.09	0.31	14.09
GYBL05	10/09/2007	11.3	2.10	3.63	0.96	13.34	0.58	0.08	4.31
GYBL05	08/09/2014	2.5	0.46	2.45	0.64	9.34	0.19	0.03	1.26
GYKI01	10/09/2007	6.0	3.42	15.06	4.01	56.51	0.23	0.03	1.50
GYWB01	04/10/2007	21.0	9.72	12.99	3.48	48.52	0.75	0.11	4.93
SE01	29/09/2007	28.5	15.37	5.64	1.53	20.84	2.73	0.42	17.88
SE01a	30/09/2007	9.6	5.75	21.21	5.69	79.08	0.27	0.04	1.88
GYSE02	11/09/2007	42.7	12.07	15.05	3.90	58.03	0.80	0.12	5.42
GYSE03	11/09/2007	17.3	5.83	11.07	2.89	42.37	0.53	0.08	3.54
GYSE03	08/09/2014	18.0	5.13	3.09	0.79	12.07	1.66	0.24	11.31

Table 6.8 (continued) HABSCORE outputs for 0+, >0+ (<20 cm) and >0+ (>20 cm) brown trout for HABSCORE surveys in the Upper Mersey sub-catchment (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) and shaded cells (HUI lower C.L. column; green) represent sites where the observed population was significantly greater (HUI lower C.L. >1 than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
>0+ <20 cm									
GO02	12/09/2007	50.4	16.79	12.35	2.76	55.21	1.36	0.22	8.47
GO03	12/09/2007	31.3	5.01	3.50	0.84	14.65	1.43	0.24	8.34
GYGO05	11/09/2007	3.0	0.92	2.35	0.56	9.88	0.39	0.07	2.33
GYGO05	08/09/2014	2.0	0.35	1.49	0.35	6.41	0.24	0.04	1.43
GYGO06	12/09/2007	14.0	2.57	0.92	0.21	4.03	2.78	0.46	16.92
GYGO20	08/09/2014	1.4	0.12	0.79	0.18	3.48	0.15	0.02	0.92
GYBL01	04/10/2007	45.0	25.01	5.63	1.35	23.58	4.40	0.75	26.18
GYBL02	04/10/2007	8.1	4.85	7.13	1.70	29.96	0.68	0.12	4.03
GYBL04	04/10/2007	10.6	2.61	0.80	0.19	3.40	3.25	0.54	19.34
GYBL05	10/09/2007	18.9	3.52	1.22	0.29	5.11	2.88	0.46	18.07
GYBL05	08/09/2014	16.6	3.03	1.23	0.29	5.24	2.46	0.41	14.71
GYKI01	10/09/2007	10.0	5.70	4.08	0.95	17.49	1.40	0.23	8.39
GYWB01	04/10/2007	40.2	18.65	7.76	1.87	32.22	2.40	0.41	14.06
SE01	29/09/2007	16.3	8.81	3.32	0.80	13.79	2.65	0.45	15.55
SE01a	30/09/2007	57.9	34.67	8.28	1.95	35.19	4.19	0.70	24.98
GYSE02	25/06/2007	177.0	50.00	3.12	0.67	14.41	16.05	2.51	102.63
GYSE03	11/09/2007	8.3	2.80	4.87	1.15	20.61	0.57	0.10	3.40
GYSE03	08/09/2014	5.0	1.42	1.53	0.35	6.72	0.93	0.15	5.69

Table 6.8 (continued) HABSCORE outputs for 0+, >0+ (<20 cm) and >0+ (>20 cm) brown trout for HABSCORE surveys in the Upper Mersey sub-catchment (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) and shaded cells (HUI lower C.L. column; green) represent sites where the observed population was significantly greater (HUI lower C.L. >1 than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
>0+ (>20 cm)									
GO02	12/09/2007	9.9	3.30	1.63	0.54	4.93	2.02	0.67	6.13
GO03	12/09/2007	2.3	0.37	0.78	0.25	2.40	0.47	0.15	1.45
GYGO05	11/09/2007	5.5	1.68	0.91	0.30	2.81	1.84	0.60	5.67
GYGO05	08/09/2014	5.5	0.97	0.99	0.30	3.28	0.97	0.29	3.20
GYGO06	12/09/2007	1.0	0.18	1.17	0.37	3.73	0.16	0.05	0.50
GYGO20	08/09/2014	1.0	0.08	0.35	0.11	1.08	0.24	0.07	0.86
GYBL01	04/10/2007	3.0	1.67	4.98	1.52	16.30	0.30	0.10	1.09
GYBL02	04/10/2007	2.2	1.35	4.22	1.33	13.42	0.32	0.10	1.01
GYBL04	04/09/2007	22.6	5.56	0.59	0.19	1.86	9.37	2.99	29.33
GYBL05	10/09/2007	11.5	2.14	1.03	0.33	3.22	2.08	0.48	9.04
GYBL05	08/09/2014	5.2	0.96	0.60	0.21	2.05	1.46	0.47	4.55
GYKI01	10/09/2007	0.0	0.00	0.82	0.26	2.56	0.70	0.22	2.18
GYWB01	04/10/2007	4.9	2.27	2.45	0.79	7.56	0.93	0.30	2.87
SE01	29/09/2007	2.5	1.36	1.25	0.41	3.78	1.09	0.36	3.32
SE01a	30/09/2007	3.5	2.08	1.55	0.50	4.81	1.34	0.43	4.23
GYSE02	30/09/2007	7.3	2.08	1.08	0.36	3.28	1.92	0.63	5.85
GYSE03	11/09/2007	1.4	0.48	1.06	0.34	3.23	0.45	0.15	1.38
GYSE03	08/09/2014	2.0	0.57	4.17	1.16	15.03	0.14	0.04	0.49

Table 6.8 (continued) HABSCORE outputs for 0+, >0+ (<20 cm) and >0+ (>20 cm) brown trout for HABSCORE surveys in the Upper Mersey sub-catchment (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) and shaded cells (HUI lower C.L. column; green) represent sites where the observed population was significantly greater (HUI lower C.L. >1 than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
0+									
ETET20	08/09/2014	0.0	0.00	6.77	1.75	26.28	0.02	0.00	0.10
>0+ (<20cm)									
ETET20	08/09/2014	3.0	0.31	0.51	0.11	2.39	0.61	0.08	4.44
>0+ (>20 cm)									
ETET20	08/09/2014	5.0	0.51	0.22	0.07	0.66	2.37	0.78	7.21
0+									
TATA35	08/09/2014	0.0	0.00	3.08	0.79	12.01	0.01	0.00	0.08
CH01a	12/11/2008	7.5	2.21	10.01	2.59	38.46	0.20	0.03	1.50
CH01	13/11/2008	16.0	3.41	9.68	2.57	36.51	0.35	0.05	2.44
CH02	13/11/2008	44.9	11.53	4.88	1.29	18.38	2.36	0.35	16.04
>0+ <20 cm									
TATA35	08/09/2014	0.0	0.00	0.66	0.15	2.84	0.05	0.01	0.32
CH01a	12/11/2007	30.4	8.99	1.10	0.25	4.97	8.14	1.27	52.07
CH01	13/11/2008	43.0	9.16	2.10	0.47	9.34	4.36	0.70	27.15
CH02	13/11/2008	46.8	12.02	2.20	0.53	9.25	5.45	0.92	32.27

Table 6.8 (continued) HABSCORE outputs for 0+, >0+ (<20 cm) and >0+ (>20 cm) brown trout for HABSCORE surveys in the Upper Mersey sub-catchment (Figure 6.2) incorporating fish data from annual electrofishing surveys between 2005 and 2014. Shaded cells (HUI upper C.L. column; red) represent sites where the observed population was significantly lower (HUI upper C.L. <1) and shaded cells (HUI lower C.L. column; green) represent sites where the observed population was significantly greater (HUI lower C.L. >1 than would be expected under pristine conditions.

Main River & Site identifier	Date of survey	Observed number	Observed density	HQS (density)	HQS lower C.L.	HQS upper C.L	HUI	HUI lower C.L.	HUI upper C.L.
>0+ (>20 cm)									
TATA35	08/09/2014	0.0	0.00	0.54	0.18	1.64	0.06	0.02	0.20
CH01a	12/11/2008	1.0	0.30	0.48	0.16	1.48	0.61	0.20	1.87
CH01	13/11/2008	0.0	0.00	0.38	0.12	1.18	0.57	0.18	1.77
CH02	13/11/2008	2.6	0.68	0.45	0.15	1.35	1.52	0.47	4.99

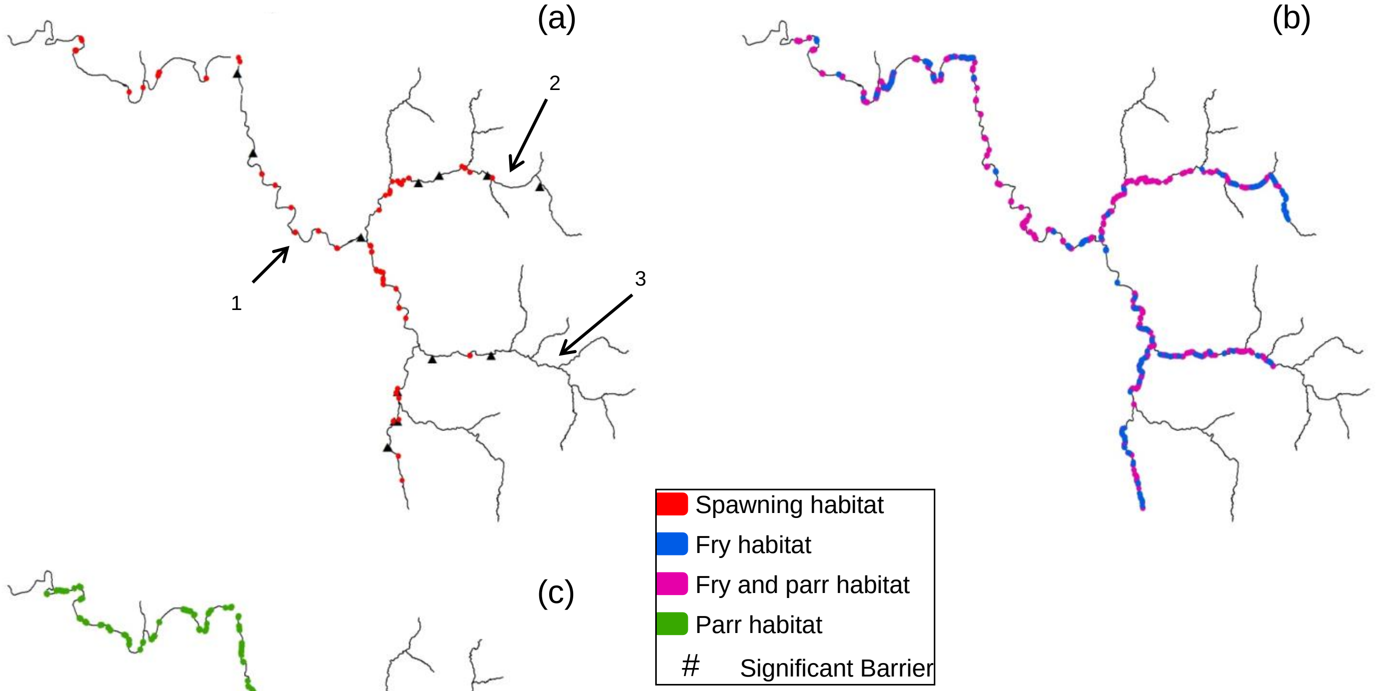
Five surveys over five sites observed 0+ trout densities greater than that predicted by HQS (HUI >1), none of which was significantly greater than predicted (Table 6.8); these sites were in the upper reaches of the catchment on the River Sett and the Chew and Black brooks (Table 6.8). Of the remaining surveys, all of which had HUI values of <1, six had observed densities of 0+ trout significantly less than that predicted by HQS, four of which were at four sites on the main River Goyt. The 2014 surveys at site GYGO20 and TATA35 revealed observed >0+ (<20 cm) trout densities significantly less than that predicted by HQS (HUI upper C.L. <1) and a further seven surveys across five sites had HUI values of <1 for >0+ (<20 cm) trout. Of the 15 surveys which had observed >0+ (<20 cm) trout densities greater than that predicted by HQS two were significantly higher, the 2007 surveys at site GYSE02 with an observed density of 50 >0+ (<20 cm) trout/100 m² and site CHO1a with an observed density of 8.99 >0+ (<20 cm) trout/100 m² (Table 6.8).

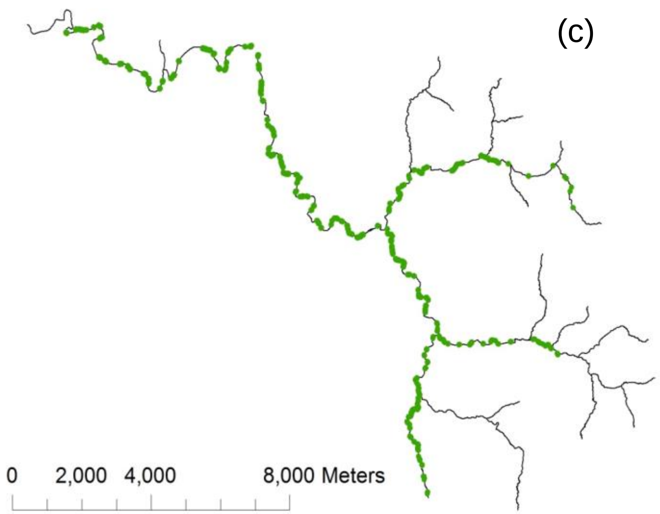
The 2008 survey at site TATA35 had significantly less observed than expected densities of trout for all age and size groups with trout being absent from this site. Sites GYGO06, GYGO20 and GYSE03 also revealed observed >0+ (>20 cm) trout densities significantly less than that predicted by HQS (HUI upper C.L. <1). 10 surveys across nine sites had observed >0+ (>20 cm) trout densities greater than that predicted by HQS one of which, site GYBL05, was significantly greater (HUI lower C.L. >1) (Table 6.8).

Walkover surveys

A total of 23.4 km of River Goyt, 7 km of Black Brook and 6 km of the River Sett, 41.2 km of the River Tame up to the confluence with the River Mersey (not the entire stretch) and 2.5 km of the tributaries the Diggle and Chew Brook were surveyed (Figure 6.7). Total areas of 414036 m², 26534 m² and 44875 m² of habitat were recorded on the River Goyt, Black Brook and River Sett respectively, and 475379 m², 7777 m², 18867 m² on the River Tame and Diggle and Chew Brooks, respectively (Figure 6.7). The River Etherow was not surveyed. Spawning habitat was distributed throughout the River Goyt and its tributaries, but much of it was upstream of significant barriers (% unknown) (Figure 6.7).

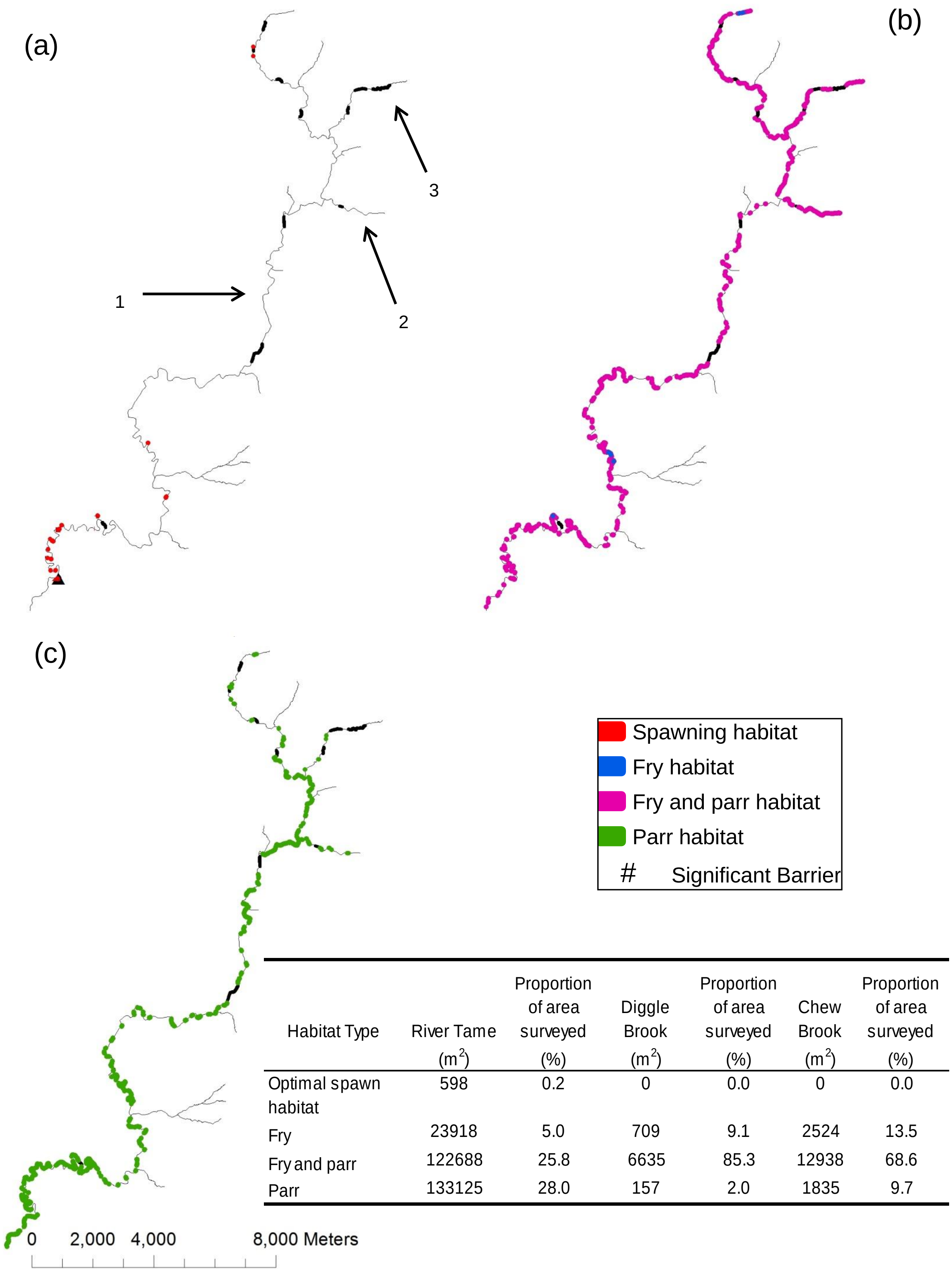
The River Goyt contained 1811 m² of optimal spawning habitat totalling just 0.4% of the total area surveyed, and the River Sett and Black Brook contained just 176 m² and 17 m² of spawning habitat, respectively. Combined fry, fry and parr and parr habitat accounted for 41.1%, 59.3%, and 57.6% of the total surveyed area on the rivers Goyt and Sett, and Black Brook, respectively (Figure 6.7).





Habitat Type	River Goyt (m^2)	Proportion of area surveyed (%)	River Sett (m^2)	Proportion of area surveyed (%)	Black Brook (m^2)	Proportion of area surveyed (%)
Optimal spawn habitat	1811	0.4	176	0.4	17	0.1
Fry	17970	4.3	4061	9.0	1480	5.6
Fry and parr	76041	18.4	15275	34.0	9103	34.3
Parr	76277	18.4	7126	15.9	4704	17.7

Figure 6.7 Locations of (a) spawning habitat (b) fry and fry and parr habitat and (c) parr habitat recorded on the rivers (1) Goyt and (2) Sett, and (3) Black Brook and a table of areas (m²) surveyed and habitat.



