THE UNIVERSITY OF HULL

Movements and population dynamics of brown trout in reservoirs and headwaters.

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ABSTRACT

To fully understand movements of fish a multi-faceted, varied approach is required. In this study, a combination of Passive Integrated Transponder (PIT) and acoustic telemetry was used in a complementary approach to understand the movements of brown trout (*Salmo trutta*) in upland reaches of two reservoir systems in Yorkshire, UK – Grimwith and Langsett Reservoirs. In particular the effects of potential barriers the weirs that are present on both tributaries at Langsett Reservoir on movements were examined. The results were interpreted in relation to fish size and environmental conditions (river flow, water temperature, time of day). Over 1000 fish were PIT-tagged: including fish from both reservoirs and the five tributaries (three at Grimwith, two at Langsett). Twenty fish were acoustically tagged in Grimwith Reservoir.

Under the discharge regimes prevailing in this study, weirs appeared to prevent fish from migrating from Langsett Reservoir into the tributaries, as no fish detected immediately downstream of the weirs were subsequently detected upstream. The habitat upstream of the weirs was subjected to analyses that i) had found it to host a significantly less dense population of brown trout than its habitat could carry, and ii) found that it would be able to support spawning trout where the habitat downstream of the weirs either could not at all, or could only do so in a very limited capacity. Therefore, it is possible that the weir was preventing a more complete exploitation, by brown trout, of the habitat.

The weirs may also be barriers to downstream migration, as up to 66% of fish detected immediately upstream of the weirs were not subsequently detected downstream. The assumption in this case being that all fish spawned upstream of the barrier should undertake a migration downstream.

Acoustically tagged brown trout did not enter Blea Gill Beck, Gate Up Gill or Grimwith Beck, suggesting either that they did not spawn during the study period or spawned elsewhere. Given that Blea Gill Beck, Gate Up Gill and Grimwith Beck are the only tributaries to Grimwith Reservoir that are viable for spawning, the only other possible spawning location is the reservoir itself.

The results have been used to make recommendations pertaining to mitigating the effects of the barriers, ultimately that one weir, that on the River Little Don should be selected for fish pass installation.

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1 GENERAL INTRODUCTION

Connectivity in riverine ecosystems can be important to facilitate movements of fish to complete their life cycles and meet daily maintenance needs, namely feeding, refuge and dispersion (Jonsson and Jonsson 2011). Man-made physical structures built for navigation, power generation and abstraction have reduced longitudinal connectivity in river systems (Gossett *et al.* 2006; Ugedal *et al.* 2008; Jonsson and Jonsson 2011). The impact of weirs on salmonid populations concerns the reduced ability of fish to perform upstream or downstream migrations to exploit specific habitats required for the completion of their life-cycles (Gossett *et al.* 2006; Ugedal *et al.* 2008; Jonsson and Jonsson 2011) and population asymmetry created by the removal of phenotypic and genetic variety via mono-directional movement across the barrier (Arnekliev *et al.* 2007; Ugedal *et al.* 2008). However, it is not always immediately obvious to what extent a weir presents a barrier to fish migration and specific local investigations are often required to determine if a fish pass is required, especially given the considerable cost associated with construction (average cost ~£200,000 but can be from under £50,000 to over £1,000,000; Coe and Kibel 2003).

Brown trout (*Salmo trutta* Linnaeus, 1758) (Figure 1) is a highly mobile species that migrates, usually upstream, to find appropriate spawning habitat (Banks 1969; Northcote 1992; Jonsson and Jonsson 2011). Flow elevations in autumn and winter act as triggers for the upstream migration of brown trout (Jonsson and Jonsson 2011). There are specific requirements for brown trout spawning grounds, which must be in cold, fast-flowing waters with a gravelly substratum (Cowx *et al.* 2004). A combination of competition and genetic drivers instigate downstream migration to habitats that offer feeding and shelter opportunities, like larger rivers, lakes/reservoirs and the sea (Jonsson and Jonsson 2011). However, some brown trout will inhabit less than ideal circumstances either through lack of exploration or lack of choice; barriers can curtail these migrations (upstream or downstream) and disrupt life cycles, creating so-called ‘ecological traps’ as described by Battin (2004). Brown trout is an indicator species, in that its population health is indicative of the health of the ecosystem in which they reside. Brown trout is the dominant species in the upper reaches of many UK rivers and, as such, are the most appropriate indicator species in these systems.

Figure 1. An adult brown trout caught in the River Little Don.

Reservoirs provide important services, in Yorkshire they are crucial in the supply of water to over 5 million people and recreation (mostly water sports and rambling routes) (Salzman 2009). Aquatic environments, such as reservoirs, lakes and rivers, are sensitive to human pressures (Irvine *et al.* 2009). The most heavily impacted ecosystems on the planet are lotic, be it pollution, overabstraction or dam/weir construction (Malmqvist and Rundle 2002). Due to these deleterious effects, there has been a growing onus to protect and conserve impacted ecosystems and restore them to greater health. Water-focussed legislation like the EU's Water Framework Directive (WFD) has been introduced to promote these actions (European Commission 2000).

The WFD was enshrined into law with The Water Environment (Water Framework Directive) (England and Wales) Regulations 2003. Implementation of the WFD in the UK is the responsibility of the United Kingdom Technical Advisory Group (UKTAG). The Department for the Environment, Food and Rural Affairs (DEFRA) and the Environment Agency (EA) coordinate efforts to comply with this Directive and standards recommended by UKTAG, working with local stakeholders to do so.