Habitat Type	River Tame (m^2)	Proportion of area surveyed (%)	Diggle Brook (m^2)	Proportion of area surveyed (%)	Chew Brook (m^2)	Proportion of area surveyed (%)
Optimal spawn habitat	598	0.2	0	0.0	0	0.0
Fry	23918	5.0	709	9.1	2524	13.5
Fry and parr	122688	25.8	6635	85.3	12938	68.6
Parr	133125	28.0	157	2.0	1835	9.7

Figure 6.7 (continued) Locations of (a) spawning habitat (b) fry and fry and parr habitat and (c) parr habitat recorded on the river (1) Tame and (2) Chew and (3) Diggle brooks and a table of areas (m²) surveyed and habitat. Black lines on map (a) denote inaccessible areas and were not surveyed.

The fry and parr and parr habitats were distributed throughout the rivers and tributaries, whereas the fry habitats were mainly confined to the mid Goyt just upstream of the Tame confluence, the upper Goyt close to and upstream of the Black Brook confluence and the upper River Sett and some areas in Black Brook (Figure 6.7). Only 598 m^2 (0.2 % of the total area surveyed) of spawning habitat was recorded in the River Tame, almost all of which was upstream of a significant barrier, and none in the Diggle and Chew Brooks (Figure 6.7). Relatively little fry habitat was recorded with 5.0, 9.1, and 13.5 % of the total area surveyed on the River Tame and Diggle and Chew brooks, respectively. Fry and parr habitat dominated the recorded habitat, especially in Diggle and Chew brooks at 87.3 and 78.3 % of the total area surveyed, respectively. However, the majority of fry and parr habitat was upstream of a significant barrier (Figure 6.7).

Proportion of sediment-sensitive invertebrates (PSI)

The rivers Goyt and Sett PSI score means were all classed as having slightly sedimented river bed condition with PSI score means of 62.8 (range 33.3 – 86.9) at site 67852, 77.8 (range 63.6 - 92) at site 77580 and 78.8 (range 65.0 – 91.0) at site 67808. Some 36% of PSI scores at sites 77580 and 67808 were >81 (minimally or unsedimented), 83% of sites had PSI scores of >70 and there were no PSI scores <61 (moderately sedimented) from 2000 – 2014 at any survey sites (Figure 6.8). In total 64% of surveys at site 67852 had PSI score <61 (moderately sedimented).

PSI scores at sites 65904 and 65655 on the River Etherow had means of 67.3 (range 55.4 – 83.3) and 69.5 (range 56.0 – 92.3) from 2000 – 2014, indicating slightly sedimented river bed conditions (Figure 6.8). Both the River Etherow sites were similar in PSI scores with 29% and 33% of surveys having PSI scores <61. The upstream River Tame site, site 67601, had a PSI score mean of 74 (range 64.5 – 87.9) (slightly sedimented) all of which were >61, slightly sedimented. Sites 69106 and 67788 had lower PSI score means of 42 (range 22 – 56) and 41 (range 19 – 64), (moderately sedimented), respectively, for 2000 to 2014. 50% of surveys at both sites had PSI scores of <41, sedimented.

Fisheries data

There was a lack of data for many sites in the Upper Mersey sub-catchment and sites were poorly represented due to an inconsistent electrofishing survey programme and poor weather conditions, especially after 2010, when surveys were frequently cancelled due to poor weather and not rescheduled by the EA.

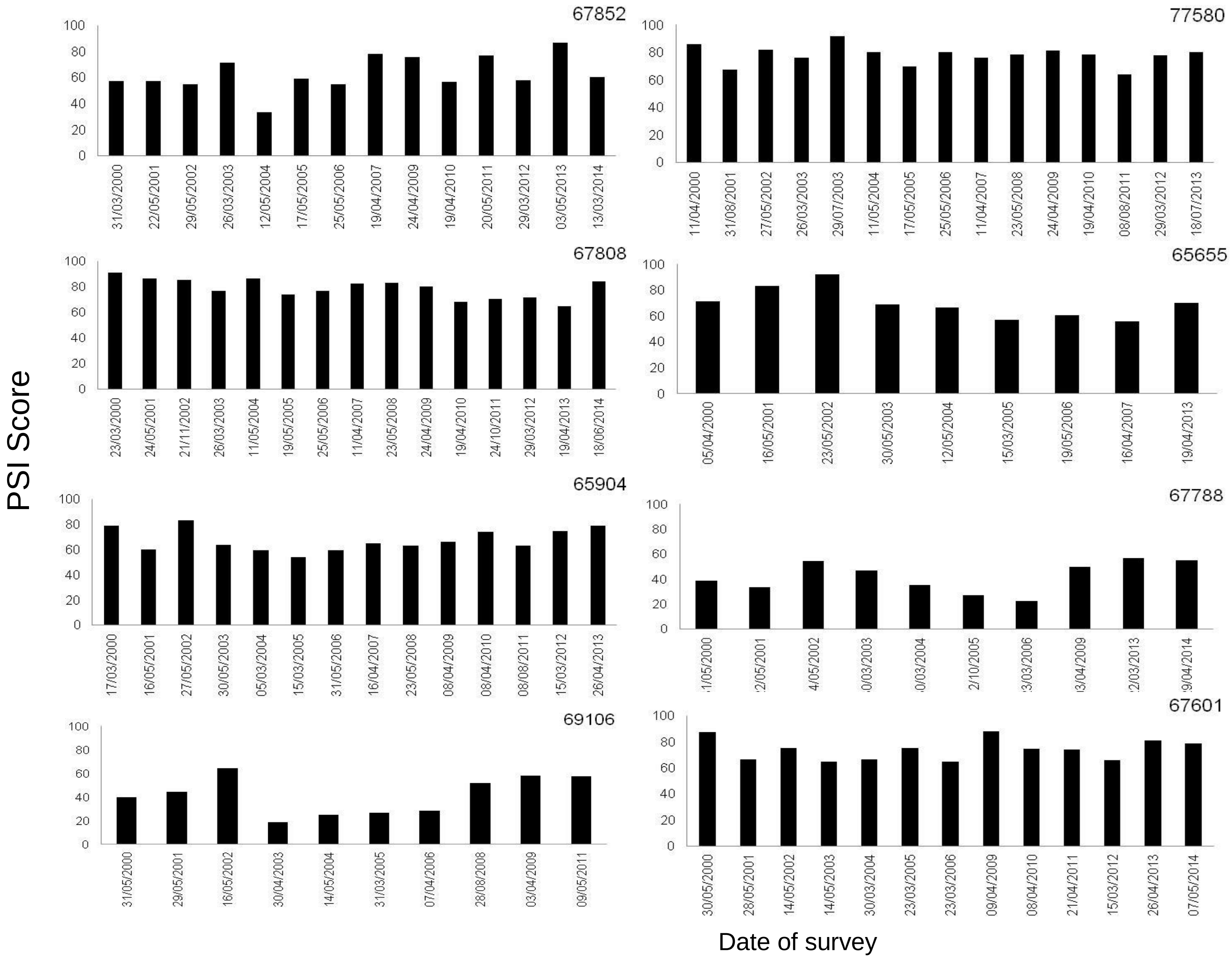


Figure 6.8 PSI scores of the rivers Goyt (67852 & 77580), Sett (67808), Etherow (65655 & 65904) and Tame (67788, 69106, & 67601).

Density estimates and abundance classifications

No juvenile salmon were captured during any of the surveys and both 0+ and ≥1+ salmon were class F at all sites.

0+ brown trout densities at site GO02 on the River Goyt ranged between 0.74 – 10.8 0+ trout/100 m^2 (class C – F) between 2000 – 2010 and there was a single run minimum density of 0.33 0+ trout/100 m^2 in 2013 (Table 6.9). Densities of 0+ trout increased from 0.74 0+ trout/100 m^2 (class E) in 2000 to 10.59 and 10.80 0+ trout/100 m^2 (class C) in 2004 and 2005 but then decreased from 2005 to lows of 1.50 - 2.81 0+ trout/100 m^2 (class E) between 2007 – 2010. 0+ brown trout densities at site GYGO10 were 0.58 0+ trout/100 m^2 (class E) in 2009 and absent (0.00 0+ trout/100 m^2 (class F)) in all other years. 0+ brown trout were also absent from site GYGO25 in all years. At site GYBL05 0+ brown trout densities ranged from 0.0 – 11.09 0+ trout/100 m^2 (class F – C) between 2008 – 2014, increasing from 2007 to 2010 then decreasing in subsequent years (Table 6.9). Single run survey minimum densities of 1.34 and 0.00 0+ trout/100 m^2 were recorded in 2007 and 2013 respectively (Table 6.9) at site GYBL05. 0+ brown trout densities at site SE01 ranged from 4.93 - 56.60 0+ trout/100m^2 (class D - A). 0+ brown trout densities were highly variable at site SE01 during this period with a density of 56.6 0+ trout/100 m^2 in 2012 but 0.00 0+ trout/100 m^2 a year later in 2013 (Table 6.9). There was an increase in trout densities from the period 2000 – 2002 (mean = 9.54 0+ trout/100 m^2) to the period 2003 – 2005 (mean = 21.73 0+ trout/100 m^2) and then in subsequent years to a low of 2.70 0+ trout/100 m^2 in 2009, similar to the 0+ trout densities at GO02 (although 0+ trout densities at site SE01 increased in 2010 and 2012).

At site EA04 0+ brown trout densities ranged from 3.7 – 19.38 0+ trout/100 m^2 (class B – E) for the period 2001 – 2003 and then fell to a density of <1.8 0+ trout/100 m^2 (class E) in the period 2005 – 2007 (Table 6.9). 0+ brown trout densities at site ETET15 were < 1.1 0+ trout/100 m^2 (class E and F) in all years for the period 2003 – 2006 and a single run survey in 2013 was fishless. 0+ trout densities at sites on the River Tame were low; trout were absent at all surveys at both sites TATA25 and TATA35 except for site TATA25 in 2006 when the 0+ trout density was 0.45 0+ trout/100 m^2 (class E). Three single run surveys at site TATA25 found 0+ brown trout densities of <0.8 0+ trout/100 m^2. 0+ trout densities at site CH01a on Chew brook ranged from 2.58 – 5.70 0+ trout/100 m^2 (class E – D) between 2008 and 2010.

Table 6.9 0+ and ≥1+ brown trout densities (trout/100m²) at electrofishing surveys in the Upper Mersey sub-catchment. Shading denotes EA FCS abundance classifications; cells with no colour are single run minimum density estimates.

A (excellent)	B (good)	C (average)	D (fair/poor)	E (poor)	F (fishless)

Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
0+ brown trout															
GO02	0.74	4.94	5.08	7.52	10.59	10.80	4.20	1.61	2.70	1.50	2.81			0.33	
GYGO10				0.00	0.00	0.00	0.00		0.00	0.58	0.00			0.00	
GYGO25					0.00	0.00				0.00	0.00			0.00	
GYBL05								1.34	1.75	4.77	11.09	0.16		0.00	0.00
SE01	7.32	14.60	6.70	26.97	19.54	21.99	18.40	10.79	4.93	2.70	16.57		56.60	0.00	
EA04		11.70	3.70	19.38		1.69	0.58	1.78							
ETET15				1.06	0.00	0.00	0.10							0.00	
TACH01a									2.58	4.06	5.70				
TATA25			0.00	0.23	0.80	0.00	0.45						0.00		
TATA35						0.00	0.00								
≥1+ brown trout															
GO02	18.50	12.00	13.44	16.19	15.59	14.18	19.81	7.41	8.08	12.42	14.55			7.30	
GYGO10				0.15	0.61	0.00	0.00		0.64	0.35	0.46			0.19	
GYGO25					0.00	0.00				0.11	0.63			0.00	
GYBL05								5.20	5.26	5.17	6.27	10.48		0.52	1.51
SE01	15.60	29.60	32.30	21.82	29.88	30.90	23.80	36.59	19.71	14.83	22.97		16.57	11.72	
EA04		15.11	6.93	10.70		3.37	1.88	0.97							
ETET15				2.71	2.71	3.50	0.93							0.30	
TACH01a									6.72	7.25	10.50				
TATA25			1.83	0.00	0.81	1.40	0.45						0.23		
TATA35						0.00	0.00								

≥1+ brown trout densities at the most upstream site on the River Goyt, site GO02, were relatively consistent ranging from 7.41 – 19.81 ≥1+ trout/100 m² (mean = 13.83) (Class B – C) between 2000 – 2010 with a single run minimum density of 7.30 ≥1+ trout/100 m² in 2013 (Table 6.9). ≥1+ brown trout densities at both GYGO10 and GYGO25 were much lower remaining <0.64 ≥1+ trout/100 m² (class F or E) at all surveys during the study period; a single run survey minimum density of 0.11 ≥1+ trout/100 m² was recorded at GYGO25 in 2009. All surveys at GYBL05 between 2007 – 2011 found ≥1+ brown trout densities of >5.17 ≥1+ trout/100 m² (class C) but after this period trout densities fell with a single run survey density of 0.52 ≥1+ trout/100 m² in 2013 and a density of 1.15 ≥1+ trout/100 m² (class E) in 2014. ≥1+ brown trout densities at site SE01 ranged from 14.83 – 36.56 ≥1+ trout/100 m² (mean = 24.5) (class B - A) between 2000 – 2010, 16.57 ≥1+ trout/100 m² (class B) in 2012 and a single run survey minimum density of 11.72 ≥1+ trout/100 m^2 in 2013 (Table 6.9).

≥1+ brown trout densities at site EA04 on the River Etherow decreased from 15.11 ≥1+ trout/100 m² (class B) in 2001 to 1.88 and 0.97 ≥1+ trout/100 m² (class E) in 2006 and 2007 (Table 6.9). ≥1+ brown trout densities at site ETET15 were class D – E between 2003 – 2006 with single run survey densities of 0.30 ≥1+ trout/100m² in 2013 (Table 6.9). ≥1+ brown trout densities at site TATA25 on the River Tame were <2 ≥1+ trout/100 m² (class E) in 2002, 2005 and 2006 with single run survey minimum densities of 0.00, 0.80 and 0.23 ≥1+ trout/100 m² in 2003, 2004 and 2012, respectively. Both the 2005 and 2006 surveys at site TATA35 found ≥1+ brown trout densities of 0.00 ≥1+ trout/100 m² (class F). ≥1+ brown trout densities at TACH01a were relatively consistent ranging from 6.72 – 10.5 ≥1+ trout/100 m² (class C) between 2008 and 2010.

Brown trout growth rates and length frequency distribution

Brown trout at the combined River Goyt sites (Table 6.10 and Figure 6.2) had growth rates lower than the national average. All growth rates were slow and the PSG was 80% (2008), 79% (2009) and 90% (2010) (Figure 6.9). 0+ brown trout were absent at the combined Goyt sites between 2008 and 2010 (Figure 6.10). Brown trout caught at the Black brook site in 2009 had average growth (PSG = 95%), although there was an absence of 0+ individuals (Figure 6.10). The PSG of brown trout caught in 2010 at the River Sett site was 89% (slow growth) and there was an absence of 0+ individuals. Brown trout from the combined sites in the River Etherow had PSGs of 104% (2007), 92% (2008) and 83% (2009), average, slow and slow, respectively (Figure 6.9). There was an absence of 0+ individuals at the Etherow sites.

Table 6.10 Sites and surveys used to generate growth rate graphs (Figure 6.9) and length frequency graphs (Figure 6.10). Note, not all fish caught during a survey were measured and aged. See figure 6.9 for number of fish used to produce growth rate graphs.

River	Sites	Years
Goyt	GO02 & GO03	2008, 2009 & 2012
Etherow	ET02 & ET04	2007, 2008 & 2009
Sett	SE01 & SE01a	2010
Black Brook	GYBL04 & GYBL05	2009
Tame	TATA05	2011
Tame	TATA30	2005
Chew Brook	TACH01, TACH01a & THCH02	2008, 2010 & 2011

Brown trout caught at site TATA05 in 2011 on the River Tame (Table 6.10 and Figure 6.2) had a PSG of 91% (slow growth rate) and those caught at site TATA30 in 2005 a PSG of 58% (very slow growth rate) (Figure 6.9). There was an absence of 0+ brown trout at both sites and trout were represented by a narrow length distribution of 80 – 150 mm (aged 1 – 2 years) at each site (Figure 6.10). Brown trout PSG at the combined sites of Chew brook was 86% (2008), 100% (2010) and 101% (2011), slow, average and average, respectively. There was an absence of 0+ brown trout but a number of >200mm trout were captured (Figure 6.10).

6.4 DISCUSSION

Chapters 3, 4 and 5 demonstrate that stray salmon are entering the River Mersey in low numbers and a few are successfully spawning. Chapter 6 focussed on habitat availability, accessibility and quality and how this might affect potential juvenile productivity. Chapter 6 demonstrated that there is little spawning habitat; much of this was inaccessible to migrating adult salmon. Fry and parr habitat is also present throughout the catchment although these habitats are low productivity environments, where sedimentation may be an issue and much of which is inaccessible to migrating adult salmon.

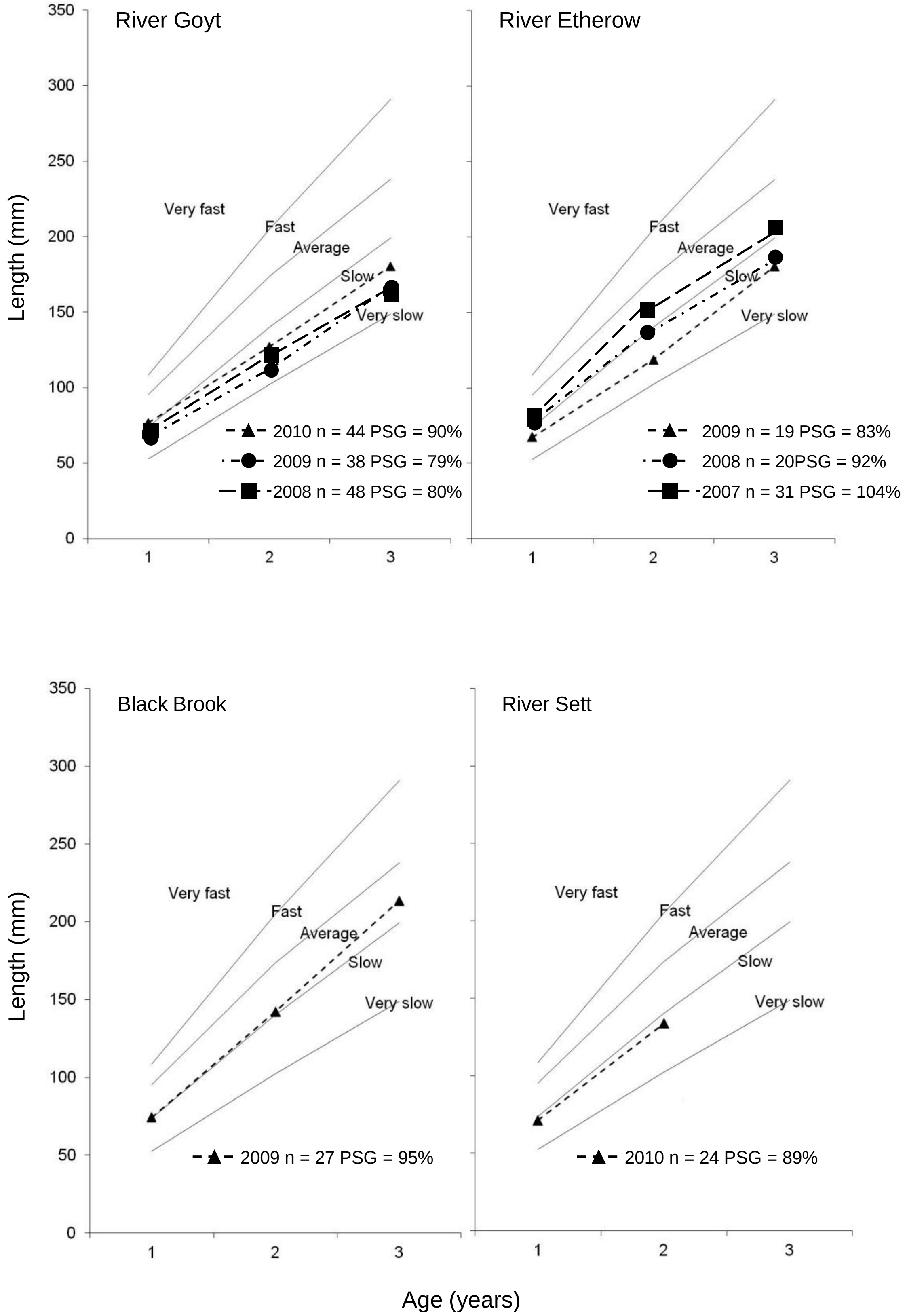


Figure 6.9 Growth rate plots for rivers in the Upper Mersey sub-catchment.