There are 398 WFD monitoring sites in Yorkshire, only 59 (>15%) sites were achieving "Good Ecological Status"/Potential, which is the mandated target of WFD, as of 2015, (Environment Agency 2016). The status of rivers in this study of brown trout in Yorkshire are discussed in detail in Section 3 – they are classed as 'Heavily Modified Waterbodies' and have ecological status less than 'good'. Some remediation steps, like water treatment and pollutant reduction, can be straightforward, although expensive. Other measures, like removing flood defences, weirs and dams, could be hazardous to human life and potentially damaging to aquatic life if toxic chemicals that historically have been trapped in sediment at these sites are released into the aquatic environment. Restoring connectivity in rivers must be explored though as free passage for migratory fish is a key requirement of the WFD (EC, 2000). As a result, mitigation measures are explored with fish passes, installations that allow transcendence of obstacles (Jungwirth 1996; Katapodis *et al.* 2001; Calles and Greenberg 2005; Arnekliev *et al.* 2007; Haugen *et al.* 2008; Parasiewicz *et al.* 2009); “Trap-and-transport” collecting fish one side of an obstacle and manually translocating them to the other side (Schmetterling 2003; DeHaan and Bernall 2013); and stocking, releasing fish into rivers that are fish-poor (Bohlin *et al.* 2002; Hansen 2002; Hansen *et al.* 2009). Each specific site can require a bespoke approach to mitigate its particular problems.

There are 126 reservoirs in Yorkshire, UK, covering 1.3% of the county (Figure 2).

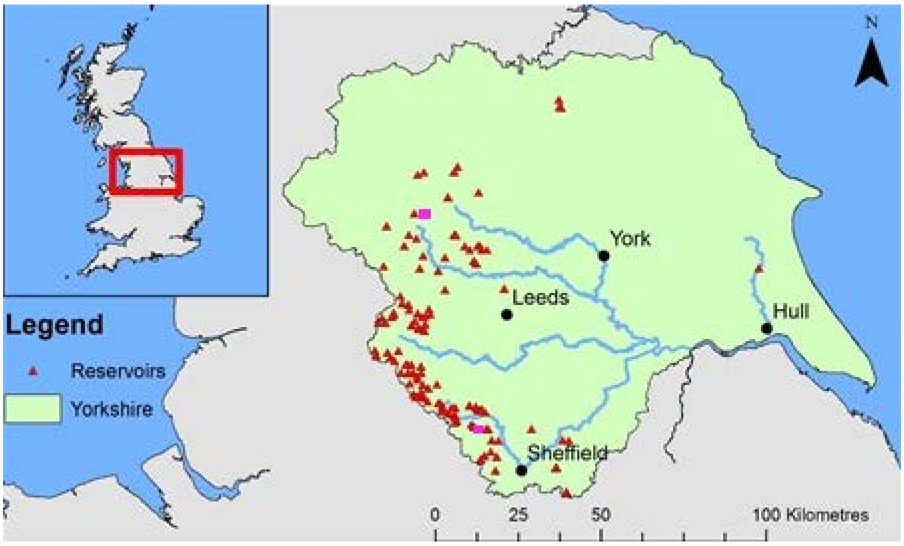


Figure 2. Locations of all reservoirs in Yorkshire, UK – the main study reservoirs are demarcated with pink squares. Grimwith Reservoir is north west of Leeds and Langsett Reservoir is north west of Sheffield. (*Adapted from a file courtesy of Timothy J. Stone, HIFI, 2016*).

In this study, large, historic weirs (with heritage value) situated at the mouths of the only two viable spawning tributaries of Langsett Reservoir in Sheffield, the River Little Don and Thickwoods Brook, prevent access to suitable brown trout spawning habitat upstream. The weir on the River Little Don is larger than that on Thickwoods Brook. This size difference is pertinent when harsh weather conditions (for example, complete freezing of spawning streams) or insufficient flows do not to allow the biggest and most fecund members of the population upstream to spawn (Frost and Brown 1967; Thaulow *et al.* 2014). Despite these studies, there is still a paucity of information about the spatial behaviour and ecology of wild brown trout in reservoirs and their tributaries, including those without barriers to movement. The results at Langsett Reservoir were compared with those in a parallel study at Grimwith Reservoir, near Harrogate, where trout in two tributaries (Blea Gill Beck and Gate Up Gill) had unimpeded access into the reservoir and back to the tributaries.

It is possible that brown trout can adapt to impediments to migration into rivers and spawn in lakes reservoirs (Brabrand *et al.* 2002, 2006; Thaulow *et al.* 2014). Brabrand *et al.* (2002, 2006) outlined conditions under which lake-spawning of brown trout can be expected to occur, and indicated a combination of substrata conducive to spawning and continuous groundwater flow must be present. Notwithstanding, Thaulow *et al.* (2014) stated that lake spawning of brown trout was not necessarily an adaption to local conditions and may be attributed to individuals spontaneously utilising a suitable spawning area.

In the cases of the systems at Grimwith and Langsett Reservoirs, the Environment Agency has done large scale assessments and found 'Ecological Potential', 'fish' and 'mitigation measures' are lower than the target rating and, as such, an investigation into what might be responsible for these low ratings was necessary. In particular, it was vital to ascertain whether or not the structures present on the tributaries were having an effect on the fish populations; if so and if mitigation could be implemented, the scores in the three mentioned categories should improve. The structures had not been classified, but if an artificial barrier prevents over 80% of migrating fish (upstream or downstream) that would otherwise be able to do so then it would be deemed to have 'Poor Status' and would contribute to a poor score overall for a system (UKTAG, 2015). If this was found to be the case then mitigating the barriers on the reaches should increase the WFD ratings. For instance, if the barriers were preventing upstream spawning migrations, then allowing fish passage of the obstacle could increase fish populations (increasing the 'fish' score), eliminate asymmetric gene flow and increase the ecological potential of the system. It would be in itself a mitigation measure so that score would also increase. If they were found not to be having an effect on the systems then they can be ruled out of future considerations for ecological improvement and resources focussed elsewhere to find other solutions to the issues.

The overall aim of this study was to assess the influence of barriers on fish populations in Langsett Reservoir (study reservoir) by comparing a study concurrently duplicated at Grimwith Reservoir (control reservoir) into the movement, behaviour and distribution of fish in these systems and suggest the most appropriate methods to ensure the sustainability of these populations, with particular focus on obstacle alleviation, whilst considering EU directives. In addition to this, an acoustic study was undertaken at Grimwith Reservoir to attempt to understand temporal variations in behaviour and habitat use. Due to large operational costs the investigation was performed at Grimwith Reservoir only.

2 LITERATURE REVIEW

A scientific literature review was conducted to evaluate current knowledge of brown trout and similar species and their migratory tendencies in fresh water, be it rivers, lakes or reservoirs. The aim was to evaluate the impact barriers elicit upon individuals and whole populations of salmonids. By reviewing how the scientific community has investigated these issues thus far, best practices, knowledge gaps and established processes can be discerned. Alleviation methods were also researched.

Aim:

- Provide general scientific background of brown trout, its life history and how their migrations can be disrupted.

Objectives:

- Identify the brown trout life cycle and how individuals' needs change as they develop and grow.
- Describe individual populations of salmonids, particularly brown trout, in freshwater habitats (rivers, lakes, etc.).
- Describe how habitats affect brown trout and how brown trout use their habitats.
- Describe brown trout migrations.
- Discuss methods used to track fish and how migrations are impacted by barriers, and how these can be alleviated.

2.1 Brown trout in headwater streams

Brown trout are well adapted to headwater streams, having been extant in what is considered their current form for over 2 million years (Bernachetz 2001). They are found throughout the UK, much of Europe and parts of Asia. They are also present in USA, Australasia and Far East Asia as an invasive species due to historic introductions (Jonsson and Jonsson 2011).

Adult brown trout are generally 33 – 41 cm in length. Their bodies are olive brown or green shading to a yellowish white on the belly. The sides of the fish have red spots surrounded by a pale halo. They exhibit bilateral symmetry and are ectothermic. They have 3 – 4 dorsal spines; 10 – 15 soft dorsal rays; 3 – 4 anal spines; 9 – 14 soft anal rays and 57 – 59 vertebrae. The body of the brown trout takes a fusiform shape (derived from Fishbase; Froese and Pauly 2016).

2.1.1 *Spawning and recruitment*

In Europe, brown trout usually spawn in rivers, on riverbeds of stone and gravel between November and January (Klemetsen *et al.* 2003; Jonsson and Jonsson, 2011). In shallow waters (6-91cm), females use their caudal fins to cut into the gravel, to create depressions, where eggs are deposited (Cowx *et al.* 2004). Elevated flows during autumn and winter trigger salmonids to migrate upstream to spawn (Jonsson and Jonsson 2011). Although it may seem counterintuitive to migrate when rivers are at their most powerful, it has the benefits of turbulent water providing cover from visual predators and the inundation of river features that are barriers at lower flows (Trepannier *et al.* 1996; Olsson and Greenberg 2004; Jonsson and Jonsson 2011). It has been suggested that fish move upstream to spawn to alleviate the natural drift in alevins with rising waters in spring (Ovidio *et al.* 1998). Also, floods (which are more common and powerful further downstream) interfere with the digging of redds by salmonids (Baglinière *et al.* 1979), as well as bringing with them high sediment loads which affect the permeability of gravel beds and affect their suitability for embryonic development (Tappel and Bjornn 1983) due to lack of oxygen.

Brown trout in the UK usually spawn between November and January. The ideal spawning substratum is clean gravel of 20 – 30 mm mean grain size with less than 15% fine sediments and a water depth of approximately 15 – 25 cm (Smallwood, 2016). Brown trout spawn in redds they excavate within gravel beds; the excavation allows silt to be washed downstream, cleaning the gravels. Redds are typically located in gravel beds at the downstream end of pools where water velocity increases prior to entering a riffle, where flow of water through the gravel interstices would be sufficiently beneficial for the eggs. A flow of cool water is required for egg and alevin (an embryonic life stage living within the gravels feeding on a yolk sac) survival and development as it delivers oxygen and removes toxic metabolic waste products (Smallwood, 2016).

The female begins depositing her eggs in her redd (nest) and a dominant male (who controls access to the female) swims alongside and fertilises most of the eggs (smaller, less dominant, less fecund males can rely on opportunism and release their milt (sperm) into the spawning area too). The female subsequently covers the eggs with gravel and excavates a new redd. This process continues until the trout are spent, when they return downstream (Jonsson and Jonsson, 2011). Brown trout that have spawned and returned to their residential lakes do not necessarily spawn again the next year, some have been shown to observed for a year – e.g. fifty per cent of one studied population in Dunalastair Reservoir and Lough Moraig (Stuart 1953). Populations of brown trout with individuals that spawn in multiple years can be considered robust (multiple consecutive years of complete recruitment failure required for extinction) (Lobón-Cerviá and Rincon 2004).

Recruitment (the change in a natural population as progeny grow and new members arrive) is the most immediate factor in population size, and is affected by stream discharge and water temperature (Lobón-Cerviá and Mortensen 2005). Recruitment, however, affected growth and mortality, in that, high recruitment means reduced growth and higher mortality (Lobón-Cerviá 2009). These trends have also been seen in stocked rivers (Bohlin *et al.* 2002).

2.1.2 *Emergence/Juveniles*

Alevins remain in the gravels until their yolk sac (a legacy of their embryonic stage) is almost completely diminished. At this point, they emerge and begin feeding exogenously (Jonsson and Jonsson 2011). As soon as the yolk sac has been exhausted young trout are called fry; further growth, whilst still in the juvenile stage, along with the development of dark rings along the body signify the 'parr' stage. Following this, further growth and morphological changes, in particular a silvering in hue, signal the 'smolt' stage.

The gravels that are used for spawning also offer protection to newly emerging trout. As soon as brown trout (Figure 3) emerge they become territorial. Holding a territory with valuable feeding opportunities is advantageous, enabling the successful individual to devote more effort than one that holds a poorer territory, to growing, thereby growing larger and becoming more dominant in that system (Jonsson and Jonsson 2011). Excessive quantities of fine sediments can act directly upon young stages by settling on egg surfaces and reducing oxygen uptake or choking the gills of alevins. Fine particles can also have an indirect effect by obstructing the spaces within the gravel beds and impeding the emergence of alevins into the water column. The extent to which sand and smaller particles fill the spaces around gravel and larger particles is known as embeddedness. If eggs are deposited shallow in gravels, they are more prone to wash out in spates as are the developing alevins. Deeper gravel depths and a larger adults allow deeper burial of the eggs, which gives greater protection and an increased likelihood of survival to emergence.