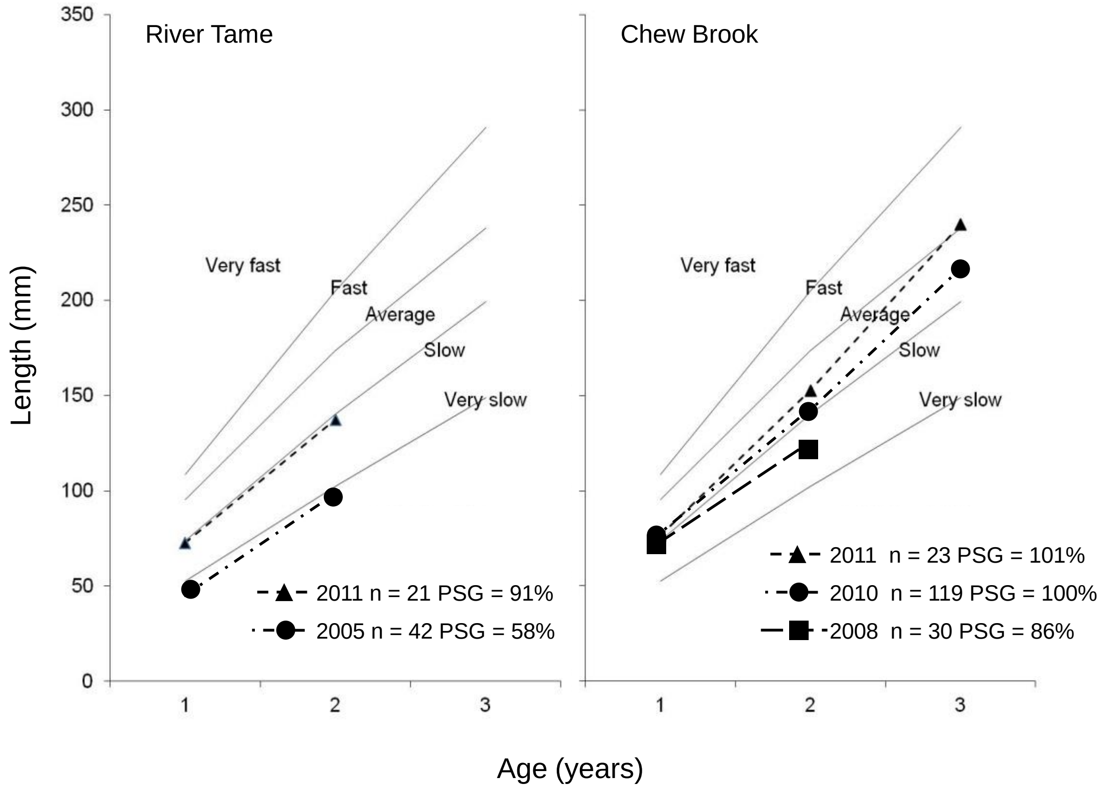


Figure 6.9 (continued) Growth rate plots for rivers in the Upper Mersey sub-catchment.

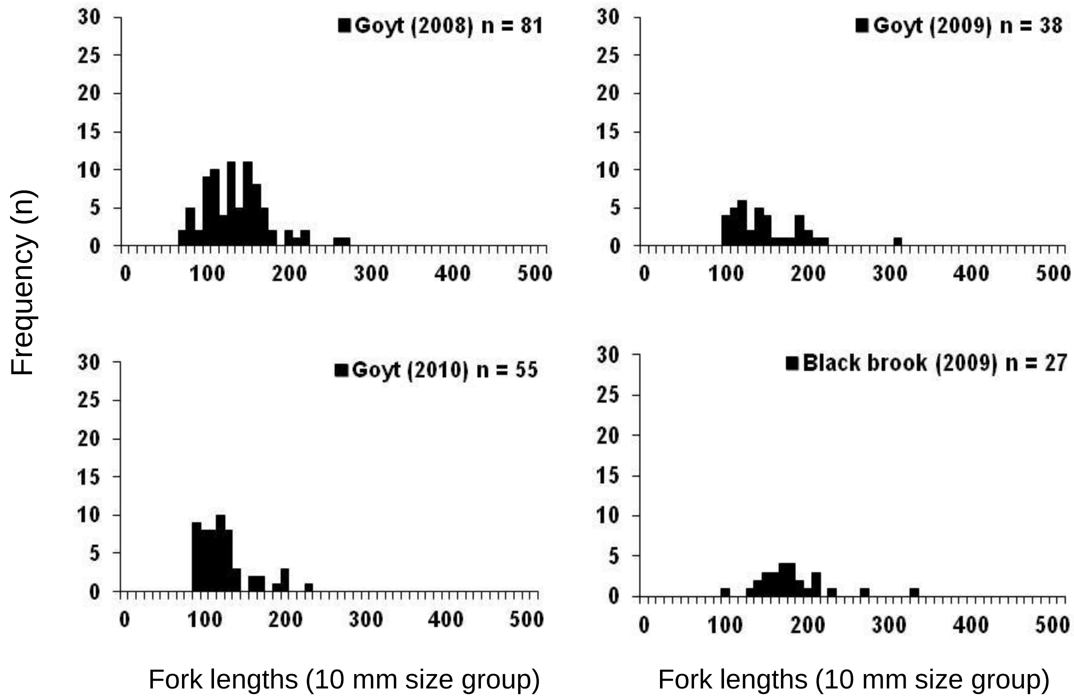


Figure 6.10 Length frequency plots for rivers in the Upper Mersey sub-catchment.

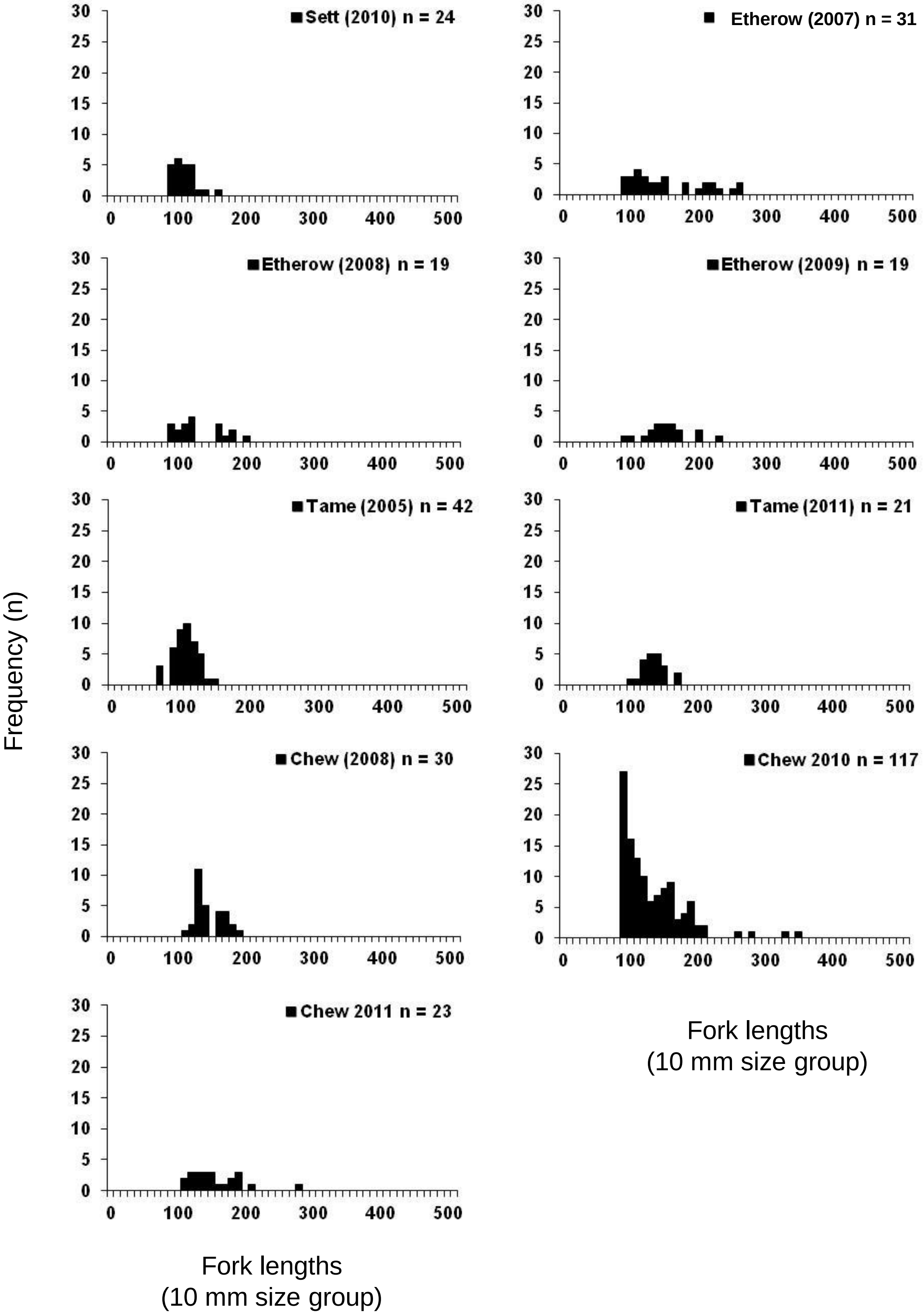


Figure 6.10 (continued) Length frequency plots for rivers in the Upper Mersey sub-catchment.

6.4.1 Overview of the spawning and juvenile habitat in the Mersey catchment

Bollin sub-catchment

There were very low amounts of spawning habitat found the Bollin sub-catchment; 2104 m² of optimal spawning and 9645 m² of sub-optimal (sedimented) spawning habitat. Almost all optimal spawning habitat and the majority of sub-optimal spawning habitat is upstream of significant barriers and inaccessible to migrating salmon. It is worth noting that the single juvenile salmon caught in 2010 in the River Bollin (Chapter 3) was caught downstream of Styal weir, which was then impassable (fish pass constructed in 2014) and in an area classed as sub-optimal spawning habitat. This demonstrates salmon are able to spawn in the sub-optimal spawning habitat. Kondolf & Wolman (1993) documented salmon spawning in substrates with proportions of fine sediments above levels shown to be detrimental to embryo survival. No other juvenile salmon has been caught in the River Bollin sub-catchment (section 3.4.2).

The proportion of sediment-sensitive invertebrates scores (PSI) suggests slightly and moderate sedimentation in the River Bollin, with downstream sites more sedimented, and moderate sedimentation in the River Dean. The Bollin catchment is known to suffer from sedimentation (Environment Agency, personal communication; personal observations; Hendry, 2004) (Figure 3.2). Fry and parr habitat is distributed throughout the catchment and more plentiful than spawning habitat; with 158,452 m² of combined juvenile habitat in the Bollin sub-catchment. However, similar to the spawning habitat much of this was found in the upper reaches of the rivers and upstream of impassable barriers to migrating adult salmon.

As expected (Chapter 3), observed juvenile salmon densities were significantly lower at all sites than predicted from the Habitat Quality Score. A lack of recruitment resulting from low numbers of salmon entering the River Bollin (Chapter 3 and 5) compounded by barriers to migration (Chapter 3 and 6; Figures 6.3 & 6.7) are clear causes of the low or zero densities. However, HABSCORE outputs suggested that even in pristine conditions the current habitat would limit productivity, or juvenile densities, with predictions ranging from class E – C for 0+ and class D for >0+ salmon. Sites BO03, BOBO01 and BOBO02 exhibit the variability in habitat found in the catchment with the predicted densities of 0+ salmon of >23 0+ salmon/100 m² (class C) at sites BO03 and BOBO01 and <9 0+ salmon/100 m² at site BOBO02 (class E and D). These sites are 3.2 km of each other. This also illustrates the difficulty of basing catchment wide assumptions on only a few surveys.

Trout densities at site BO01 (HABSCORE site BOBO01) were highly variable (class A – F). This may result from the natural variability of fish populations (England *et al*., 2007). However, all other sites revealed low densities of class E and F for both 0+ and ≥1+ brown trout suggesting these sites are low productivity sites. HABSCORE outputs suggested trout densities are less than expected at six out of the eight surveys for 0+ trout demonstrating possible issues with water quality or recruitment in the River Bollin. Trout densities were greater than predicted for >0+ trout for five of the eight surveys, which suggests the low 0+ trout densities may be due to recruitment. HABSCORE surveys predicted the lowest trout densities at site BOBO02, but it was only site BOBO02 on the River Bollin that had a HUI score of >1 for 0+ trout (observed density greater than the predicted). The lower expected than observed trout densities illustrate the limitations of HABSCORE as a predictive tool when making site specific predictions of mobile fish populations (England *et al*., 2007; Roy *et al*., 2013). Growth curves describing slow growth rates in the first year of life and predominantly slow in later age groups suggest bottlenecks to growth; the reasons for this are likely to be multifactorial possibly arising from limited food resource, poor habitat, water quality issues or low flows increasing competition for habitat or food.

Mersey sub-catchment

There were very limited amounts of optimal spawning habitat in the upper Mersey sub-catchment: 538 m² and 2004 m² in the Tame and the Goyt and its tributaries, respectively. Excluding <30 m² of spawning habitat in the River Tame (personal observation), all spawning habitat in the River Tame and the majority of spawning habitat in the Goyt was upstream of barriers to adult migration. Reviewing the habitat and juvenile salmon catch data in GIS and by using the GIS measuring tool it was found that the 20 juvenile salmon caught in the River Goyt between 2005 – 2011 (Table 3.5; Figure 3.16) were captured on or very close (<50 m) to the spawning habitat found downstream of all barriers to adult salmon migration. Spawning habitat was confined to the lower reaches of the River Tame and distributed throughout the Goyt. There were large amounts of mixed juvenile habitat distributed throughout the rivers Tame and Goyt and tributaries: 304,529 m² and 212,037 m², respectively. Almost all mixed juvenile habitat in the River Tame and the majority in the River Goyt and its tributaries was upstream of barriers to migrating adult salmon. This is reflected by 22 out of 23 HABSCORE surveys in the Upper Mersey sub-catchment having actual (observed) densities of zero salmon present for both age groups. The PSI score revealed the most upstream sites in River Goyt and Sett to be in good condition with minimal or unsedimented conditions. However, other sites especially the most downstream sites did show signs of sedimentation.

Excluding site SE01 on the River Sett and three surveys at site GO02, the upper Mersey sub-catchment had low densities of 0+ trout (class D – F) suggesting a possible issue with recruitment as with the Bollin trout densities. ≥1+ brown trout densities were more consistent between years at sites and again found trout populations at the most upstream sites to be more productive; the sites which adult salmon are prevented from reaching due to barriers to migration. This was supported by the trout HABSCORE findings with HUI scores of >1 at upstream sites on the rivers Goyt and Sett and the Black, Kinder and Chew brooks and the River Etherow, for all ages of trout. HABSCORE outputs also suggested the more downstream sites performed poorly with observed trout densities lower than the HQS prediction. Sites TATA35 and GYGO05, 06 and 20 performed particularly poorly and the observed trout densities were significantly lower than those predicted by HABSCORE at 9 of the 15 surveys across these sites.

HABSCORE predicted salmon densities were consistent for >0+ salmon (class C – D) for all sites but there was a high variability in the predicted 0+ densities between sites and sections of rivers. Some upstream sites on the Chew and Kinder brooks and rivers Goyt and Etherow had high 0+ predicted densities (Class B – A) and some upstream sites had low predicted densities (E – D). The high variability in predicted salmon densities is well demonstrated by sites SE01a and SE01 which are separated by 1.1 km but have density predictions of 82.74 (class B) and 1.69 (class E) 0+ salmon/100 m^2, respectively. This again illustrates the difficulty in representing a river or catchment by a few surveys; a result of finite resources available to undertake surveys. Predicted salmon densities suggesting salmon populations would be mainly class C – D (average - fair/poor) suggest issues with the habitat and that even if barriers are removed or mitigated the habitat would limit productivity. Growth rates were slow across much of the catchment except the most upstream sites on the River Etherow and Black and Chew brooks supporting the suggestion the upper catchment is more productive than the lower catchment. Similarly to the Bollin there was an absence of <100 mm trout, possibly resulting from poor recruitment.

6.4.2 Potential juvenile salmon and smolt productivity in the Mersey catchment

Potential juvenile salmon density

Juvenile habitat data can be combined with HABSCORE density predictions to provide an estimate of the potential density of juvenile salmon in areas of the catchment that were surveyed. Twenty five of the HABSCORE sites were included in the stretches of river surveyed during the walkovers surveys and were assigned a habitat type (e.g. Fry). The remaining HABSCORE sites were in stretches not surveyed during the walkover surveys and therefore were not assigned a habitat type.

Densities of 0+ salmon as predicted by HQS across all HABSCORE surveys were variable ranging from 1.69 – 175.11 0+ salmon/100 m^2 (mean = 32.76). To estimate potential salmon densities in the Mersey catchment each EA FCS classification for 0+ salmon was assigned a score (A = 1, B = 2, C = 3, etc.). The mean score for HABSCORE sites that were included in the walkover surveys was 3.36. Although 3.36 is closer to Class C, Class D was used to estimate potential 0+ salmon densities in the catchment so as not to overestimate potential densities. Class D was also thought to reflect the catchment better as the catchment has been shown to be a low productivity environment. Twenty of the 25 surveys had HQS predictions of densities of 3.0 – 4.90 >0+ salmon/100 m^2 (class D for >1+ salmon) and the remainder 7.27 – 14.18 >0+ salmon/100 m^2 (class C for >1+ salmon). As such class D was used to estimate potential >0+ salmon densities. Using this rationale the following potential density figures were applied to each habitat type to give an indication of potential salmon production:

- Fry (0+ salmon) habitat: 9 – 22.90 salmon/100 m^2
- Fry and parr (0+ and >0+ salmon) habitat: 3 – 22.90 salmon/100 m^2
- Parr habitat (>0+ salmon): 3 – 4.90 salmon/100 m^2

The total area of each habitat type (m^2) was converted into 100 m^2 and then multiplied by the relevant potential density.

Based on the stretches of rivers in the Mersey catchment surveyed during the walkovers, which included extensive surveys on the rivers Bollin, Tame and Sett, the Black and the Chew and Diggle brooks and the majority of the River Goyt, the catchment could potentially support between 24,500 – 54,354 juvenile salmon (Table 6.11).

Table 6.11 An estimate of the potential numbers of juvenile salmon that stretches of rivers in the Mersey catchment surveyed during the walkover surveys could support.