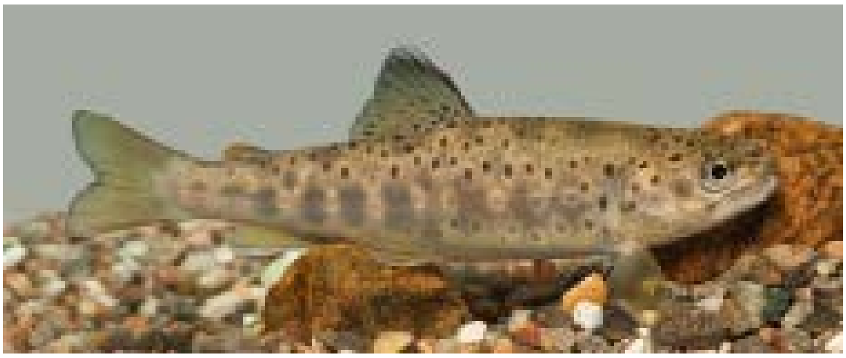


Figure 3. A juvenile brown trout (Jonsson and Jonsson 2011).

Care must be taken when surveying populations because growth, density, mortality and production are site-specific (Lobón-Cerviá, 2014), therefore all sites pertinent to a study must be studied to allow accurate population analysis.

Stream discharge (and rainfall) in March and favourable site depth for newly emerged juveniles and environmental variability were significant in determining survival rates, in that favourable conditions promoted higher survival rates (Lobón-Cerviá and Rincon, 2004; Lobón-Cerviá, 2014).

Brown trout is essentially carnivorous after using up the yolk sac, eating mostly aquatic organisms, usually insects, molluscs and crustaceans (eating them at all life stages). Weed fragments, moss, etc., are probably ingested accidentally. Movement of prey items, either of their own volition or via the water, is key to the trout deciding to ingest. With feeding behaviours comes territoriality, with larger juveniles holding the most advantageous territories and defend them with aggression against encroachers (Frost and Brown, 1967).

Brown trout are temperature-resilient once they reach the juvenile period - Ojanguren and Brañta (2000) found that swimming performance remained above a threshold of 90% of maximal capacity in the range of 12.2 – 19.9˚C, in their study in Spain. This resilience is reflected in their ability to tolerate adversarial conditions – in juvenile brown trout, if food availability is low when their foraging skills are still developing and inefficient, nutrients need to be reabsorbed to increase chances of survival; resultantly negative growth (shrinkage) can be experienced (Huusko *et al.* 2010). By contrast, egg mortality rises with increasing temperature; a survival rate of zero at >16˚C, and high mortality at >14°C (Ojanguren and Braña, 2003).

2.1.3 *Adults*

Brown trout are highly motile, and it has been extensively reported (Banks, 1969) that they migrate upstream to find appropriate spawning habitat. It has also been observed that the majority of individuals in some populations can be relatively sedentary (Schulz and Berg, 1992; Popoff and Neumann, 2005); therefore displaying a high variation in life history strategies. Territorial behaviour does not extend through the entire life span of the brown trout. Typically, beyond the parr stage the fish enter size-structured dominance-hierarchies; in these hierarchies trout do not have individual territories, but reside in a region described throughout literature as a "home range" (Valdimarsson and Metcalfe, 2001; Venter *et al.* 2008). Studies on the home ranges of brown trout have shown that the best feeding opportunities are exploited by the dominant resident who will forage throughout the range, restricting feeding opportunities to the subordinate fish (Frost and Brown, 1967; Dolinsek *et al.* 2007). In Young's (1994) study 37 out of 54 radio-tagged brown trout occupied home ranges of more than 50 m. Larger trout (over 340 mm in length) moved more frequently than smaller trout and occupied larger home ranges. More movements were recorded in autumn than other seasons, in terms of both frequency and distance. The possibility of two different life history strategies was discerned from movement patterns, i.e. highly mobile vs non-mobile. A study involving 11 radio-tagged brown trout (Diana *et al.* 2004) reported that some fish utilised multiple home sites (over 500 m between sites). Fish tracked from more than one year used the same home sites each summer, generally exhibiting similar behaviour each year. Fish were categorised into either mobile or stationary subgroups similarly to Young (1994). Mobile fish were in their home sites for only 43% of the time, whereas stationary fish did not move far even at night. An extra facet of the study was that three fish were tracked extensively over 36 days. Diana *et al*. (2004) found that hourly activity increased drastically at dawn and dusk, was low during the night and near zero during the day.

It was proposed that stream gradient may be a key factor to movement, in the regard of an energetic trade off. Stationary fish generally resided in areas of greater stream gradient (Diana *et al.* 2004). Making concerted moves in this environment is energetically costly, so fish adopt a more fixed positional approach. However, as they grow, brown trout become more able to tolerate deeper and faster flows (Jonsson and Jonsson, 2011).

Movement of radio-tagged brown trout in New Zealand decreased steadily over spring and summer as flows decreased and water temperatures increased (Young *et al.* 2010). Increased amounts of movement were recorded in autumn, similar to their previous study (Young, 1994). Heterogeneity was seen in movement behaviours – some sedentary fish became highly mobile and *vice versa*. Deep pools were largely favoured for residence during summer, when the lowest rates of movements were recorded as they offered refuge against uncomfortably high temperatures (Young *et al.* 2010). Despite the trends at a population level, individuals showed that large movements are still undertaken at this time, further evidencing the diversity in behaviour elicited in a population. Also of note is that large floods during winter killed over 60% of tagged trout, showing the susceptibility of populations to catastrophic events. This factor corroborates Gresswell and Hendricks' (2007) recommendations that, when conducting analyses, it is important to consider any restoration on a whole system scale, as although movements are mostly highly localised, the individuals that can recolonise after extirpation events are those that move greater distances.