Rivers	Fry (n)	Fry and Parr (n)	Parr (n)
Bollin	2040 - 5191	1128 - 5191	1128 - 1842
Dean	1440 - 3663	406 - 3663	406 - 663
Tame	2153 - 5477	3994 - 5477	3994 - 6523
Diggle Brook	64 - 162	5 - 162	5 - 8
Chew Brook	227 - 578	55 - 578	55 - 90
Goyt	1617 - 4115	2288 - 4115	2288 - 3738
Sett	365 - 930	214 - 930	214 - 349
Black Brook	133 - 339	141 - 339	141 - 230
Total	8040 - 20456	8230 - 20456	8230 - 13443

Although these figures should be treated with extreme caution as they are approximate estimates based on relatively few surveys in a catchment with high variability in habitat quality, water quality and productivity between sites and years, they give an indication of numbers of juveniles the Mersey catchment could potentially support.

Potential egg deposition

A total of 4706 m² of optimal spawning habitat and 2104 m² of suboptimal spawning habitat were identified during the walkover surveys in the Mersey catchment (Figure 6.3 & 6.7). Egg deposition (eggs/100 m²) is highly variable between salmon populations and depends on a range of environmental and biological factors (Dumas & Prouzet, 2003; de Eyto *et al*., 2015). To convert the amount of spawning habitat found in the Mersey to potential juvenile production an estimation of egg deposition was made. A deposition value of 240 – 650 eggs/100 m² is widely cited in the literature to maintain salmon stocks and to give optimal smolt production (Elson, 1957; 1975; Egglishaw *et al*., 1984, Buck & Hay, 1984; Kennedy, 1988; Kennedy & Crozier, 1993; 1995; Jonsson *et al.*, 1998; Dumas & Prouzet, 2003). A value of 240 eggs/100 m² is used by Canadian Department of Fisheries and Oceans to define the spawning escapement for Atlantic salmon below which no fishing should occur (Gibson & Claytor, 2012). The conservation limits (CLs) of all 64 rivers in England and Wales classed as 'salmon rivers' and requiring a CL by the EA were used to establish an estimation of potential egg deposition in the Mersey catchment. CLs exist on all major salmon rivers in England and Wales and set at a stock size (defined in terms of eggs deposited) below which stocks should not be allowed to fall. The mean egg deposition (eggs/100 m²) for those rivers requiring a CL in England and Wales is 217 eggs/100 m² (range 70 to 395) (Environment Agency, unpublished data); although this includes rivers very different, in terms of water and habitat quality and river and catchment size and type, to the rivers in the Mersey catchment. Using this mean and the deposition values cited in the literature (referenced above) a value of 240 egg/100 m² was used to estimate potential egg deposition in the Mersey catchment. The spawning and sub-optimal spawning habitat identified in the stretches of rivers surveyed in the Mersey catchment during the walkover surveys could potentially support 34,442 eggs, 81% of which is in the Bollin sub-catchment (Table 6.12). However, 82% of spawning habitat in the Bollin sub-catchment was recorded as sub-optimal spawning habitat and therefore it is likely fewer eggs than predicted could be supported due to sedimentation and the resulting reduction in egg survival. Conversely sub-optimal spawning habitat was not recorded in the rivers Goyt and Tame and their tributaries and the estimated egg deposition may under-represent actual potential egg deposition in these rivers. In addition, neither juvenile density nor egg deposition estimates include the River Etherow, which has been shown to be a potentially productive environment. Put into perspective, the River Etherow is 30 km in length (not including its tributaries) compared to the 51.8 km of the River Bollin or 41.2 km of the River Tame surveyed.

Table 6.12 Potential egg deposition in the Mersey catchment in areas surveyed during the walkover surveys. Note; sub-optimal spawning habitat has been combined with optimal spawning habitat in the Rivers Bollin and Dean.

Rivers	egg deposition (n)
Bollin	17719
Dean	10478
Tame	1435
Diggle Brook	0
Chew Brook	0
Goyt	4346
Sett	422
Black Brook	41
Total	34442

The 34,442 eggs the 155 km of river surveyed during the walkover surveys in the Mersey catchment could support seems low. To put this in context, the 321 km of the River Tyne, a post industrial river in the North east of England recently recolonised by salmon (Milner *et al.*, 2004), has had an estimated annual egg deposition rate of over

40 million eggs since 2000 (Williams, 2008; Environment Agency, personal communication) equivalent to an egg deposition rate of 289 eggs/m² (Williams, 2008). This illustrates the lack of suitable spawning habitat in the Mersey catchment severely limits potential egg production, even if barriers were mitigated.

Egg to parr and smolt survival

As indicated above, there is very little spawning habitat in the Mersey catchment, which based on 240 eggs/100 m², could potentially support 34,442 eggs. There is a range of egg to smolt survival rates reported in the literature (Table 6.13) and studies have documented large variability in survival rate of eggs to smolts in rivers between years (Rivot, 2003; Bagliniere *et al.*, 2005) suggesting survival rates can depend on non-density dependent environmental fluctuations (Rivot, 2003; Molin *et al.,* 2010). Using an egg to smolt survival rate of 1% (the mean survival rate of those studies quoted in Table 6.13 with the Freshwater Brook study removed owing to a very high survival rate thought to be unrealistic for the Mersey catchment) the Mersey could produce 344 smolts from the deposition of 34,442 eggs.

There is a range of egg to 0+ parr survival rated reported in the literature (Table 6.13). A survival rate of 2% has been used to estimate egg to 0+ parr survival rate in the Mersey catchment; the mean survival rate of 10% of the studies cited in table 6.13 was not thought to represent the Mersey catchment as it contained rivers free from the impacts of heavy human activities (Southwest Miramichi, Fender Burn and Shelligan Burn) so these were removed when generating a mean survival rate (2%).

A survival rate of 2% would result in the potential production of 689 0+ salmon form 34,442 eggs, 1.3 - 2.8% of the potential densities of 24,500 – 54,354 juvenile salmon the Mersey catchment could support based on available habitat (Table 6.11). From a visual examination of the walkover findings in GIS it is estimated only 5%, 20% and 15% of spawning and sub-optimal spawning habitat in the rivers Tame, Goyt and Bollin and their tributaries is downstream of a significant barrier and accessible to adult salmon. Using a 2% egg to 0+ parr survival rate these available spawning areas would produce just 2, 38 and 85 0+ parr or using the 1% egg to smolt survival rate 1, 19 and 43 smolts from the rivers Tame, Goyt and Bollin and their tributaries, respectively.

Table 6.13 Egg to 0+ parr and egg to smolt survival rates in some northern American and European Atlantic salmon populations (taken from Bagliniere *et al.* (2005)).

River	Egg to 0+ parr survival (%)	Egg to smolt survival (%)	Reference
Polett	4.0	2.0	Elson (1975)
Big salmon		0.2	Jessop (1975, 1986)
Western Arm Brook		1.7	Chadwick (1981), Chaput *et al*. (1992), Caron (1992)
Trinite		3.2	Caron (1992)
Bec-Scie		1.6	Caron (1992)
Conne		0.5	Dempson *et al.* (1995), Dampson & Furey (1997)
Northeast Brook		0.4	O'Connell *et al.* (1992)
Freshwater Brook		52.0	O'Connell *et al*. (1992)
Southwest Miramichi	26.0	0.4	Cunjak & Therrien (1998)
Northwest Miramichi		0.7	Chaput *et al.* (1998)
Fender Burn	12.9		Egglishaw & Shackley (1980)
Shelligan Burn	16.5		Gardiner & Shackley (1991)
Bran			Mills (1964)
Girnock Burn		0.9	Buck & Hay (1984), Hay (1991)
Wye			Gee *et al*. (1978)
Exe			Nott (1970)
Bush		1.2	Kennedy & Crozier (1993), Crozier & Kennedy (1995)
Burrishoole		0.6	Anon. (1970 - 1994)
Nivelle	1.0		Dumas & Prouzet (2003)
Oir	1.1	0.4	Bagliniere *et al*. (2005)

A range of parr to smolt survival rates have been reported in the literature for salmon, for example, 0.01 – 35% in rivers in North Wales, UK (Pedley & Jones, 1978), 13% in the West River, Vermont, USA (McMenemy, 1995), 27 - 46% in three tributaries of the West River, Vermont, U.S.A (Whalen *et al.*, 2000), 8 – 25% (Achord *et al.*, 2007), 2.9 – 7.2% in the Margaree River, Nova Scotia (Breau *et al.,* 2010) and 9.6 – 81.7 (Connor & Tiffan, 2012). A standard parr to smolt survival rate of 50% is used by the Environment Agency in Salmon Action Plans for the River Tyne and Tees in the North East of England (Williams, 2003). To illustrate potential smolt production from the potential density of 24,500 – 54,354 juveniles based on available juvenile habitat identified in the Mersey catchment and using an illustrative parr to smolt survival rate of 30% the Mersey catchment could currently potentially produce 7350 – 16,306 smolts. This is significantly more than the predicted 344 smolts from the deposition of 34,442 eggs, indicating spawning habitat is a significant limiting factor in the Mersey catchment. To further illustrate this; in support of setting conservation limits in salmon rivers in 2003 the Environment Agency set new marine survival rate values for salmon of 11% for one sea winter salmon and 5% for multiple sea winter fish (Anon, 2003). Using 11% survival rate a smolt production of 7350 – 16,306 individuals could result in 808 - 1794 adults returning to the Mersey compared to a smolt production of 344 which could result in 38 adults returning to the Mersey.

6.4.3 Conclusions

This chapter began with the hypothesis that habitat availability, accessibility and quality is not a limiting factor in the Mersey catchment and would not inhibit the survival or growth of juvenile salmon. It has been demonstrated that habitat accessibility, particularly spawning habitat, resulting from barriers to migration (Figures 6.3 & 6.7), is likely to severely limit juvenile and smolt production in the Mersey catchment. River connectivity is fundamental to the upstream migration of salmon (Thorstad *et al.,* 2008) and anything acting to prevent access to key spawning habitats will be detrimental to a salmon population (Gowans *et al.*, 2003; Thorstad *et al.*, 2008 Lucas *et al.*, 2009) or in the case of the Mersey, limit or potentially prevent recolonisation. The cumulative effect of multiple partial barriers on the upstream migration and motivation of salmon has been documented (Gowans *et al.,* 2003; Thorstad *et al*., 2005) and the many partial barriers to salmon migration in the Mersey catchment (Figure 3.5) may further reduce the number of adults accessing the available spawning habitat. Salmon have been documented using unsuitable areas to spawn as a result of barriers to migration (Thorstad *et al.*, 2008), which will reduce the survival of eggs and newly emerged fry (Armstrong *et al.*, 2003; Jonsson & Jonsson, 2011). The single juvenile capture downstream of Styal weir suggests this is occurring in the River Bollin (section 3.4.2).

The total area and distribution of suitable spawning gravel are of fundamental importance in determining the productivity of a river and may limit the productivity in many streams (Kondolf & Wolman, 1993; Armstrong *et al.*, 2003). The total area of spawning habitat in the Mersey catchment is low and even if all barriers were mitigated (e.g. removal or provision of fish passes) this will remain a significant limiting factor in salmon production in the Mersey catchment. There are large areas of fry and parr habitat available, estimates of juvenile production from egg deposition suggest these habitats will go under-utilised and the amounts of fry and parr habitats may not serve as a limiting factor in themselves; they are, however, frequently found upstream of barriers to adult salmon and so remain inaccessible.

Habitat quality is central to the performance of juvenile salmon (Stradmeyer & Thorpe, 1987; Armstrong *et al*., 2003; Finstad *et al.,* 2007; Jonsson & Jonsson, 2011).

HABSCORE predicted low densities of salmon juveniles which suggests habitat quality may also limit salmon productivity, which is supported by the walkover surveys and PSI scores. Trout fisheries and HABSCORE data found the catchment to be underperforming suggesting recruitment or issues such as connectivity or water quality are limiting trout performance. These same issues are likely to affect salmon and so limit productivity and a potential recolonisation. Water quality issues, for example ammonia concentrations, which exceed the FFD Guideline concentration of <0.04 mg l^{-1} in all rivers in the study area, are known to exist (section 3.3.3). As discussed in Chapter 3 water quality may not prevent a recolonisation but it is likely to reduce salmonid performance. Roy *et al*. (2013) found variation in salmonid movement behaviour was in response to changing environmental conditions rather than a behavioural trait. The high degree of variability in trout densities between years at sites in the Mersey may therefore indicate changing environmental conditions possibility resulting from water quality issues. Between 2000 and 2015 the EA has recorded 28 category 1, 151 category 2 and 25 category 3 incidents on rivers in the Mersey catchment (where category 1 is major (e.g. persistent, extensive or serious damage to water quality, >100 fish killed or closure of abstraction point) category 2 is significant (e.g. significant damage to ecosystem, 0 – 99 fish killed) and category 3 is minor incident (Anon. 2013b)).

Adult salmonids avoid spawning in substrates with high proportions of fine sediment (Soulsby *et al*., 2001; Moir *et al*., 2002), although some salmon spawn in sediments with proportions of fine sediments above levels shown to be detrimental to embryo survival (Kondolf & Wolman, 1993). A high content of fines (particles of 0.0-2.0 mm diameter (Crisp, 1996)) is known to adversely affect the development of embryos by preventing sufficient permeation of oxygenated water into the interstitial spaces within the gravel (O'Connor & Andrew, 1998; Armstrong *et al.*, 2003; Jonsson & Jonsson, 2011). It has been demonstrated that the Mersey suffers from moderate to slight sedimentation and that the River Bollin contains a relatively large amount of sub-optimal (sedimented) spawning habitat. Sedimentation will limit egg survival in the Mersey catchment and so may limit the potential for future recolonisation. This is of significance as salmon survival during the first year may be regulated by survival in the redd substrate (Dumas & Prouzet, 2003).

Fluctuations in discharge influence the transport and deposition of fine silt and movements in stream-bed gravel (Crisp, 2000) and elevated flows are known to 'clean' silted gravels and so improve the spawning substrate and survival rate of eggs and gravel related larval life stages in fish (Reiser *et al*., 1989; Wood & Armitage, 1997;

Milhouse, 1998). Flow in the Mersey catchment is regulated with typically reduced higher flows and low flows augmented above natural levels (Chapter 3). The reduction in higher flows in the Mersey catchment could potentially increase sedimentation and limit the creation, amount and the quality of spawning and juvenile habitat. Small weirs have significant effects on flow, sediment transport and stream habitat (de Leaniz, 2008) and, in addition to reduced flows, the effect of impoundments in the form of the large number of weirs and obstructions in the catchment (Figure 3.5) may also increase sedimentation. As well as increased sedimentation and as described in Chapter 3 the reduced higher flows and low flows augmented above natural levels in the Mersey catchment, particularly in the autumn months, may also limit the upstream migration of adult salmon by impacting on flow dependent behaviours such as upstream migration and upstream movement past physical barriers (Chapter 2). Reductions in flow can also have a direct effect on egg and embryo survival through dewatering during the incubation period (Malcolm *et al.*, 2012). The risks can be pronounced in regulated rivers where redds constructed during higher discharges will be dewatered as flows return to compensatory flow (Gibbins & Acornley, 2000). It is not known if spawning habitat is vulnerable to dewatering in the Mersey catchment and although unlikely due to augmented low flows this warrants further investigation.

A number of other factors are known to affect juvenile survival such as shade and overhead cover (Gibson, 1978; Pickering *et al*., 1987; Heggenes *et al.,* 1999) or inter-species competition (Armstrong *et al*., 2003; Milner *et al*., 2003). However, these are beyond the scope of this study and warrant further investigation in the Mersey catchment. It should also be noted that this study is based on few fisheries, HABSCORE and PSI sites and surveys which have been sampled inconsistently and while conclusions and estimates of productivity have been made these should be treated with caution. The natural variability in fish populations (England *et al.,* 2007) and limitations of electrofishing surveys (Niemela *et al*., 2000; Specziar *et al*., 2012; Benejam, 2012) also mean the results and conclusions should be treated with caution. The lack of consistency of sampling at some sites and the few sites included in this investigation prevent temporal trends from being clearly identified or diagnosed, such as the possible decrease in 0+ brown trout abundance from 2003 at sites on the rivers Etherow, Goyt and Sett or the apparent increase in growth rate of brown trout in the River Bollin, where the time of year of the survey may have affected ageing accuracy. In addition, surveyors often choose fisheries sites, and therefore HABSCORE sites, with easy access and sites which are believed to contain good habitat and so fish populations, so the results of these surveys may not reflect the catchment as a whole. However, the information provides a high-level description of the catchment and highlights some of the key issues and limiting factors that may affect recolonisation and establishing a self-sustaining salmon population.

The data suggest the Mersey catchment is highly variable in habitat quality and fisheries performance, although there appears to be less sedimentation, more productive environments and greater amounts of key salmonid habitat in upstream stretches. These areas are all upstream of significant barriers and inaccessible to adult salmon; the inaccessibility of key habitats therefore may well go beyond limiting a recolonisation in the Mersey catchment but in fact inhibits one. Despite this, if some barriers were mitigated, by removal or provision of fish passes, habitat quality and quantity is such that adults could spawn in the catchment and juvenile salmon could survive, although the catchment is currently capable of producing only a limited number of smolts (approximately 344) limited by the amount of spawning habitat. Potential mitigation measures are discussed in Chapter 7.

6.4.4 Summary

1. Very low amounts of salmon spawning habitat were found in both the Bollin and Upper Mersey sub-catchments most of which was inaccessible to adult salmon.

2. Greater amounts of fry and parr habitat are available compared to spawning habitats and estimates of juvenile production from potential egg deposition suggested these habitats will go under-utilised. Much of these habitats, however, are inaccessible to adult salmon due to man-made barriers.

3. HABSCORE predicted poor performance of salmon juveniles which suggests habitat quality may also limit juvenile salmon and smolt productivity.

4. Trout fisheries and HABSCORE data suggest the catchment to be underperforming signifying recruitment or issues such as connectivity or water quality are potentially limiting trout performance. These same issues are likely to affect salmon and so limit productivity and recolonisation.

5. Sedimentation of gravels is occurring in the Mersey catchment and will limit egg survival and so limit a future recolonisation.

7 GENERAL DISCUSSION

7.1 INTRODUCTION AND OVERVIEW

The overall aim of the study was to review the recent history of the Mersey catchment and the current status of the salmon population, to investigate the origins, success and factors effecting the natural recolonisation of River Mersey, and to suggest key management and conservation measures to support a natural recolonisation. This chapter will review the previous chapters and conclude whether the Mersey catchment could be naturally recolonised by salmon in its current state and suggest key management and conservation measures to either support a natural recolonisation or to restore salmon to the Mersey catchment. The chapter will also focus on the likelihood of success, the resources required and ultimately if the potential restoration of salmon warrants the effort and resources required.

Most salmon populations are anadromous and undertake large-scale transitional migrations between marine and freshwater habitats to spawn (Chapter 2). The habitat and water quality requirements of spawning salmon, their eggs and juveniles are highly specific (Chapter 2). Straying is thought to be a natural component of salmon population biology allowing the colonization of newly available habitats and as such conservation efforts are now seen as an alternative management strategy to the stocking of salmon (Chapter 2). A number of studies have documented salmon forming naturally occurring, self sustaining populations through natural straying and the mitigation of historic limiting factors alone (Vasemagi *et al*., 2001; Schreiber & Diefenbach 2005; Kiffney *et al.,* 2009), sometimes over relatively short time frames, with some occurring within as little as 1 – 5 years after salmon first began entering a newly available river (Bryant *et al*, 1999; Glen, 2002). The time period for colonisation and establishment of self sustaining populations, regardless of whether the new habitat is newly opened or re-opened, very rarely exceeded 30 years and most occurred within 20 years (Chapter 2).