Brown trout have varied diets, both intra-specifically and temporally; individuals can exploit different niches in their environment (Jonsson and Jonsson, 2011). Daily growth rates are three times higher for piscivorous (fish-eating) trout when compared with those feeding on invertebrates. As visual feeders, water transparency is an important factor for vertical distribution, deeper feeding behaviour was recorded in clearer lakes (Langeland *et al.* 1991). Brown trout rarely feed deeper than 1 – 2 secchi-disks from the lake's surface (Klemetsen *et al.* 2003). However, Frost and Brown (1967) observed that in deep lakes, large trout seem to spend all of their time in deep water, and Jonsson and Jonsson (2007) also reported that larger individuals feed in the deeper areas. As fish get larger, the probability of them being piscivorous increases, and fast-growing individuals tend to switch to this diet earlier than smaller conspecifics (Klemetsen *et al.* 2003). Jonsson *et al.* (1999) found the mean age of piscivorous brown trout to be 4 years, yet found invertebrate feeders of 9 years.

Optimum water temperatures for maximum growth for invertebrate feeders and piscivorous brown trout are 13.9˚C and 17.0˚C respectively (Elliott and Hurley, 2000a). Elliott and Hurley (2000b) calculated gross efficiency for converting energy intake from food in 292 brown trout, and found, purely in terms of efficiency, invertebrate-feeders had a maximum conversion efficiency of 31.8% (at 8.9˚C) and was over 30% at 7.0 – 11.0˚C. Piscivorous feeder were 41.8% efficient at 9.3˚C, which was the maximum, over 40% in the range 6.5 – 12.0˚C and over 30% within the range 4.0 – 16.0˚C. Keeley and Grant (2001) suggested that the difference in growth potential between streams (low), lakes (medium) and marine (high) environments is partly related to the size at which piscivory first occurs: marine (8 cm); lakes (15 cm); streams (27 cm). Fish that move downstream grow to greater sizes, in less time than those that do not. Due to their size they are more fecund and, as such, have a greater reproductive value for the population.

Kennedy and Fitzmaurice (1971) noted that the growth of trout in alkaline waters was fast, whilst growth in acidic waters was slow. The observed length of brown trout was also influenced by the length of time they spent in natal streams, specifically those that moved earlier growing to a larger size. In barren lakes, due to restricted spawning, there were few trout, however they grew quickly and to large sizes (>40 cm), whilst facing little competition. In more productive lakes, stock density was higher and, as such, competition led to slower growth and smaller trout at all ages than less productive lakes. Ferox (large, piscivorous) trout were more commonly found in lakes of moderate alkalinity, and were rare in highly alkaline lakes.

Ombredane *et al.* (1998) observed over 2000 0+ brown trout which had been PIT-tagged, and found no significant effect on growth or survival. The rate of recapture decreased with fish size, due to larger fish apparently migrating further, probably into the main river system – this finding indicates that results returned in these studied fish can be applied to general populations, in that PIT-tagged individuals behaved no differently from those that had not been PIT-tagged.

2.2 Downstream migration of juvenile brown trout

A smolt migration similar to that performed by anadromous brown trout (those which inhabit seas and migrate into freshwater upstream to spawn) occurs in lake and reservoir populations. However, rather than moving into rivers and then the sea, their migration ceases once they have reached a habitat that is capable of carrying them (Arnekleiv *et al.* 2007). There is swaths of evidence for considerable downstream migration of brown trout alevins and young in lake nursery streams (Stuart, 1957; Thorpe, 1974; Lien, 1979; Gordon and MacCrimmon, 1982).

In Scottish lochs and a Norwegian lake, young trout moved from small streams into the lakes during autumn and back to the stream in spring each year until they matured (Stuart, 1957; Lien, 1979). The summer migrations into the nursery stream suggest a similar pattern for Lake Frongoch (Swales, 1986). Many brown trout, if they have access, will gradually move downstream into a lake (or out to sea if connectivity is sufficient) for feeding purposes (Jonsson 1989; Jonsson and Jonsson, 2011).

Brown trout were found to have been delayed by approximately 7 days by weirs during smolt migration. Some smolts will undergo desmoltification and remain river resident due to these delays, abandoning their downstream migration (Aarestrup and Koed, 2003).

2.2.1 *Drivers*

Newly emerged and young trout may undertake downstream migrations due to intraspecific and aggressive territorial behaviours (losing competitive interactions with larger conspecifics); this dispersal regulates density (Kalleberg, 1958; LeCren, 1973). The strength of water may also move juveniles passively downstream shortly after they have emerged (Ottoway and Clarke, 1981). Northcote (1978) suggested that older fish performing similar movements could have different drivers behind them, namely physiological, environmental or genetic stimuli. LeCren (1973) assumed that the displacement of juveniles would force them into unsuitable habitat downstream and, as such, represent a density dependent mortality. Swales (1986) suggested that in lentic systems the opposite was the case, as lacustrine habitats could support trout of all ages. Movements described by Swales (1986) corroborate with studies (Stuart (1957) in Scotland, and Lien (1979) in Norway) that found that young trout moved from small streams into lakes during autumn and back into lotic waters yearly until they became mature.

Smaller trout migrate downstream earlier than larger conspecifics in a dynamic process of elimination by territorial fish (ergo, smallest are forced downstream first, then larger and larger individuals move downstream for the same reason until the larger resident trout are left) – all of this was observed in laboratory environment and echoed in field studies. Competition for food and space was the main driver – promoted by variations in hydrological conditions (decreasing water depth) (Landergren, 2004). As discussed in Section 2.1.3, these smaller, out-competed fish however, may find a niche to exploit in a larger body of water downstream and compensate for their prior reduced growth.

Olsson and Greenberg (2004) reported that when population density in streams was low and fish growth rate high, no migration to the adjacent lake occurred, seemingly due to the fish's needs being met adequately in their current environment. However, if the opposite was true (high density, low growth rate) over 90% of 0+ and 1+ individuals migrate to the lake. 2+ individuals behaviour was unaffected by these factors. Migrants had higher growth rates than non-migrants.