The Mersey catchment, situated in the North West of England, historically supported a large salmon population before the Industrial Revolution and during the 20th Centaury salmon became extirpated from the Mersey catchment. The Mersey catchment is highly modified, with regulated flows, residual water quality issues, total or partial obstructions to upstream migration of salmon present and limited spawning habitat (Chapters 3, 5 and 6). Despite these issues, salmon began entering the Mersey estuary and then the River Mersey and its tributaries in the 1990s. Between 2001 and

2013 230 ascending adult salmon have been captured at a fish pass fitted to Woolston weir and 21 juvenile salmon have been captured between 2005 and 2011 in the rivers Goyt and Bollin (Chapter 3). However, the number of adult and juvenile salmon are not increasing over time and the presence of smolts has never been recorded by or reported to the EA (Chapter 3). The River Mersey is still dependent on stray salmon with the majority of strays entering the River Mersey from rivers in the Solway and Northwest England areas; there is also evidence of long distance straying by salmon from a range of areas into the River Mersey and only a few salmon entering the River Mersey were of a farmed origin (Chapter 4). There also appears to be a southerly direction of straying by salmon in the eastern Irish Sea (Chapter 4).

This study has identified several key issues hindering or preventing a recolonisation of the Mersey by salmon. These issues result in too few salmon reaching spawning grounds to establish a self sustaining population. The key issues are:

1. Low numbers of adults entering the Mersey catchment. Based on catches of salmon at the fish trap fitted to Woolston weir between 26 and 70 adult salmon are entering the Lower Mersey a year.

2. Barriers to migration. The findings of the tracking studies demonstrate salmon cannot move freely within and upstream of the lower Mersey catchment; only 26% (n = 9) of tagged salmon moved upstream of the receiver network. Walkover surveys and GIS data sets have identified several impassable and significant barriers and many passable barriers in the Mersey catchment.

3. The Manchester Ship Canal. The complex nature of the Ship Canal and the existence of the locks prevent salmon form locating optimum migratory routes (i.e. locating confluences), cause erratic behaviour, increases salmon exposure to environmental stressors and prevent salmon from moving downstream of the lower Mersey catchment into the Lower River Mersey.

4. Availability and accessibility of spawning habitat. Only 4706 m^2 of optimal spawning habitat and 2104 m^2 of suboptimal spawning habitat were identified in the Mersey catchment. The majority of this, and the identified juvenile habitat, was found upstream of impassable barriers and so therefore inaccessible to migrating adult salmon.

5. Cumulative impact of limiting factors. In addition to the above: water quality in the catchment, particularly in the Ship Canal, was found to be poor with ammonia concentrations in all rivers and dissolved oxygen in the Ship Canal and Upper and

Lower River Mersey not meeting FFD guideline concentrations; habitat quality was found to be poor and low productivity environments suffering from sedimentation; all rivers in the catchment are subject to artificial influences from both discharges and impoundments and there is a typical trend of reduced higher flows and low flows above Q75 augmented above natural levels. As a result the lower Mersey catchment will likely serve to elevate levels of stress in salmon and the cumulative effect of a range of limiting factors are therefore likely to affect fitness, motivation and the likelihood of salmon moving upstream and spawning successfully.

6. Although not investigated as part of this study the cumulative effect of moving downstream over barriers and the Ship Canal and the potential difficulty locating the Lower River Mersey are likely to impact on the seaward migration of smolts.

7.2 MANAGEMENT AND CONSERVATION MEASURES OF SALMON

The scientific literature and a range of management guides contain a range of tools and techniques for restoring and enhancing salmon populations (Hendry *et al*., 2003; Pretty *et al.,* 2003; Jonsson & Jonsson, 2009; Skaala *et al*., 2014; Beechie *et al*., 2015) many of which are to mitigate or remove anthropogenic impacts (Hendry *et al*., 2003; Pretty *et al.,* 2003; Saltveit *et al*., 2014). A full review of management techniques is beyond the scope of this thesis (see Hendry *et al.,*2003 and Jonsson & Jonsson, 2009 for a review) and instead the chapter will provide a high level review of the most common tools and techniques available to fisheries managers.

Stocking, the release of hatchery reared salmon at various life stages into rivers or estuaries, has been seen as a rapid solution to declining numbers of fish (Milner *et al.,* 2004; Fraser 2008; Jonsson & Jonsson, 2009) and can be an effective tool (McDowall, 1990; Bielak *et al.*, 1991; Thorpe, 1994; Aprahamian *et al*., 2003; Milner *et al.*, 2004; Ciancio *et al*., 2005). Stocking is often used to supplement natural reproduction when it is below the rivers' natural carrying capacity (Table 7.1 a). Stocking can be targeted to the periods of the life cycle of salmon where there is a marked reduction in abundance because of a population bottleneck and is often used in regulated rivers where dams prevent adults from reaching spawning grounds (Jonsson & Jonsson, 2009).

Table 7.1 (a) and (b) Common salmon population enhancement and river restoration techniques available to fisheries managers; stocking, barrier mitigation, habitat restoration and enhancement, water quality and quantity.

Technique	Description	Benefits and use	Risks and difficulties	Sources
Supportive Breeding	Gathering of artificially stripped and fertilized gametes, progeny are reared in hatcheries and released at various life stages	Useful to supplement yields especially if access to or amount of nursery areas limit natural production	Ecological competition; interbreeding with native fish reducing success; spreading of diseases and parasites	Einum & Fleming, 2001; Jonsson & Jonsson, 2009
Egg Planting	Fertilised salmon eggs placed in boxes or freely in river gravels to hatch	Success of planting eggs can reach 90% and can be more cost effective than rearing and releasing hatchery fry, parr or smolts	Eggs are easily killed through mechanical shock; too high an egg density can result in infection; very specific gravel conditions required	Barlaup & Moen, 2001; Coghlan & Ringler, 2004.
Fry and Parr Stocking	Point or scatter stocking of juvenile salmon raised in hatcheries in a river	Useful when spawning sites or key juvenile habitats are limited or when density of natural bred conspecifics is low	Influenced by the quality, size, density and time and place of stocking; huge range in survival and cost:benefit; survival dependent on in river conditions and can be density-dependent	Hyatt *et al* ., 2005; Saltveit, 2006; Jonsson & Jonsson, 2009
Smolt Release	Released in spring in the river or estuary to start their seaward migration immediately	When freshwater habitat limits salmon production or when impoundments prevent adults accessing headwaters	Poor cost effectiveness when compared to stocking parr; higher straying and survival rates than juvenile releases and natural smolts	Hansen et al., 1993; Jonsson & Jonsson, 2009
Post Smolt Release	To avoid coastal predation post-smolts are released directly into the ocean	Provide significantly higher recapture rates than releasing smolts	Exhibit higher straying rates and temporal delay in river accent than smolt releases as adults	Hansen et al., 1993; Jonsson & Jonsson, 2009
Barrier Mitigation				
Fish Pass	Several forms of passes including fish ramps, bypass channels and technical fish passes (pool-type and baffle passes)	Restores river connectivity without disrupting the functioning of the dam / barrier	Can be size selective; fish can have problems locating entrances, especially in the face of higher flows elsewhere; stress and physiological cost of using fish pass	Gowans *et al.,* 2003; Meixler *et al* ., 2009; Robson *et al* ., 2011.
Barrier removal or demolition	Removing the dam or obstacle form river completely	Can be cheap and easy to remove small weirs; completely removes barrier; can return river flow to normal (pre-barrier) dynamics both up and downstream of barrier and lead to the creation of spawning / juvenile habitat	Complex engineering required; some dams serve an operational need; risk of flooding or unforeseen change in flow and river dynamics; sometimes high cost of removal; some rivers may not recover as long term changes are not always reversible	de Leaniz, 2008; Robson et al., 2011.
Transporting adult salmon upstream or juvenile downstream of barriers	Capture adult salmon downstream of a barrier(s) and transport and release them upstream; capture escaping smolts and transport them further downstream to prevent them having to negotiate barriers	Does not require complex engineering work; can release fish at preferable location, i.e. spawning ground, headwaters or estuaries	Requires annual catch-transport work; can be stressful and damaging to salmon, not a long term solution	Fast, 2005; Liedtke *et al.* , 2009; Anon, 2015

Table 7.1 (c) Common salmon population enhancement and river restoration techniques available to fisheries managers; stocking, barrier mitigation, habitat restoration and enhancement, water quality and quantity.

Technique	Description	Benefits and use	Risks and difficulties	Sources
Gravelling	Placing gravel in river channel to improve or increase spawning habitat	Specific gravel size can be deposited in areas with ideal flow or water quality. Has been documented as highly effective in increasing salmon production	Gravels vulnerable to river flows and deposited gravels can be washed out and sedimentation can occur	Hendry, 2004; Jonsson & Jonsson, 2009
Gravel cleaning	Removing the silt from the gravel by mechanically means such as a vibrating bucket, raking or ploughing gravel or using high power hose	Clean gravels available to salmonids; gravels have been naturally deposited and likely to remain	Invasive and costly technique; silt often returns as causes of siltation remain, causes siltation downstream; limited period when this can be done so as not to impact on migrating salmon or eggs already laid.	Hendry *et al* ., 2003; Hendry, 2004; Jonsson & Jonsson, 2009
Woody debris	Placing (and fixing) logs and braches in stream	Increases abundance of insect larvae for juvenile salmon to prey on; increases shelter and overhead cover for salmon	Washed away in high flows; can act to trap silt and reduce available gravels; can trap other material and form dams or blockages	Jonsson *et al* ., 1998; Armstrong *et al* ., 2003; Jonsson & Jonsson, 2009
Instream structures	Placing boulders, digging pools, raising stream beds to form riffles, or woody debris in stream	Increases habitat complexity and heterogeneity; alters flow regimes, increase turbulence and provide refuges	Can have unknown consequences on both upstream and downstream sections, e.g. can act to trap silt and reduce available gravels; can trap other materials and form dams or blockages	Jonsson *et al* ., 1998; Armstrong *et al* ., 2003; Hendry *et al* ., 2003; Pretty *et al* ., 2003; Jonsson & Jonsson, 2009
Riparian structures	Structures such as deflectors, overhangs or boulders built into or placed in or along bank	Increases habitat complexity and heterogeneity; alters flow regimes, increase turbulence and provide refuges	Can have unknown consequences on both upstream and downstream sections, e.g. can act to trap silt and reduce available gravels; can trap other materials and form dams or blockages	Jonsson *et al* ., 1998; Jonsson & Jonsson, 2009
Control of riparian vegetation	Pruning and removing grasses, shrubs and scrub trees, typically to prevent over shading	Can have significant effect on standing crop of juvenile salmonids	Riparian shade is critical and removing too much will have negative impact	Hendry *et al.* , 2003
Protection of riparian vegetation	Protecting or the planting of vegetated banks and sources of riparian shade and cover	Provide overhead cover and shade, reduces summer temperatures, increases bank stability and run off from banks	Tunnel vegetation can over shade stream and reduce salmon population productivity	Armstrong et al., 2003; Jonsson & Jonsson, 2009; Broadmeadow *et al.* , 2010

Table 7.1 (d) Common salmon population enhancement and river restoration techniques available to fisheries managers; stocking, barrier mitigation, habitat restoration and enhancement, water quality and quantity.

Technique	Description	Benefits and use	Risks and difficulties	Sources
Water Quality				
Aeration	Often in extreme oxygen depletion situation aeration, either as a temporary instillation or a purpose designed solution, used increase dissolved oxygen concentration	Can dramatically increase dissolved oxygen concentrations quickly and easily	Can be costly; reliant on repeat treatment; does not treat cause and river still vulnerable to low dissolved oxygen; is not a long term solution.	Hendry *et al.* , 2003
Working with farmers	Mitigating or reducing the impacts of poor farming practices, particularly in response to agricultural intensification	Reduce sheep dip pollution, sedimentation resulting from poor land use and cattle poaching, organic of chemical fertilizer pollution, bank erosion	Costly and resource intensive often ineffective over large scales; reliant on good will of farmers.	Millbrand, 1997; Hendry *et al* ., 2003;
Work with and influence industry and regulators	Work with key industries to reduce industrial contaminants, such as heavy metals or organic chemicals discharged from point sources, and sewage work discharges	Reduce chronic and acute point source pollution and episodic events at source	Very difficult to influence industry, decisions usually need to be economically or politically driven.	Hendry *et al* ., 2003;
Work with and influence political decision makers and regulators	To tackle wider issues such as urban diffuse pollution or fly tipping in an area/city wide policy or strategy may be required	Reduce chronic and acute point source and diffuse pollution and episodic events at source	Very difficult to effectively deliver over large scale; reliant on others for support; decisions usually need to be economically or politically driven	Crisp, 1996; Hendry *et al* ., 2003;

Table 7.1 (e) Common salmon population enhancement and river restoration techniques available to fisheries managers; stocking, barrier mitigation, habitat restoration and enhancement, water quality and quantity.

Technique	Description	Benefits and use	Risks and difficulties	Sources
Water Quantity				
Management of abstractions	Work with regulators to influence the balance of maximising yields of river water and environmental impacts, i.e. reduction in flow.	Sustaining flow, a key requirement of salmon, preventing low flows during key periods, e.g. upstream migration	Application of generic operating rules may be an ineffective and inefficient use of water resources	Gibbins *et al.* , 2001; Webb *et al* ., 2001; Hendry *et al* ., 2003
Compensation flows	A general feature of reservoir management is to release compensation water to the impounded river to protect a flow range or a low flow minimum	Low risk and sustainable; can be a set amount or varied seasonally; can reduce flood and peak flows and damaging scour or prevent low flows and drying out; can sustain water depths, help in the dilution of pollution and prevent high summer temperatures	Effective use depends on knowledge of the life history and environmental requirements of salmon in river; idealistic regimes are not always achievable due to engineering and operational constraints	Gibbins *et al.* , 2001; Webb *et al* ., 2001; Hendry *et al* ., 2004
Reservoir release to stimulate migration	Specific timings of releases of stored water to encourage upstream migration	Can cause upstream migration in rivers with low or regulated flows; can influence timings of upstream migration	Dependent on stored water, local considerations, such as flood risk, and operational requirements	Gibbins *et al.* , 2001; Hendry *et al* ., 2005; Milner et al., 2012
Reservoir releases to benefit juvenile stages	Enhanced flows can benefit egg incubation, fry and parr stages	A cheap and easy way to increase salmon production	Dependent on stored water, local considerations, such as flood risk, and operational requirements; sometime unknown or unanticipated effects such as wash out	Hendry *et al* ., 2003;
Channel manipulation	Channel modification to mitigate impacts of unfavourable flows, such as physical narrowing of the channel	Can reinstate favourable velocity and depth conditions	Can be costly and technically difficult; rivers flow can alter manipulation work, especially smaller scale works;	Hendry *et al* ., 2003; Pretty *et al* ., 2003

The importance and impact of river connectivity and impacts of barriers on salmon has been reviewed in Chapters 2, 3, 5 and 6. There are a number of barrier mitigation measures (Table 7.1 (b)). Habitat manipulations resulting in improved feeding opportunities and the amount and quality of spawning and nursery habitats can augment salmon abundance and growth (Hendry *et al*., 2003; Pretty *et al.*, 2003; Jonsson & Jonsson, 2009; Beechie *et al*., 2015). There are a range of techniques used by fisheries managers and conservationists to improve habitat (Table 7.1 (c)). Many of the techniques described in Table 7.1 (c) result in increased shelter and habitat complexity, the benefits of which are reviewed in section 2.2.7. Salmon have specific water quality and quantity (flow) requirements (Chapter 2). The majority of deteriorations to both water quality and quantity, to the point where they no longer meet requirements of salmon, are a result of human activity and many of the management activities look to reduce human impact (Table 7.1 (d) and (e)).

7.3 CONCLUSIONS AND RECOMENDATIONS

7.3.1 Conclusions

In reviewing success and failures of native freshwater fish reintroductions Cochran-Biederman *et al*. (2014) found 65% of failed cases did not address the initial cause of decline, whereas 68% of the successful cases did. Cochran-Biederman *et al*. (2014) went on to conclude identifying and addressing the initial causes of a decline is the most important action to take to avoid reintroduction failure and that careful research of which factors led to the declines is crucial. This approach, although seemingly obvious, is a noted observation and point of learning in several attempted reintroductions (Milner *et al.,* 2004; Fraser *et al.*, 2007; Monnerjahn, 2011; Griffiths *et al.*, 2011; Kesler, 2015). River restoration through improved water quality and connectivity and conservation strategies seeking to restore ecosystem function and continuity are now recognised as a highly effective means to facilitate natural recolonisation and so the restoration of a salmon population (Milner *et al.,* 2004; Lawton *et al.,* 2010; Ikediashi *et al*., 2012). There are a growing number of natural recoveries through straying that have been documented in recent years (section 2.3.4).

The literature remains equivocal on the suitability and success of hatchery reared and/or stocked salmon (Potter & Russell, 1994; Schroeder *et al*., 2001; Pedersen *et al*., 2007; Finnegan & Stevens 2008; Fraser 2008; O Maoileidigh *et al.,* 2008; McGinnity *et al.,* 2009; Griffiths *et al.,* 2011; section 7.2.1) and contains several examples of the negative impacts of stocking (Einum & Fleming, 2001; Ayllon *et al.,* 2006; Griffiths *et* *al.,* 2009; Griffiths *et al.,* 2011). Einum & Fleming (2001) suggested the success of stocked salmon could be improved and their negative effects, such as aggressive behaviour and reduced homing success, reduced through better management practices such as broodstock selection and mating protocols. However, with findings such as O Maoileidigh *et al.* (2008) who reviewed the success of stocking practices in Ireland between 1995 and 2008 in 45 individual rivers and concluded that the extensive stocking programmes made little or no contribution to the productivity of Irish salmon rivers or to restoring self-sustaining salmon runs, stocking is now no longer the default management tool of fisheries managers. Artificial reproduction will not lead to recovery unless fundamental problems that cause the population to decline are addressed (Jonsson *et al*., 1999).

Stocking has helped to restore some populations (section 2.3.4). Cochran-Biederman *et al*. (2014) reported that stocked salmon had a higher survival rate when the source stock was adapted to local conditions, i.e. broodstock taken from nearby river. Although care must be taken; Jonsson & Jonsson (2009) reported a decline in salmon in the River Suldalslagen, southwest Norway, resulting from broodstock being taken from the few returning adults for stocking to that river and the programme was eventually discontinued.

Biederman *et al*. (2014) reported migratory access and suitable physical habitat were the most important variables in salmonid reintroductions. There are many examples in the literature of restoration or enhancement of salmon populations through habitat improvements and barrier mitigation alone (Table 7.1 (b) and (c)), the importance of both is reviewed in sections 2.2.6 and 2.2.7, and very little evidence exists of any negative impacts of such techniques.

Water quality and quantity are more difficult for the fisheries or conservation manager to influence (Table 7.1 (d) and (e)). Water quality is affected by a range of sources, from urban diffuse pollution to point source agricultural pollution (Hendry *et al*., 2003; Saltveit *et al*., 2014) and their control and prevention is often complex and political and economically driven (Monnerjahnm, 2011; Skaala *et al*., 2014). Fisheries and conservation managers are limited in their influence and control of flow, in that operational and engineering needs, such as flood prevention or water resource management, take priority (Webb *et al*., 2001). Consenting and European legislation and directives (e.g. Freshwater Fish Directive and Urban Wastewater Treatment Directive) are the most effective means of control and influence of water quality and quantity (Hendry *et al*., 2003) and fisheries managers often have to work with policy setting organisation and regulators, for example The Environment Agency, or lobby groups, for example the Rivers Trust.