Bjornn (1971) postulated that non-anadromous fish in the streams of Idaho, USA, moved because they found the stream environment unsuitable during the winter. No water temperature preference was found. The migration occurred despite stable flows in the streams. When cover available in the substratum was insufficient due to freezing, movements took place. The number and percentage of fish moving was influenced by population density, in that the more densely populated the area, the greater the number and proportion of fish that migrated.

2.2.2 *Timing*

In mid-Wales, Swales (1986) found that March and April saw the highest numbers of brown trout moving downstream into Llyn Frongoch (a small oligotrophic lake 300 m above sea level) and the numbers generally and steadily decreased in the months afterwards.

Not all brown trout from the same cohort move downstream at the same time, or even in the same year, but if they have access to a lake many will gradually move there (Jonsson, 1989). For instance, Craig (1982) found 70% of trout migrating into Windermere, UK, were in their second year. Of the remaining 30%, 16% were in their first year and 14% in their third. No older fish were found to be moving, so were assumed to have either already moved or settled in the habitat upstream of the lake. Jonsson *et al.* (1999) found most fish moved from their natal stream into Lake Femund, Norway, at age 2 or 3 years (40% and 27%, respectively, although the range was 1 – 8 years). Frost and Brown (1967) stated that the age at which brown trout migrate into lakes from spawning streams varies. Some move in their first year, whilst others may wait until they are 3 or 4. It has been documented that some trout remain resident in their streams for their entire lives (as detailed extensively in Swales, 1986). Those that do move into lakes or reservoirs grow at a faster rate than those which do not. Those that move earliest in their lives tend to be the largest in their age class and, as such, they remain the largest individuals in their cohort due to the increased lacustrine feeding opportunities.

2.3 Existence and circumstances of entirely lacustrine brown trout populations

Some populations of brown trout refrain from the generally obligatory upstream spawning migrations entirely, instead they spawn in the lakes or reservoirs in which they reside. This may be out of choice, spontaneously electing to spawn where there appears to be suitable substrate, or out of necessity due to a lack of access to tributaries.

2.3.1 *Habitat usage*

Nettles (1983) found that females move more than males during spawning seasons, possibly because the females have to find a suitable spawning habitat whereas the males need only to find females. However, females moved further and faster than males generally too (Nettles, 1983; Nettles *et al.* 1987). The tagged trout over-wintered in 4°C water, the warmest available, vacating nearshore waters; the same trout also summered in these deeper waters because during summer the near shore water is too warm. This was the case under normal conditions but when novel habitat such as a power plant outflow was available, that was positively selected. Given preferred thermal conditions brown trout prefer to be as nearshore as possible (Nettles, 1983; Nettles *et al.* 1987).

The tracked fish moved more in spring than in autumn. The diversity identified within this population during this study led the authors to suggest that the population may partition among available habitats (Nettles *et al.* 1987) and speciation may occur.

Rader *et al.* (2007) assessed the visual capabilities of brown trout and other lacustrine fishes. Brown trout can forage during all twilight periods and during average night light intensities in open and shaded reaches. In lakes, food can still be a limiting factor for brown trout growth despite them offering greater feeding opportunities than rivers and streams. Where populations are large and the food supply is insufficient, competition can lead to reduced growth (Stuart, 1953).

2.3.2 *Lake spawning*

Lake-spawning populations have been documented (Frost and Brown, 1967; Klemetsen, 1967; Scott and Irvine, 2000; Sneider, 2000; Brabrand *et al.* 2002; Louhi *et al.* 2008; Jonsson and Jonsson, 2011). This life history trait has also been documented in other Salmonidae like Atlantic salmon (*Salmo salar* Linnaeus, 1758) (Verspoor and Cole, 2005). It would seem that the scenario of brown trout in headwater streams outlined above is not always realised *in situ*. Tributaries can be insufficient or unsuitable for spawning, for many and varied reasons such as: insufficient space in small streams for a large resident lake/reservoir population to all spawn in; tributaries may be completely devoid of spawning habitat (e.g. no gravel substratum) (Frost and Brown 1967) or there may be an inability to access spawning tributaries due to low flows or barriers (Thaulow *et al.* 2014). Brabrand *et al.* (2002 and 2006) outlined conditions under which lake-spawning of brown trout can be expected to occur, and indicated a combination of substratum conducive to spawning and continuous groundwater flow, for the development of life stages prior to swim-up larvae, must be present. Notwithstanding, Thaulow *et al.* (2014) stated that lake spawning of brown trout was not necessarily an adaption to local conditions and may be attributed to individuals spontaneously utilising a suitable spawning area.

Brown trout that spawn in lakes typically spawn in depths of between 3 m and 8 m (directly observed via scuba diving) (Brabrand *et al.* 2002). One reason for this being a viable option is groundwater influx, which permeates through gravel at significantly higher rates than sand- or mud-dominated substrata (Brabrand *et al.* 2002) trout redds need oxygen replenishment and water through-flow. Areas of high winter precipitation are most likely to facilitate lake-spawning brown trout (Brabrand *et al.* 2002).

Barlaup *et al.* (1998) found that only 0.5% and 3.5% of live embryos in the redds of lake spawning trout were viable. It was suggested that acidity can be a major factor impacting lake-spawning trout, after a programme of adding limestone gravels resulted in 33 – 36% of live embryos being viable; Ojanguren and Braña (2003) reported that ~ 67% of live embryos in optimum conditions in a stream redd were viable.

Juveniles aged 1+ were only caught in shallow littoral zones of Lake Skavatn – this area sees the largest inflow of groundwater from the surrounding catchment (Thaulow *et al.* 2014). These juveniles were also more similar genetically to the lake population, than those in the tributaries were, perhaps indicating that part of the lake population spawn and reside exclusively in the lake and the tributary populations spawn and reside solely in their natal tributary. It was also suggested that lake spawning was not necessarily an adaption to local conditions, in fact it may have more to do with individuals utilising suitable spawning area spontaneously. This is especially pertinent when harsh weather conditions (including complete freezing of spawning streams) or insufficient flows prevent the biggest and most fecund members of the population migrating upstream to spawn (Thaulow *et al.* 2014).