The River Mersey catchment has never been stocked with juvenile salmon to promote recovery, and thus is entirely dependent on the process of natural straying from local rivers and natural recruitment. Over the last 30 years considerable time, effort and money has been dedicated to the recovery of the River Mersey; water quality has improved and attempts have been made to ameliorate barriers to migration but the salmon population has not recovered in tandem (Chapter 3). In comparison, twenty years after significant efforts were made to improve the water quality in the River Tyne, the river saw a rapid increase in salmon returning (Figure 2.2). Twenty years on from the stray salmon first entering the Mersey estuary (1980s) and river (1990s) there has been no increase in salmon entering the river (captured at Woolston weir) and it could be expected that the Mersey catchment should by now have a self sustaining salmon population.

Barriers to upstream migration (both total and their cumulative effect) and the complex nature of the Mersey catchment and presence of the Ship Canal were the main limiting factors preventing natural recolonisation of the Mersey catchment by salmon. In addition, low numbers of adult salmon entering the Mersey catchment (moving upstream of Woolston weir) and habitat availability and quality were also limiting factors preventing a recolonisation. It is concluded that the Mersey catchment is unlikely to be naturally recolonised by salmon in its current state as too few salmon can spawn and their progeny survive to smolt age and migrate out to sea to establish a self sustaining Mersey salmon population. The following section will make recommendations to support a natural recolonisation of the Mersey by salmon

7.3.2 Recommendations

In 2008, the Environment Agency (EA) published its new sea trout and salmon fisheries strategy ‘Better Sea Trout and Salmon Fisheries – Our Strategy for 2008-2021’. However, the EA is limited in what it can deliver owing to financial and resource limitations. In 2014 the EA restructured in an effort to reduce staff numbers and resource costs and in 2015 the Department for Environment, Food and Rural Affairs (Defra) organisations, of which the EA is one, were tasked with delivering a further 30% - 40% reductions to national budgets. As such the recommendations below are realistic in terms of deliverability and affordability and focus on both management actions and further study.

Fish passage is improved in the lower Mersey catchment. The fish pass over Woolston weir is made fit for purpose or another fish pass is built. The fish passes on the River Bollin, and indeed all other fish passes in the Mersey catchment, are inspected and maintained at least annually - in August before salmon migrate into the catchment. Lastly, a fish pass is built over Irlam weir. Fish passes are expensive; Heatley and Little Bollington each cost £250k to build (Environment agency, personal communication). As such it is unlikely the EA will be able to fund the construction of new fish passes due to financial restrictions. The EA currently has fish passes conditioned on the developers at both Woolston and Irlam weir planned hydropower schemes. **As such it is recommended that fish passage schemes are delivered through partnerships or through regulatory conditioning**. Although it is desirable to mitigate barriers sequentially in an upstream direction, an opportunistic approach should be adopted and advantage taken of developments and funding opportunities where possible.

Chapter 5 focussed on general behaviours and route choice in the lower Mersey catchment. **It is recommended a further tagging and tracking study is carried out to identify and understand salmon behaviour in and around key barriers to migration throughout the catchment.** This would identify which barriers or combination of barriers are having the largest effect on salmon and warrant immediate or prioritised actions.

It is recommended spawning habitat availability and accessibly is improved in the Mersey catchment. Fullerton *et al.* (2006) noted that to manage salmon rivers well, it is important to protect existing high-quality habitats and Roni *et al*. (2002) recommended that restoration should focus on connecting isolated high-quality fish habitats. As such action should be taken to firstly improve and protect current accessible habitat in the River Bollin and the Upper River Mersey. The River Bollin suffers from sedimentation. **It is recommended gravel cleaning measures and maintenance are carried out together with habitat improvement measures. In addition agencies engage with land owners to identify and reduce the sources of sedimentation (Table 7.1 (c)) of sub-optimal spawning habitat below Wilmslow weir (the most downstream impassable barrier) on the River Bollin**. The current available spawning habitat on the Upper River Mersey covers a 6 km length of river 1 km below Marple Bridge gauging weir, the most downstream impassable barrier. **It is recommended agencies work with land owners and other partners to protect and improve this area with a range of habitat improvement measures (Table 7.1 (c)) so as to establish a corridor capable of supporting adult spawning and juvenile salmon.** Both the

River Bollin and Upper River Mersey improvements would be immediately downstream of impassable barriers which, if they do not cause salmon to move downstream, could concentrate salmon towards the improved areas.

In addition to habitat improvements it is recommended an extensive programme of consistent juvenile salmonid surveys and HABSCORE surveys is develop and delivered. This programme should include several sites on the rivers Dean, Bollin, Goyt, Tame and Etherow and their tributaries. It was apparent from the results presented in Chapters 3 and 6 that consistent juvenile survey and habitat data for the Mersey catchment are missing making long term temporal or spatial trends difficult to identify. **A previously recommended a tracking study focussing on barriers could be widened to include receivers in the upper reaches of the catchment to identify preferred spawning grounds.** These data could be then used to direct management actions if and when the catchment is made accessible through barrier mitigation.

The Water Framework Directive (WFD) obliges all countries throughout the European Union to manage the water environment to consistently high standards. Under the WFD, the EA is obliged to deliver the following WFD objectives; prevent any further deterioration in the classification status of aquatic ecosystems, protect and improve the ecological condition of waters, to achieve at least good status for all waters and to progressively reduce or phase out the release of individual pollutants or groups of pollutants that present a significant threat to the aquatic environment. The EA has a statutory duty to deliver these objectives of improved water quality in the Mersey catchment and improve the chances of salmon recolonisation. **It is recommended management actions to improve salmon stocks are included in Water Framework Directive (WFD) programmes of measures for the Mersey catchment.** WFD programme of measures are included in River Basin Management Plans (RBMP). RBMPs are produced by the EA and set statutory objectives for river, lake, groundwater, estuarine and coastal waterbodys and summarises the measures needed to achieve them; details of the mitigation measures for the Mersey can be found in RBMP North West River Basin District, Annex B and include measures such as ‘appropriate channel maintenance strategies – woody debris’ and ‘re-opening existing culverts’ (Anon, 2009c). Any management actions should also include the protection of an establishing salmon population from angling or illegal trapping, such as a local policy that anglers return caught fish or extra water bailiff patrols during peak salmon runs.

Of particular concern to recolonization of salmon in the Mersey catchment is the Ship canal. The Ship Canal Company (who operate the canal) will not alter flow in the canal other than for commercial or flood prevention reasons (Peel Holdings, personal communication (the owners of the Ship Canal after buying The Ship Canal Company)). Water quality in the upper reaches of the Ship Canal has improved in the past with the construction and operation of a system to oxygenate the turning basin of the Ship Canal. This was discontinued in 2011 as the equipment was costly to maintain and the costs of supplying the liquid oxygen were prohibitive. Such a scheme if operated during the salmon run (e.g. September – December) could go some way to ameliorate the poor dissolved oxygen and other water quality issues in the Ship Canal. It is unlikely that a costly aeration system will be viable. Another option may be to employ non-physical behavioural barriers to alter migration routes of both adult salmon and smolts to reduce their time in the Ship Canal. Bui *et al*. (2013) reported reared Atlantic salmon in sea cages elicited a marked change in vertical distribution in response to light, infrasound and the combination of infrasound and surface disturbance treatments; the authors went on to suggest that avoidance barriers could be used in the manipulation of salmon behaviour. Perry *et al*. (2014) used a bio-acoustic fish fence (BAFF) composed of strobe lights, sound and a bubble curtain, which were able to divert juvenile Chinook salmon (*Oncorhynchus tshawytscha*) from entering a low survival migration route by 40%. **It is recommended that a feasibility study is carried out into the use of a non-physical behavioural barriers to guide salmon into the River Bollin directly from the Lower River Mersey or at least prevent adult salmon moving further downstream in the Ship Canal than the confluence with the River Bollin. This should also include the use of a behavioural barrier to guide smolts out of the Ship Canal and into the Lower River Mersey should a smolt run occur.**

Adequate information about adult spawner abundance is a critical aspect of a viable salmon population management strategy and is used to estimate run size, determine in river survival, estimate escapement to spawning grounds and establish and monitor various compensation and enhancement programmes (Skaala *et al.*, 2014). **It is recommended that a number of fish passes at strategic locations, e.g. Woolston weir, Little Bollington and Irlam weir, are used to monitor numbers adult salmon moving upstream.** A range of salmon counting technologies are available that are relatively inexpensive and do not require a significant resource to operate (Washburn *et al*., 2008). Digital videoing of fish passes together with supporting software exists to identify and count salmon. For example, FishTick (www.wecountfish.com) or resistivity counters which use the lower electrical resistance of a fish compared to the surrounding water to count passing fish as they swim over electrodes (Forbes *et al*., 2000) would work at fish pass exits in the Mersey catchment. **In addition a fish counter at Woolston weir would provide a comprehensive data set of the number of adults entering the Mersey catchment, which is currently not available.** This would support productivity and smolt production estimates, estimates of the amount of spawning habitat required, identify long term trends, peak runs and crucially if enough salmon are returning to establish a population.

Tetzlaff *et al.* (2005) identified that much of what we know about fish populations is based on coarser temporal scales and such analyses are likely to underplay the fact that the biological effects of many environmental variables, especially temperature and flow, often occur much more rapidly. **It is recommended further study is undertaken in the Mersey catchment to understand better the effect of flow and water quality on the behaviour of adult salmon, particularly in the Ship Canal and upper catchment.** This will better inform management actions and support the influencing of and working with industry and the Ship Canal Company to protect and support the restoration of salmon. This would require routine monitoring of flow and water quality and further tagging and tracking of adult salmon.

The success of stocking practices without corresponding improvements in river water quality, habitat quality and connectivity are limited. Stocking can be effective to supplement low numbers of returning adults (Table 7.1 (a)) as in the Mersey catchment. **It is recommended a juvenile stocking programme is devised using locally sourced broodstock in line with the findings of Chapter 4, e.g. salmon from rivers from the Northwest England and Solway regions.** This should be done only when other efforts to improve river water quality, habitat quality and connectivity have been carried out. Stocking will also allow the monitoring of smolts. **It is recommended smolt tagging and tracking is carried out to identify if and how smolts migrate out to sea.** Rotary screw traps (RST) are routinely used to trap smolts (Music *et al.*, 2010). RSTs are usually positioned in a section of river where the river channel or flow funnels smolts into the RST, which uses a revolving helical central tube mounted on a floating barge to draw fish into a holding box. RST can be easily transported, are cheap and do not typically damage smolts (Music *et al.*, 2010). Smolts could then be tagged and tracked as described in a number of studies (Hearn *et al.,* 2014; Karppinen *et al*., 2014). Technologies for tagging smolts are well developed (www.vemco.com). Only when this has been completed will suitable management actions be able to address all salmon life stages in the Mersey catchment and only then will the potential for a recolonisation be fully understood and able to be fully supported.

Salmon Action Plans (SAPs) are developed by the EA in consultation with local fishery interests and have been developed for the 64 rivers that have been designated ‘principal salmon rivers’ in England and Wales. The status of Principle Salmon Rivers must be reported annually in a SAP, which includes the current and predicted performance, limiting factors and proposed actions for those rivers. Although not classed as a Principle Salmon River and therefore not requiring a SAP, the recommendations made in section 7.3.1 and future River Mersey conservation actions would benefit from a management structure, coordination and annual reporting. This would provide a strategic approach to mitigation measures and a focus and advocate when engaging with and working with partners. **It is recommended a small team, perhaps established through the Defra Catchment-based approach funding, take on responsibility for the above recommendations and future management of salmon restoration in the Mersey catchment.** This would be of particular benefit in the absence of the now finished Mersey Basin Campaign, which had played a pivotal role in bringing parties together and facilitating partnership working.

Finally, these recommendations should be combined into work packages or programmes that are feasible, affordable and politically acceptable and most of all complimentary. For example, a programme of work might include:

- the mitigation of Woolston weir,
- the use of a behavioural barrier to guide salmon into the River Bollin,
- the maintenance of fish passes, and
- the cleaning and improvement of spawning and nursery habitat in the River Bollin.

The number of adult salmon required to achieve a recovery will be highly river specific, however studies have identified <200 salmon can permit recolonisation (Ciancio *et al*., 2005; Fraser *et al*., 2007). Based on catches of salmon at the fish trap fitted to Woolston weir between 26 and 70 adult salmon are entering the Lower Mersey a year and Chapter 5 demonstrated <50% of salmon could locate and/or use the Woolston weir fish pass. Therefore, it is assumed that a fit for purpose fish pass over Woolston weir could result in between 50 and 140 salmon entering the Lower Mersey catchment and, in conjunction with the other actions in the example programme of work, successfully spawn. Fecundity in salmon varies (Thorpe *et al*., 1984; Bacon *et al*., 2012; Reid & Chaput, 2012; Caballero, 2013; de Eyto *et al*., 2015). Using an illustrative egg production of 3398 eggs per female, the mean eggs per female from Irish rivers as reported by de Eyto *et al*. (2015), 22 to 61 females (44% (the proportion of females caught during the tracking) of a 50 – 140 salmon run) each capable of producing 3300 eggs could produce between 72,600 and 201,300 eggs . Using the 240 egg/100 m² potential egg deposition identified in Chapter 6, 22 to 61 female salmon would require between 302 and 838 m² of suitable spawning habitat. The recommendations to mitigate Woolston weir, maintain the fish passes on the River Bollin, the use of a behavioural barrier and the creation and/or maintenance of spawning and nursery habitat downstream of Wilmslow weir on the River Bollin could support this number of females and this level of production. Using the egg to smolt survival rate of 1% identified in Chapter 6, the River Bollin could produce between 726 and 2013 smolts which, if smolt seaward migration could be ensured and using the marine survival rate of 11% (Chapter 6), could result in between 80 and 221 adults returning to the Mersey catchment. This would lead to a year-on-year increase in adult salmon returning to the Mersey, which supplemented with stray salmon, would ultimately lead to a successful recovery.

It should be noted that the majority of recommendations focus on river restoration, the value of which goes beyond an effective alternative to stocking and will yield broader benefits such as improvements in biodiversity and additional ecological benefits.

7.3.3 Benefits of salmon restoration

Radford *et al*. (1991) carried out an economic evaluation of salmon fisheries in the UK and calculated rent on a capitalised basis based on the market value of fishing rights. The EA and other groups, such as the Ribble River Trust, use an average value of rod caught salmon in England and Wales of £8000 per salmon as estimated by Radford *et al*. (1991) (updated to 1995 prices) (Hendry, 2004; EA, personal communication: Ribble Rivers Trust, personal communication). Actual values per rod caught salmon vary considerably with a general trend of increasing value with decreased distance from urban areas. For example the value of rod caught salmon in the River Exe in Devon, southwest England, is £14,000 per rod caught salmon (Hendry, 2004) compared to the River Spey, North East Scotland, a prolific salmon river with a 1998–2002 average total annual rod catch of 7,599,which is £4000 - 7000 per rod caught salmon (Butler *et al.*, 2009). As the Mersey catchment is in close proximity to the Manchester and Warrington conurbations and near several other large conurbations, for example Liverpool and Leeds, Mersey salmon could be expected to be valued at least £8000 per rod caught salmon. A salmon run of between 50 and 140 salmon entering the River Bollin and/or the Upper River Mersey, which could have a rod caught value of between £400,000 and £1,120,000. If managed properly the value of salmon in the Mersey could off-set the cost of restoration.

7.3.5 Final statement

The establishment of restoration goals is often hindered by limited knowledge about the status of the fish population and management decisions are often taken in the face of uncertainty (Jonsson & Jonsson, 2009). It was not immediately evident what factors may be functioning as bottlenecks for salmon in the Mersey catchment preventing successful recolonisation, although several were hypothesised (Chapter 2). This study has identified key factors that may be preventing recolonisation by salmon and set out a range of recommendation to mitigate some of these. This study also identified the origins of stray salmon entering the River Mersey and found evidence of long distance straying.

Any management actions need reviewing and updating, ideally on a continuous basis, but at least annually. In reviewing the return of salmon to urban rivers in Oslo, Norway, resulting from improved water quality, Saltveit *et al*. (2014) concluded that most of Oslo's rivers appeared to have reached their limit of improvement in ecological state with the measures that have been implemented over the last 20 to 30 years. Any action undertaken on the Mersey must also take into account future changes, especially climate change and future commercial or industrial developments. Upwards of 70,000 new homes are proposed to be built by 2021 in Liverpool and several key regional towns and cities and some of the underperforming historic urban locations in and around the Mersey catchment are national regeneration priorities (Anon, 2013c). It is likely these developments will put pressure on the Mersey catchment and surrounding environment. Changes in the British climate resulting from climate change are predicted to become more pronounced with time and the most likely scenarios are for higher temperatures, wetter winters, drier summers and more extreme events of flooding and drought (Hulme *et al*., 2002). Recent modelling of the effect of increased river temperatures based on predicted climate change scenarios suggest several rivers in the UK, mainly those in the south and east, would be uninhabitable by Atlantic salmon by 2080 (Elliott, 1981; 1991; Webb & Walsh, 2004).

Until recently, salmon were last captured in the River Mersey in 1908; an adult in the estuary and a smolt found dead between Irlam and Latchford locks in the Ship Canal

(Hardy, 1931; Ellison & Chubb, 1962). Forty-seven years prior to this a report of the Commissions on the status of salmon in the River Mersey wrote:

> "we could scarcely express in too strong terms our conviction that the existence of these obstructions in the rivers, unprovided with any means for enabling the fish to get up to spawn, is a cause fully adequate, even if no other existed, to account for the gradual disappearance of fish, and that if effectual means be not taken to obviate this evil the gradual extinction of the breed of salmon in the rivers thus circumstanced must in no long time be anticipated."

(Anon, 1861). It is sobering to think that 154 years later barriers to migration are still one of the main factors preventing salmon recolonising the Mersey catchment.

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APPENDIX

Appendix 1. Table of individual assignment likelihood scores of each individual salmon from the River Mersey (2001 – 2010) for both assignment tests.