Kokko and Sutherland (2001) stated that species use indirect cues when assessing habitat quality, and it is possible that habitats may change and a discrepancy between true quality of habitat and the cues animals receive from the habitat may arise. This can be referred to as an ‘ecological trap’. This is not just pertinent to lake spawning trout but also to those spawning in streams or even just selecting habitat in an under-exploited system.

These (Kokko and Sutherland 2001 and Thaulow *et al.* 2014), can be considered additionally to the conditions outlined in Brabrand *et al.* (2002 and 2006) that brown trout spawning in lakes can be expected to occur where a combination of continuous water flow (which is sufficient for all stages of development prior to emergence) through gravel and substrata conducive to spawning is present.

When three lakes were studied in Norway, all three were found to contain young of year cohorts in the littoral areas with groundwater inflow. All three lakes also had restricted upstream riverine habitat and high recruitment, indicators of lake-spawning (Heggenes *et al.* 2009).

2.4 Upstream migrations into tributaries

Fish in reservoirs and lakes have been found to congregate near the entrances of spawning rivers and exhibit shoaling behaviour near the entrances of spawning streams (Frost and Brown, 1967). These movements can occur any time during the spawning period based on the usual drivers (gonad hormones and ripening, flow, water temperature; (Frost and Brown, 1967; Klemetsen *et al.* 2003; Jonsson and Jonsson, 2011)) reservoir and lake populations of brown trout do not exhibit any difference from other populations in this respect.

2.4.1 *Timing*

Upstream movements from Llyn Frongoch, Wales (coinciding with the highest littoral temperatures) were recorded in July, August and September (Swales, 1986).

Oananiche (a French term for freshwater (lake-trapped) salmon) were recorded moving upstream after high flows when levels were falling (decreasing rather than increasing flows). Larger individuals moved earlier than smaller individuals, possibly as a result of being able to negotiate more powerful flows, congruently it was also reported that 3-lake year salmon moved earlier than 2-lake year salmon. Most (96%) returning spawning individuals had spent 2 or 3 years in the river (Trepanier *et al.* 1996).

In the Moravka Reservoir, Czech Republic, reservoir-resident brown trout spawned in October/November, peaking between 28 October and 3 November. Spawning occurred when water levels rose and water temperature dropped to below 8°C in the reservoir. In one of the three years (2002) there was a significant preference for nocturnal spawning (Piecuch *et al.* 2007).

2.4.2 *Barriers to migration*

Upstream migrations can be severely disrupted by, amongst other things, impoundments, some of which are man-made (Sheer and Steel, 2006). The nature of these structures is to alter the flow regime of a river or stream. Impounding a river or stream has possible consequences for: discharge, water velocity, temperature, dissolved oxygen, river bed movement, siltation and suspended solids (Crisp, 1993). Some man-made barriers such as low-head dams and small weirs may not represent a permanent or insurmountable barrier to fish migration, but can still have significant effects on animal movements, flow and temperature regimes, sediment transport, biogeochemistry, and stream habitat (Larinier, 2001).

An analysis of streams conducted by Denic (2010) stated that several migration barriers — particularly where lakes and rivers meet — prevent successful spawning migrations at normal water levels; the problems posed by these barriers were exacerbated by low discharge. Barriers to movement are probably the main limiting factor for reproduction of lacustrine brown trout. The habitat requirements of both spawners and juveniles were met by the rivers (Denic, 2010).

Weirs or hydropower schemes can increase the mortality risk of migrating fish if they make repeated attempts to surmount impoundments. This has a negative effect on energy reserves and can result in increased spawning mortality or fewer successful spawning events (Gerlier and Roche, 1998). Migrations that are delayed expose migrating fish to risks; opportunistic predators (such as the great cormorant, *Phalacrocorax carbo* Linnaeus, 1758) may use weirs as vantage points (Garcia de Leaniz, 2008). Furthermore, efforts spent by trout as they wait downstream of barriers for (sometimes high) flow thresholds to be met compromises reproductive success and survival (Aarestrup and Jepsen, 1998).

Gosset *et al.* (2006) radio-tagged 40 brown trout and noted that each trout seemed to select only one tributary for spawning. Inside this tributary, after an initial upstream progression, movements were usually restricted. In the main channel, when fish were stopped by a weir, hardly any attempts were made to enter alternate tributaries. Although they may have spawned downstream in the main stem, it is possible that it was not the most preferable option. It was also noted that there were different degrees of passability at different weirs. One in particular was easily transcended at high flows. One further upstream with a poorly designed fish pass (which was in the middle of the channel, obscured relative to the flow of water cascading over the weir and in poor condition probably because of it being old and poorly maintained) proved a much more significant barrier. It was concluded that fragmentation has strongly affected migration in this system. In another example, populations of brown trout that reside in Lake Mjøsa, Norway, and migrate upstream to spawn in the River Gulbrandsdalslågen were subject to a selective pressure as a waterfall near the lake prevented small trout from ascending any further and, as such, were unable to exploit any spawning habitat upstream of the barrier. That was the case until a fish passage was installed, which permitted a great size-range of individuals to ascend the barrier (Haugen *et al.* 2008).

Sediment deposition (‘silting-up’) upstream of weirs increases whilst downstream gravel recruitment decreases as a result of the change in river morphology caused by weirs (Kondolf, 2000). When restoring catchments to “Good Ecological Status”, longitudinal connectivity of rivers and lakes is often put forward as one of the initial steps. The benefits of barrier removal can be clear – increased or even initialised fish passage. These improvements can be brought to bear relatively quickly in comparison to other techniques used in restoration (Roni *et al.* 2002). Fish passes, however, do need continual maintenance and their operational capabilities may be reduced by low flows or incomplete maintenance (Beechie and Bolton, 1999). The re-instatement of historical, natural flow regimes encourages the movement of sediment and organic materials down the river system, as well as larger debris, like wood (Roni *et al.* 2002). Weirs and other impoundments can scupper attempts to enhance habitat instream (e.g. addition of spawning gravels or habitat creation through woody debris installation), either by rendering them inefficient or limiting the length of time for which they are operational. This can be rectified by proper prior consideration (Roni *et al.* 2002). Beechie and Bolton (1999) stated that improving habitat for fish and biodiversity and improving longitudinal connectivity should be primary goals.