	GeneClass 2		ONCOR	
Salmon reference	Reporting Region	Assignment likelihood scores (%)	Reporting Region	Assignment likelihood scores (%)
River Mersey salmon				
Mer.adu01.01	Scotland	82.95	Scotland	84.9
Mer.adu01.02	Solway & NW Eng	88.79	Solway & NW Eng	96.1
Mer.adu01.03	Solway & NW Eng	72.30	Solway & NW Eng	89.9
Mer.adu01.04	Solway & NW Eng	47.08	Solway & NW Eng	73.4
Mer.adu02.01	Scotland	75.81	Scotland	51.5
Mer.adu02.02	Scotland	35.09	Solway & NW Eng	69.3
Mer.adu02.03	Solway & NW Eng	50.99	Solway & NW Eng	76.3
Mer.adu02.04	Scotland	60.03	Scotland	55.3
Mer.adu02.06	Solway & NW Eng	51.67	Solway & NW Eng	77.2
Mer.adu02.07	Solway & NW Eng	97.19	Solway & NW Eng	99.2
Mer.adu02.08	Solway & NW Eng	87.87	Solway & NW Eng	96.7
Mer.adu02.09	Scotland	69.34	Solway & NW Eng	55.1
Mer.adu02.10	Solway & NW Eng	54.14	Solway & NW Eng	79.3
Mer.adu02.11	Solway & NW Eng	60.57	Solway & NW Eng	84.1
Mer.adu02.12	Scotland	48.15	Scotland	40.2
Mer.adu02.13	Scotland	52.74	Scotland	49.3
Mer.adu02.14	Solway & NW Eng	45.96	Solway & NW Eng	65.5
Mer.adu02.15	Solway & NW Eng	88.85	Solway & NW Eng	98.5
Mer.adu02.16	Solway & NW Eng	82.85	Solway & NW Eng	94.7
Mer.adu02.17	SW Eng & Wales	76.91	SW Eng & Wales	66.9
Mer.adu02.18	Solway & NW Eng	85.08	Solway & NW Eng	93.8
Mer.adu02.19	Scotland	44.16	Scotland	67.0
Mer.adu02.20	Solway & NW Eng	64.21	Solway & NW Eng	85.1
Mer.adu02.21	SW Eng & Wales	66.58	Solway & NW Eng	62.4
Mer.adu04.01	SW Eng & Wales	40.30	Solway & NW Eng	61.1
Mer.adu06.01	N Ireland	93.42	N Ireland	49.7
Mer.adu06.02	SW Eng & Wales	79.05	SW Eng & Wales	72.3
Mer.adu06.04	Solway & NW Eng	78.52	Solway & NW Eng	93.0
Mer.adu06.05	SW Eng & Wales	74.75	SW Eng & Wales	68.4
Mer.adu06.06	Scotland	74.69	Scotland	54.8
Mer.adu06.07	Scotland	47.07	Scotland	45.8
Mer.adu06.08	Solway & NW Eng	92.89	Solway & NW Eng	97.6
Mer.adu07.01	SW Eng & Wales	96.90	SW Eng & Wales	90.4
Mer.adu07.02	France	98.99	France	88.3
Mer.adu07.03	Southern England	55.61	Solway & NW Eng	77.8
Mer.adu07.04	Solway & NW Eng	99.92	Solway & NW Eng	100.0
Mer.adu07.05	France	88.83	SW Eng & Wales	36.7
Mer.adu07.06	France	94.53	France	58.6
Mer.adu07.07	SW Eng & Wales	75.21	SW Eng & Wales	55.8
Mer.adu07.09	Norway	65.84	SW Eng & Wales	58.2
Mer.adu07.10	Solway & NW Eng	92.86	Solway & NW Eng	97.9
Mer.adu07.11	Solway & NW Eng	60.77	Solway & NW Eng	94.5
Mer.adu07.12	Scotland	94.36	Scotland	91.3
Mer.adu07.13	N Ireland	99.93	N Ireland	98.3
Mer.adu07.14	Scotland	54.62	Scotland	55.7
Mer.adu07.15	Solway & NW Eng	98.09	Solway & NW Eng	99.4
Mer.adu07.16	Solway & NW Eng	73.54	Solway & NW Eng	90.6
Mer.adu07.17	Scotland	43.94	Solway & NW Eng	46.6
Mer.adu07.18	Solway & NW Eng	75.18	Solway & NW Eng	91.6
Mer.adu07.19	SW Eng & Wales	61.56	Solway & NW Eng	66.9
Mer.adu07.20	Solway & NW Eng	91.74	Solway & NW Eng	97.7
Mer.adu07.21	Scotland	83.59	Scotland	75.3
Mer.adu07.22	Solway & NW Eng	96.27	Solway & NW Eng	98.6
Mer.adu07.23	SW Eng & Wales	73.39	SW Eng & Wales	62.8
Mer.adu07.24	Scotland	43.81	Solway & NW Eng	74.0
Mer.adu07.25	Solway & NW Eng	37.83	Solway & NW Eng	67.8
Mer.adu07.26	Solway & NW Eng	67.91	Solway & NW Eng	84.7
Mer.adu07.27	Solway & NW Eng	68.46	Solway & NW Eng	90.7
Mer.adu07.28	N Ireland	99.99	N Ireland	99.9
Mer.adu07.29	Solway & NW Eng	70.11	Solway & NW Eng	85.6
Mer.adu07.30	SW Eng & Wales	75.98	SW Eng & Wales	56.3
Mer.adu07.31	Solway & NW Eng	65.08	Solway & NW Eng	84.6
Mer.adu07.33	SW Eng & Wales	89.52	SW Eng & Wales	82.5
Mer.adu08.02	Scotland	53.47	Scotland	66.2
Mer.adu08.03	Solway & NW Eng	69.16	Solway & NW Eng	87.9
Mer.adu08.04	Scotland	86.07	Scotland	93.7
Mer.adu08.05	Solway & NW Eng	82.22	Solway & NW Eng	93.0
Mer.adu08.06	Scotland	80.80	Scotland	75.7
Mer.adu08.07	Solway & NW Eng	94.86	Solway & NW Eng	98.2
Mer.adu08.08	Solway & NW Eng	98.67	Solway & NW Eng	99.6
Mer.adu08.09	N Ireland	79.61	Solway & NW Eng	84.0
Mer.adu08.10	Solway & NW Eng	92.43	Solway & NW Eng	97.6
Mer.adu08.11	Solway & NW Eng	99.82	Solway & NW Eng	100.0
Mer.adu08.12	Norway	85.14	Solway & NW Eng	99.9
Mer.adu08.13	Solway & NW Eng	83.14	Solway & NW Eng	94.4
Mer.adu08.14	SW Eng & Wales	77.83	SW Eng & Wales	57.0
Mer.adu08.15	SW Eng & Wales	94.27	SW Eng & Wales	92.9
Mer.adu08.16	Solway & NW Eng	83.74	Solway & NW Eng	95.7
Mer.adu08.17	Scotland	87.40	Scotland	73.5
Mer.adu08.18	Solway & NW Eng	88.30	Solway & NW Eng	96.3
Mer.adu08.19	Solway & NW Eng	51.56	Solway & NW Eng	98.5
Mer.adu08.20	Scotland	81.14	Scotland	77.6
Mer.adu08.21	Scotland	76.84	Scotland	83.7
Mer.adu08.22	Scotland	32.01	Solway & NW Eng	50.0
Mer.adu08.23	Solway & NW Eng	68.48	Solway & NW Eng	97.6
Mer.adu08.24	Solway & NW Eng	99.06	Solway & NW Eng	99.8
Mer.adu08.25	Solway & NW Eng	46.88	Solway & NW Eng	90.6
Mer.adu08.26	N Ireland	56.23	Solway & NW Eng	74.7
Mer.adu08.27	SW Eng & Wales	62.51	SW Eng & Wales	92.8
Mer.adu08.28	Scotland	47.46	Solway & NW Eng	61.9
Mer.adu08.29	Scotland	42.40	Solway & NW Eng	53.9
Mer.adu08.30	SW Eng & Wales	97.78	SW Eng & Wales	96.7
Mer.adu08.32	Solway & NW Eng	63.42	Solway & NW Eng	86.3
Mer.adu08.33	Scotland	60.18	Solway & NW Eng	51.0
Mer.adu08.34	Scotland	86.83	Scotland	70.2
Mer.adu08.35	Norway	87.53	Solway & NW Eng	58.5
Mer.adu08.36	Solway & NW Eng	90.76	Solway & NW Eng	97.9
Mer.adu08.37	Norway	79.44	Solway & NW Eng	58.6
Mer.adu08.38	SW Eng & Wales	96.97	SW Eng & Wales	92.8
Mer.adu08.39	Solway & NW Eng	98.70	Solway & NW Eng	99.6
Mer.adu08.40	Solway & NW Eng	90.22	Solway & NW Eng	96.5
Mer.adu08.41	Solway & NW Eng	78.93	Solway & NW Eng	91.3
Mer.adu08.42	SW Eng & Wales	65.54	Solway & NW Eng	57.0
Mer.adu08.43	SW Eng & Wales	54.73	SW Eng & Wales	68.8
Mer.adu09.02	SW Eng & Wales	39.42	Solway & NW Eng	60.8
Mer.adu09.03	Solway & NW Eng	82.60	Solway & NW Eng	94.2
Mer.adu09.04	SW Eng & Wales	73.00	SW Eng & Wales	53.0
Mer.adu09.05	Solway & NW Eng	98.69	Solway & NW Eng	99.6
Mer.adu10.01	SW Eng & Wales	97.37	SW Eng & Wales	96.8
Mer.adu10.02	Solway & NW Eng	88.62	Solway & NW Eng	95.9
Mer.adu10.04	Scotland	70.91	Scotland	49.5
Mer.adu10.05	Solway & NW Eng	69.38	Solway & NW Eng	86.3
Mer.adu10.06	SW Eng & Wales	67.91	SW Eng & Wales	60.9
Mer.adu10.07	Scotland	87.36	Scotland	81.4
Mer.adu10.08	Solway & NW Eng	69.23	Solway & NW Eng	87.6
Mer.adu10.11	Norway	57.15	Solway & NW Eng	61.1
Mer.adu10.12	Solway & NW Eng	39.81	Solway & NW Eng	69.0
Mer.adu10.13	Scotland	87.83	Scotland	76.2
Mer.adu10.14	Scotland	98.44	Scotland	99.0
Mer.adu10.15	Solway & NW Eng	79.49	Solway & NW Eng	93.3
Mer.adu10.16	Solway & NW Eng	45.07	Solway & NW Eng	70.2
Mer.adu10.17	Solway & NW Eng	90.91	Solway & NW Eng	96.7
Mer.adu10.18	SW Eng & Wales	90.74	SW Eng & Wales	75.4
Mer.adu10.19	Scotland	52.14	Scotland	70.7
Mer.adu10.20	Scotland	62.31	Scotland	79.1
Mer.adu10.21	SW Eng & Wales	87.81	SW Eng & Wales	82.6
Mer.adu10.22	SW Eng & Wales	50.91	Solway & NW Eng	75.8
Mer.adu10.23	Solway & NW Eng	75.63	Solway & NW Eng	91.3
Mer.adu10.24	Solway & NW Eng	53.27	Solway & NW Eng	78.6
Mer.adu10.25	Solway & NW Eng	55.40	Solway & NW Eng	83.6
Mer.adu10.26	Scotland	68.46	Scotland	65.6
Mer.adu10.27	Scotland	81.09	Scotland	70.8
Mer.adu10.28	Scotland	34.72	Scotland	42.9
Mer.adu10.30	Scotland	73.78	Scotland	51.5

Appendix 1 (continued). Table of individual assignment likelihood scores of each individual salmon from the River Dee (1991, 1994 and 2008) for both assignment tests.

	GeneClass 2		ONCOR	
Salmon reference	Reporting Region	Assignment likelihood scores (%)	Reporting Region	Assignment likelihood scores (%)
River Dee salmon				
/Dee.adu08.01	SW Eng & Wales	96.11	SW Eng & Wales	96.1
/Dee.adu08.02	SW Eng & Wales	66.09	SW Eng & Wales	64.0
/Dee.adu08.03	SW Eng & Wales	45.91	SW Eng & Wales	46.5
/Dee.adu08.04	Solway & NW Eng	58.45	Solway & NW Eng	60.7
/Dee.adu08.05	SW Eng & Wales	96.83	SW Eng & Wales	97.5
/Dee.adu08.06	Scotland	78.25	Scotland	76.8
/Dee.adu08.07	Scotland	42.26	Scotland	40.9
/Dee.adu08.08	SW Eng & Wales	88.06	SW Eng & Wales	87.9
/Dee.adu08.09	SW Eng & Wales	69.75	SW Eng & Wales	69.9
/Dee.adu08.10	Scotland	75.18	Scotland	74.2
/Dee.adu08.11	Scotland	53.04	Scotland	53.8
/Dee.adu08.12	SW Eng & Wales	90.70	SW Eng & Wales	90.7
/Dee.adu08.13	SW Eng & Wales	61.32	SW Eng & Wales	61.4
/Dee.adu08.14	SW Eng & Wales	78.43	SW Eng & Wales	78.5
/Dee.adu08.15	SW Eng & Wales	51.07	SW Eng & Wales	50.9
/Dee.adu08.16	Solway & NW Eng	36.93	Solway & NW Eng	36.7
/Dee.adu08.17	SW Eng & Wales	63.78	SW Eng & Wales	63.2
/Dee.adu08.18	Scotland	79.02	Scotland	81.2
/Dee.adu08.19	Scotland	75.58	Scotland	75.1
/Dee.adu08.20	Solway & NW Eng	78.54	Solway & NW Eng	80.0
/Dee.adu08.21	Scotland	78.67	Scotland	79.1
/Dee.adu08.22	N Ireland	88.93	N Ireland	88.4
/Dee.adu08.23	SW Eng & Wales	99.14	SW Eng & Wales	99.1
/Dee.adu08.24	Solway & NW Eng	95.91	Solway & NW Eng	96.0
/Dee.adu08.25	Solway & NW Eng	59.86	Solway & NW Eng	60.0
/Dee.adu08.26	France	83.61	France	84.0
/Dee.adu08.27	Solway & NW Eng	48.93	Solway & NW Eng	46.2
/Dee.adu08.28	SW Eng & Wales	81.26	SW Eng & Wales	79.8
/Dee.adu08.29	Solway & NW Eng	94.95	Solway & NW Eng	94.8
/Dee.adu08.30	Norway	83.71	Norway	83.7
/Dee.adu08.31	Solway & NW Eng	75.79	Solway & NW Eng	73.9
/Dee.adu08.32	France	72.75	France	72.8
/Dee.adu08.33	SW Eng & Wales	59.90	SW Eng & Wales	60.2
/Dee.adu08.34	SW Eng & Wales	52.10	SW Eng & Wales	52.2
/Dee.adu08.35	France	86.16	France	86.2
/Dee.adu08.36	SW Eng & Wales	62.19	SW Eng & Wales	62.0
/Dee.adu08.37	Solway & NW Eng	73.19	Solway & NW Eng	73.0
/Dee.adu08.38	SW Eng & Wales	71.06	SW Eng & Wales	71.4
/Dee.adu08.39	Scotland	49.39	Scotland	49.7
/Dee.adu08.40	Solway & NW Eng	77.45	Solway & NW Eng	78.8
/Dee.adu08.41	SW Eng & Wales	92.25	SW Eng & Wales	92.4
/Dee.adu08.42	Solway & NW Eng	99.95	Solway & NW Eng	100.0
/Dee.adu08.43	Solway & NW Eng	73.99	Solway & NW Eng	75.8
/Dee.adu08.44	France	49.57	SW Eng & Wales	52.0
/Dee.adu08.45	Scotland	90.94	Scotland	90.5
/Dee.adu08.46	Solway & NW Eng	66.39	Solway & NW Eng	64.9
/Dee.adu08.47	Scotland	60.33	Scotland	61.4
/Dee.adu08.48	Solway & NW Eng	88.44	Solway & NW Eng	88.5
/Dee.adu08.49	Scotland	82.25	Scotland	84.9
/Dee.adu08.50	SW Eng & Wales	54.23	SW Eng & Wales	52.6
/Dee.adu08.51	Solway & NW Eng	50.69	Solway & NW Eng	50.3
/Dee.adu08.52	SW Eng & Wales	79.93	SW Eng & Wales	79.1
/Dee.adu08.53	SW Eng & Wales	99.57	SW Eng & Wales	99.6
/Dee.adu08.54	Scotland	74.51	Scotland	74.0
/Dee.adu08.55	Scotland	91.16	Scotland	92.2
/Dee.adu08.56	Solway & NW Eng	72.75	Solway & NW Eng	72.8
/Dee.adu08.57	France	59.19	France	58.9
/Dee.adu08.58	Solway & NW Eng	80.90	Solway & NW Eng	81.4
/Dee.adu08.59	Solway & NW Eng	32.04	Solway & NW Eng	31.4
/Dee.adu08.60	Solway & NW Eng	43.19	Solway & NW Eng	43.2
/Dee.adu94.01	SW Eng & Wales	38.30	SW Eng & Wales	36.6
/Dee.adu94.02	France	72.10	France	72.6
/Dee.adu94.03	Scotland	52.98	Scotland	51.1
/Dee.adu94.04	SW Eng & Wales	91.44	SW Eng & Wales	90.6
/Dee.adu94.05	SW Eng & Wales	93.40	SW Eng & Wales	93.6
/Dee.adu94.06	Solway & NW Eng	32.10	Solway & NW Eng	32.8
/Dee.adu94.07	N Ireland	85.11	N Ireland	85.4
/Dee.adu94.08	Scotland	73.06	Scotland	77.8
/Dee.adu94.09	Scotland	59.20	Scotland	52.1
/Dee.adu94.10	Solway & NW Eng	73.23	Solway & NW Eng	73.2
/Dee.adu94.11	SW Eng & Wales	81.56	SW Eng & Wales	82.2
/Dee.adu94.12	Norway	67.57	Norway	65.0
/Dee.adu94.13	SW Eng & Wales	82.80	SW Eng & Wales	83.0
/Dee.adu94.14	SW Eng & Wales	83.58	SW Eng & Wales	83.8
/Dee.adu94.15	Solway & NW Eng	66.77	Solway & NW Eng	66.9
/Dee.adu94.16	SW Eng & Wales	80.37	SW Eng & Wales	80.2
/Dee.adu94.17	SW Eng & Wales	83.79	SW Eng & Wales	85.1
/Dee.adu94.18	Scotland	70.45	Scotland	64.3
/Dee.adu94.19	SW Eng & Wales	44.76	SW Eng & Wales	47.0
/Dee.adu94.20	Scotland	93.79	Scotland	93.6
/Dee.adu94.21	N Ireland	43.89	N Ireland	43.8
/Dee.adu94.22	SW Eng & Wales	86.21	SW Eng & Wales	86.8
/Dee.adu94.23	N Ireland	81.33	N Ireland	79.7
/Dee.adu94.24	Solway & NW Eng	71.64	Solway & NW Eng	70.5
/Dee.adu94.25	Scotland	68.22	Scotland	66.5

	GeneClass 2		ONCOR	
Salmon reference	Reporting Region	Assignment likelihood scores (%)	Reporting Region	Assignment likelihood scores (%)
River Dee salmon				
/Dee.adu94.26	SW Eng & Wales	86.77	SW Eng & Wales	86.8
/Dee.adu94.27	SW Eng & Wales	93.90	SW Eng & Wales	93.9
/Dee.adu94.28	France	50.83	France	50.8
/Dee.adu94.29	Norway	45.06	Norway	44.8
/Dee.adu94.30	SW Eng & Wales	37.10	SW Eng & Wales	36.3
/Dee.adu94.31	Scotland	78.80	Scotland	76.8
/Dee.adu94.32	SW Eng & Wales	86.50	SW Eng & Wales	85.3
/Dee.adu94.33	Scotland	96.00	Scotland	95.6
/Dee.adu94.34	Scotland	43.58	Scotland	40.6
/Dee.adu94.35	Scotland	39.86	Scotland	40.2
/Dee.adu94.36	Solway & NW Eng	67.51	Solway & NW Eng	68.0
/Dee.adu94.37	SW Eng & Wales	67.51	SW Eng & Wales	67.2
/Dee.adu94.38	N Ireland	48.25	N Ireland	47.3
/Dee.adu94.39	Solway & NW Eng	76.14	Solway & NW Eng	75.9
/Dee.adu94.40	Scotland	50.94	Scotland	64.4
/Dee.adu94.41	Solway & NW Eng	56.06	Solway & NW Eng	56.2
/Dee.adu94.42	SW Eng & Wales	44.28	SW Eng & Wales	44.1
/Dee.adu94.43	Solway & NW Eng	42.95	Solway & NW Eng	42.8
/Dee.adu94.44	N Ireland	66.07	N Ireland	65.8
/Dee.adu94.45	SW Eng & Wales	84.77	SW Eng & Wales	84.4
/Dee.adu94.46	Solway & NW Eng	95.29	Solway & NW Eng	95.2
/Dee.adu94.47	SW Eng & Wales	88.64	SW Eng & Wales	88.8
/Dee.adu94.48	Scotland	56.30	Scotland	54.3
/Dee.adu94.49	Solway & NW Eng	37.57	Solway & NW Eng	37.6
/Dee.adu94.50	SW Eng & Wales	60.20	SW Eng & Wales	60.8
/Dee.adu94.51	SW Eng & Wales	75.65	SW Eng & Wales	76.2
/Dee.adu94.52	SW Eng & Wales	52.97	SW Eng & Wales	52.8
/Dee.adu94.53	Solway & NW Eng	64.89	Solway & NW Eng	65.6
/Dee.adu94.54	France	93.80	France	94.6
/Dee.adu94.55	SW Eng & Wales	44.02	SW Eng & Wales	44.0
/Dee.adu94.56	France	46.06	France	46.1
/Dee.adu94.57	SW Eng & Wales	59.10	SW Eng & Wales	57.8
/Dee.adu94.58	SW Eng & Wales	71.09	SW Eng & Wales	71.4
/Dee.adu94.59	Scotland	67.99	Scotland	69.3
/Dee.adu94.60	SW Eng & Wales	89.23	SW Eng & Wales	89.7
/Dee.adu91.01	Solway & NW Eng	58.29	Solway & NW Eng	57.5
/Dee.adu91.03	SW Eng & Wales	93.58	SW Eng & Wales	93.4
/Dee.adu91.04	Solway & NW Eng	68.71	Solway & NW Eng	66.9
/Dee.adu91.05	Norway	39.54	Norway	39.5
/Dee.adu91.06	Solway & NW Eng	42.86	Solway & NW Eng	41.5
/Dee.adu91.07	SW Eng & Wales	82.43	SW Eng & Wales	82.4
/Dee.adu91.08	SW Eng & Wales	73.20	SW Eng & Wales	72.6
/Dee.adu91.10	SW Eng & Wales	37.31	SW Eng & Wales	37.5
/Dee.adu91.11			Scotland	64.2
/Dee.adu91.12	N Ireland	47.86	N Ireland	48.3
/Dee.adu91.13	Norway	49.42	Norway	49.0
/Dee.adu91.14	SW Eng & Wales	99.72	SW Eng & Wales	99.7
/Dee.adu91.15	Scotland	63.94	Scotland	64.9
/Dee.adu91.16	France	73.09	France	73.3
/Dee.adu91.18	Solway & NW Eng	65.56	Solway & NW Eng	66.2
/Dee.adu91.19	Solway & NW Eng	69.22	Solway & NW Eng	67.8
/Dee.adu91.20	SW Eng & Wales	79.91	SW Eng & Wales	80.4
/Dee.adu91.21			SW Eng & Wales	62.9
/Dee.adu91.22	N Ireland	83.48	N Ireland	83.5
/Dee.adu91.23	Solway & NW Eng	80.38	Solway & NW Eng	80.4
/Dee.adu91.24	Solway & NW Eng	37.72	Solway & NW Eng	38.3
/Dee.adu91.25	SW Eng & Wales	96.57	SW Eng & Wales	96.8
/Dee.adu91.26	Scotland	67.43	Scotland	70.5
/Dee.adu91.27	Solway & NW Eng	75.75	Solway & NW Eng	75.3
/Dee.adu91.28	France	77.23	France	76.4
/Dee.adu91.29	SW Eng & Wales	56.71	SW Eng & Wales	56.6
/Dee.adu91.30	SW Eng & Wales	88.64	SW Eng & Wales	88.8
/Dee.adu91.31	Scotland	62.57	Scotland	65.6
/Dee.adu91.33	SW Eng & Wales	93.86	SW Eng & Wales	93.8
/Dee.adu91.34	Scotland	65.86	Scotland	64.3
/Dee.adu91.37	SW Eng & Wales	67.77	SW Eng & Wales	65.7
/Dee.adu91.38	SW Eng & Wales	91.09	SW Eng & Wales	91.5
/Dee.adu91.39	Scotland	91.43	Scotland	90.1
/Dee.adu91.44	Solway & NW Eng	53.12	Solway & NW Eng	53.0
/Dee.adu91.45	Scotland	99.94	Scotland	99.9
/Dee.adu91.46	SW Eng & Wales	76.20	SW Eng & Wales	76.0
/Dee.adu91.47	France	60.54	France	60.4
/Dee.adu91.48	SW Eng & Wales	60.80	SW Eng & Wales	62.2
/Dee.adu91.49	SW Eng & Wales	85.23	SW Eng & Wales	85.8
/Dee.adu91.50	Scotland	42.22	SW Eng & Wales	39.9
/Dee.adu91.51	SW Eng & Wales	83.15	SW Eng & Wales	83.1
/Dee.adu91.52			Scotland	75.2
/Dee.adu91.53	Scotland	89.10	Scotland	88.0
/Dee.adu91.54	SW Eng & Wales	65.65	SW Eng & Wales	57.3
/Dee.adu91.55			SW Eng & Wales	69.2
/Dee.adu91.56	SW Eng & Wales	63.77	SW Eng & Wales	62.8
/Dee.adu91.57	Solway & NW Eng	53.91	Solway & NW Eng	58.8
/Dee.adu91.58	Scotland	90.10	Scotland	90.4
/Dee.adu91.59	SW Eng & Wales	37.65	SW Eng & Wales	36.0
/Dee.adu91.60	Solway & NW Eng	84.96	Solway & NW Eng	85.4

Appendix 1 (continued). Table of individual assignment likelihood scores of each individual salmon from the River Lune (2008) and River Ribble (2008) for both assignment tests.

	GeneClass 2		ONCOR	
Salmon reference	Reporting Region	Assignment likelihood scores (%)	Reporting Region	Assignment likelihood scores (%)
River Lune salmon				
/Lun.adu08.01	Solway & NW Eng	72.94	Solway & NW Eng	72.3
/Lun.adu08.02	Solway & NW Eng	82.67	Solway & NW Eng	81.9
/Lun.adu08.03	Solway & NW Eng	96.21	Solway & NW Eng	95.4
/Lun.adu08.04	Solway & NW Eng	95.63	Solway & NW Eng	96.0
/Lun.adu08.05	Solway & NW Eng	83.95	Solway & NW Eng	83.5
/Lun.adu08.06	Solway & NW Eng	94.06	Solway & NW Eng	94.0
/Lun.adu08.07	France	56.90	France	53.6
/Lun.adu08.08	Norway	91.80	Norway	91.8
/Lun.adu08.09	Solway & NW Eng	73.59	Solway & NW Eng	74.5
/Lun.adu08.10	France	53.04	France	53.1
/Lun.adu08.11	Solway & NW Eng	55.35	Solway & NW Eng	50.2
/Lun.adu08.12	Solway & NW Eng	85.99	Solway & NW Eng	85.7
/Lun.adu08.13	Solway & NW Eng	97.64	Solway & NW Eng	97.6
/Lun.adu08.14	France	47.91	France	47.0
/Lun.adu08.15	Solway & NW Eng	81.94	Solway & NW Eng	82.3
/Lun.adu08.16	Solway & NW Eng	99.85	Solway & NW Eng	99.8
/Lun.adu08.17	Solway & NW Eng	89.10	Solway & NW Eng	89.1
/Lun.adu08.18	Solway & NW Eng	96.85	Solway & NW Eng	96.7
/Lun.adu08.19	Solway & NW Eng	99.89	Solway & NW Eng	99.9
/Lun.adu08.20	Solway & NW Eng	92.03	Solway & NW Eng	93.1
/Lun.adu08.21	Solway & NW Eng	56.29	Solway & NW Eng	58.4
/Lun.adu08.22	Solway & NW Eng	66.03	Solway & NW Eng	66.0
/Lun.adu08.23	Solway & NW Eng	89.02	Solway & NW Eng	88.4
/Lun.adu08.24	Solway & NW Eng	63.39	Solway & NW Eng	60.4
/Lun.adu08.25	Solway & NW Eng	84.78	Solway & NW Eng	84.1
/Lun.adu08.26	Solway & NW Eng	84.08	Solway & NW Eng	83.0
/Lun.adu08.27	SW Eng & Wales	77.87	SW Eng & Wales	77.9
/Lun.adu08.29	SW Eng & Wales	69.44	SW Eng & Wales	69.5
/Lun.adu08.30	Solway & NW Eng	67.54	Solway & NW Eng	67.5
/Lun.adu08.31	Solway & NW Eng	43.58	Solway & NW Eng	46.8
/Lun.adu08.32	Solway & NW Eng	99.34	Solway & NW Eng	99.4
/Lun.adu08.33	Solway & NW Eng	91.01	Solway & NW Eng	90.5
/Lun.adu08.34	Solway & NW Eng	69.66	Solway & NW Eng	69.7
/Lun.adu08.35	Solway & NW Eng	53.19	Solway & NW Eng	52.0
/Lun.adu08.36	Solway & NW Eng	58.14	Solway & NW Eng	53.1
/Lun.adu08.37	SW Eng & Wales	81.93	SW Eng & Wales	81.8
/Lun.adu08.38	Solway & NW Eng	47.90	Solway & NW Eng	47.6
/Lun.adu08.39	SW Eng & Wales	67.88	SW Eng & Wales	67.9
/Lun.adu08.40	Solway & NW Eng	95.96	Solway & NW Eng	95.5
/Lun.adu08.41	Scotland	95.27	Scotland	96.1
/Lun.adu08.42	Solway & NW Eng	78.98	Solway & NW Eng	75.2
/Lun.adu08.43	Solway & NW Eng	61.70	Solway & NW Eng	56.5
/Lun.adu08.44	Solway & NW Eng	62.96	Solway & NW Eng	61.4
/Lun.adu08.45	Solway & NW Eng	89.52	Solway & NW Eng	89.0
/Lun.adu08.46	Solway & NW Eng	92.14	Solway & NW Eng	91.6
/Lun.adu08.47	Solway & NW Eng	97.55	Solway & NW Eng	97.2
/Lun.adu08.48	Solway & NW Eng	46.87	Solway & NW Eng	49.6
/Lun.adu08.49	Solway & NW Eng	76.77	Solway & NW Eng	77.0
/Lun.adu08.50	Solway & NW Eng	98.87	Solway & NW Eng	98.9
/Lun.adu08.51	Solway & NW Eng	99.78	Solway & NW Eng	99.8
/Lun.adu08.52	Solway & NW Eng	99.58	Solway & NW Eng	99.5
/Lun.adu08.53	Solway & NW Eng	74.03	Solway & NW Eng	73.9
/Lun.adu08.54	Scotland	59.77	Scotland	56.8
/Lun.adu08.55	SW Eng & Wales	80.28	SW Eng & Wales	81.9
/Lun.adu08.56	Solway & NW Eng	85.54	Solway & NW Eng	86.2
/Lun.adu08.57	Scotland	51.92	Scotland	52.1
/Lun.adu08.58	Solway & NW Eng	76.94	Solway & NW Eng	75.4
/Lun.adu08.59	Solway & NW Eng	41.06	Solway & NW Eng	39.9
/Lun.adu08.61	Solway & NW Eng	51.96	Solway & NW Eng	50.4
/Lun.adu08.62	Solway & NW Eng	37.54	Solway & NW Eng	38.2
/Lun.adu08.63	Solway & NW Eng	98.02	Solway & NW Eng	98.0
/Lun.adu08.64	Solway & NW Eng	98.12	Solway & NW Eng	98.2
/Lun.adu08.65	Norway	72.85	Norway	72.0
/Lun.adu08.66	Solway & NW Eng	81.62	Solway & NW Eng	82.0
/Lun.adu08.67	Solway & NW Eng	95.72	Solway & NW Eng	96.3
/Lun.adu08.68	Scotland	54.02	Scotland	56.9
/Lun.adu08.69	SW Eng & Wales	60.67	SW Eng & Wales	61.7
/Lun.adu08.70	Scotland	96.83	Scotland	97.4
/Lun.adu08.71	Scotland	73.15	Scotland	74.7
/Lun.adu08.72	Solway & NW Eng	95.37	Solway & NW Eng	95.3
/Lun.adu08.73	Scotland	73.68	Scotland	73.4
/Lun.adu08.74	N Ireland	98.77	N Ireland	98.7
/Lun.adu08.75	Solway & NW Eng	62.16	Solway & NW Eng	62.0
/Lun.adu08.76	Solway & NW Eng	41.40	Scotland	41.6
/Lun.adu08.77	Solway & NW Eng	92.16	Solway & NW Eng	91.6
/Lun.adu08.78	SW Eng & Wales	88.42	SW Eng & Wales	88.4
/Lun.adu08.79	Solway & NW Eng	78.35	Solway & NW Eng	77.3
/Lun.adu08.80	Solway & NW Eng	97.98	Solway & NW Eng	97.7
/Lun.adu08.81	Solway & NW Eng	93.36	Solway & NW Eng	93.2
/Lun.adu08.83	Scotland	52.10	Scotland	45.1

	GeneClass 2		ONCOR	
Salmon reference	Reporting Region	Assignment likelihood scores (%)	Reporting Region	Assignment likelihood scores (%)
River Ribble salmon				
/Rib.adu08.01	France	96.81	France	96.9
/Rib.adu08.02	Solway & NW Eng	40.19	Solway & NW Eng	40.1
/Rib.adu08.03	Scotland	83.42	Scotland	80.3
/Rib.adu08.04	Scotland	85.05	Scotland	84.8
/Rib.adu08.05	Solway & NW Eng	54.75	Solway & NW Eng	54.7
/Rib.adu08.06	SW Eng & Wales	40.47	SW Eng & Wales	40.8
/Rib.adu08.07	Scotland	50.47	Scotland	53.4
/Rib.adu08.08	Solway & NW Eng	49.27	Solway & NW Eng	49.2
/Rib.adu08.10	Solway & NW Eng	86.01	Solway & NW Eng	85.8
/Rib.adu08.11	Scotland	93.13	Scotland	93.6
/Rib.adu08.12	Scotland	64.75	Scotland	65.4
/Rib.adu08.13	SW Eng & Wales	94.76	SW Eng & Wales	96.0
/Rib.adu08.14	Solway & NW Eng	63.76	Solway & NW Eng	61.5
/Rib.adu08.15	Solway & NW Eng	77.15	Solway & NW Eng	76.7
/Rib.adu08.16	Solway & NW Eng	95.76	Solway & NW Eng	95.8
/Rib.adu08.17	Solway & NW Eng	54.42	Solway & NW Eng	53.8
/Rib.adu08.18	N Ireland	36.20	N Ireland	35.7
/Rib.adu08.19	Scotland	45.36	Scotland	44.3
/Rib.adu08.20	Solway & NW Eng	97.72	Solway & NW Eng	97.7
/Rib.adu08.21	Solway & NW Eng	99.18	Solway & NW Eng	99.2
/Rib.adu08.22	Solway & NW Eng	83.55	Solway & NW Eng	83.4
/Rib.adu08.23	Solway & NW Eng	52.35	Solway & NW Eng	51.8
/Rib.adu08.24	Solway & NW Eng	62.97	Solway & NW Eng	68.1
/Rib.adu08.25	Solway & NW Eng	95.18	Solway & NW Eng	95.3
/Rib.adu08.26	Scotland	89.94	Scotland	89.8
/Rib.adu08.27	Solway & NW Eng	69.76	Solway & NW Eng	69.9
/Rib.adu08.28	Scotland	87.39	Scotland	87.9
/Rib.adu08.29	SW Eng & Wales	65.88	SW Eng & Wales	65.9
/Rib.adu08.30	Solway & NW Eng	59.81	Solway & NW Eng	62.1
/Rib.adu08.31	France	44.51	France	44.5
/Rib.adu08.32	Scotland	59.43	Scotland	62.9
/Rib.adu08.33	SW Eng & Wales	99.58	SW Eng & Wales	99.6
/Rib.adu08.34	Solway & NW Eng	98.15	Solway & NW Eng	98.0
/Rib.adu08.35	Scotland	69.08	Scotland	63.6
/Rib.adu08.36	Solway & NW Eng	80.46	Solway & NW Eng	77.3
/Rib.adu08.37	SW Eng & Wales	65.56	SW Eng & Wales	68.4
/Rib.adu08.38	SW Eng & Wales	83.31	SW Eng & Wales	87.7
/Rib.adu08.39	Solway & NW Eng	65.78	Solway & NW Eng	66.6
/Rib.adu08.40	Scotland	55.22	Scotland	51.5
/Rib.adu08.41	Solway & NW Eng	81.31	Solway & NW Eng	79.0
/Rib.adu08.42	SW Eng & Wales	82.71	SW Eng & Wales	82.7
/Rib.adu08.43	SW Eng & Wales	79.72	SW Eng & Wales	80.3
/Rib.adu08.44	SW Eng & Wales	43.61	SW Eng & Wales	43.7
/Rib.adu08.45	Solway & NW Eng	56.82	Solway & NW Eng	53.2

Appendix 2. Table of the 44 salmon tagged in year 1 and year 2 tracking studies.

Date of tagging	Tag Serial number	Sex	Age (years)	Length (cm)	Weight (g)	Condition Factor
01/09/2010	38938	Female	2.1+	62	2400	0.997
02/09/2010	38937	Male	2.1+	58	1850	0.938
07/09/2010	38936	Female	2.1+	60	2100	0.997
07/09/2010	38935	Male	2.1+	68	3450	1.122
08/09/2010	38942	Male	3.1+	65	2750	1.025
08/09/2010	38941	Male	2.1+	53	1150	0.768
09/09/2010	38940	Female	2.2+	82	5920	1.070
09/09/2010	38939	Male	2.1+	59	2210	1.054
09/09/2010	38946	Male	2.1+	60	2180	1.035
09/09/2010	38945	Male	2.1+	59	2190	1.072
09/09/2010	38944	Male	1.1+	59	2185	1.075
09/09/2010	38943	Female	2.1+	59	2710	1.340
11/09/2010	3169	Male	2.1+	60	1950	0.926
11/09/2010	3168	Male	2.1+	60	2250	1.052
12/09/2010	3167	Male	2.1+	65	2590	0.926
14/09/2010	3166	Female	2.1+	59	2080	1.003
17/09/2010	3170	Male	RS.1+	64	2550	0.996
18/09/2010	3171	Female	2.1+	61	2550	1.152
21/09/2010	3172	Male	2.1+	60	2900	1.349
21/09/2010	3173	Male	2.1+	66	3900	1.388
21/09/2010	3174	Male	2.1+	59	2650	1.277
22/09/2010	3175	Male	2.1+	63	3450	1.413
23/09/2010	3181	Female	RS.1+	64	2800	1.068
23/09/2010	3179	Female	2.1+	57	1850	0.999
24/09/2010	3176	Female	2.1+	56	1650	0.950
24/09/2010	3178	Male	RS.1+	63	2600	1.045
24/09/2010	3180	Female	2.1+	65	2900	1.081
24/09/2010	3183	Female	2.2+	85	6100	0.986
05/10/2010	3177	Male	RS.1+	62	2100	0.903
06/10/2010	3182	Male	2.1+	60	2100	0.958
30/08/2011	41813	Female		57	1850	1.010
30/08/2011	41818	Male		61	2500	1.101
31/08/2011	41817	Male		85	4900	0.812
31/08/2011	41812	Male		54	1750	1.143
08/09/2011	41810	Female		60	2500	1.187
12/09/2011	41816	Female		81	5000	0.958
16/09/2011	41811	Female		77	4400	0.964
20/09/2011	41809	Female		61	2600	1.174
20/09/2011	41814	Male		85	6100	0.993
25/09/2011	41815	Male		59	2200	1.077
30/09/2011	1508	Male		72	3700	1.000
30/09/2011	1507	Female		76	3300	0.743
02/10/2011	1512	Female		75	3900	0.921
04/10/2011	1511	Female		78	4200	0.882