2.5 Fish tracking

McCutcheon *et al.* (1994) reported that two independent PIT-tag monitoring systems were installed at the exit area of a weir leading into a fish trap on the north-shore fish ladder at Bonneville Dam, Columbia River, USA. One hundred PIT-tagged rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) were released in groups of 10 into an enclosed area of the ladder downstream from the detectors. The tagged fish were detected after swimming through the weir of their own volition and sliding through the detection system. Overall PIT-tag reading efficiency was 98% and no tag-reading errors were recorded. Individual tag code, date, and time of the passage of each tagged fish were automatically recorded into a computer file. These results showed that PIT-tag investigations similar to this could be deployed to interrogate migrating salmonids. PIT-tagged salmonids do not exhibit any negative effects in feeding (a sensitive, stress-affected behaviour) or swimming performance (a behaviour critical to survival) (Newby *et al.* 2007). This is crucial because the survival of the tagged fish may depend on those two characteristics (Newby *et al.* 2007).

PIT-telemetry can provide continuous monitoring at fixed locations, which allows for evaluation of the influence of environmental factors (e.g., water temperature and flow rate) on movement and passage success (Lucas and Baras, 2000). An example of this is the study undertaken by Martins Fontes Junior *et al.* (2012), which identified bottlenecks in the Parana River system in Brazil, installing PIT antennae upstream and downstream of certain suspected barriers to ascertain passability at each location.

PIT systems are more frequently being used as a cheap and effective method of monitoring the movements of a variety of species. The technology works by inducing an electrical current within a coil of wire inside the tag, which transmits a unique identification number (ID). This ID is detected up by stationary monitoring equipment and saved onto a logger system. As tags only give emit signal when electrically induced, there is no need for the tag to hold a battery, thus greatly saving on tag weight. This gives the tags unlimited life expectancy, allowing them to be used over multiple year studies, or used in other studies if retrieved.

2.6 Conclusions

Habitat and environment are crucial to brown trout, and salmonids in general, throughout their life histories – but they are a robust species. As they develop their needs change. It is not currently known to what extent barriers effect brown trout at population level. It is hoped that this study will elucidate the issues facing the populations in the Langsett and Grimwith systems. If these knowledge gaps are filled then appropriate management plans can be created to adhere to the ultimate goal of increased Ecological Potential.

Spawning migrations are not necessarily widely understood either, and coupled with barriers in a system these can lead to problems when attempting to mitigate problems in a system or in attempts to rehabilitate it. To maximise the health of a system it must be understood, so human activity which hinders the system can be arrested and steps taken to assist it.

There is a paucity of information available about salmonids spawning in lakes in the UK, despite the requisite conditions for lake-spawning being established. This study hoped to provide insight into whether this may be happening in Grimwith Reservoir.

The tags used, PIT and acoustic and the methods deployed are well-established and likely to have minimal effect on the tagged fish, and as such results can be considered reliable in this sense.

3 MATERIALS AND METHODS

The overall aim of this study was to assess the influence of barriers on fish populations in Langsett Reservoir (study reservoir) by comparing a study concurrently duplicated at Grimwith Reservoir (control reservoir) into the movement, behaviour and distribution of fish in these systems and suggest the most appropriate methods to ensure the sustainability of these populations, with particular focus on obstacle alleviation, whilst considering EU directives. In addition to this, an acoustic study was undertaken at Grimwith Reservoir to attempt to understand temporal variations in behaviour and habitat use.

The objectives of this study were as follows:

- Discern whether or not brown trout migrate between the tributaries and reservoirs and, if so determine the age and approximate size of fish, the timing (related to spawning season, river flow and water temperature) of movements and possible impacts (e.g. delay) that weirs have on fish movements over the lifetime of the tagged individuals. Passive integrated transponder (PIT) tags were surgically implanted in brown trout and fixed-location telemetry (without recapture) was used to investigate the longitudinal movements (including direction) of brown trout at the mouth of the tributaries entering Langsett and Grimwith (control) Reservoirs. Knowing the passability of the barriers in both an upstream and downstream direction may help inform the type and scale of remediation work to be performed and establish if future remediation work will improve connectivity.

- To understand the habitat use of brown trout in a reservoir, especially during the spawning period, with no barriers to upstream migration on two of its tributaries, acoustic telemetry were deployed at Grimwith Reservoir.

- To identify which remediation works are most likely to have a significant impact on the brown trout population in the reach upstream of the barriers. Quantitative (triple run) electric fishing surveys in tributaries upstream of Langsett and Grimwith Reservoirs in 2014 and 2015. If populations upstream of barriers are lower than expected according to HABSCORE assessment, and the weirs are deemed to be significant to the extent that they prevent brown trout spawning migrations, the likelihood of mitigation measures being necessary and successful will be higher than if the populations are at a healthy number, and the weirs are not completely impassable.

- Determine appropriate mitigation methods, if necessary, with the aim of improving fish populations in the study rivers. These could be:

i) Do nothing – there may be insufficient data to make any significant conclusions, and, as such, no further action could be taken other than to continue monitoring.

ii) Remove the weirs – this could be a very costly solution and have dire consequences for downstream water bodies. The weirs are over 100 years old and may have trapped deleterious chemicals from upstream. Removing the weirs may release these.

iii) Fish pass solutions – building a fish pass facility either onto or around the weirs could alleviate the connectivity problems without having an effect on the sediments. This is another expensive option, and would have a bespoke design as each may have different conditions that would optimise use, in terms of flows or fish size.

iv) “Trap-and-transport” – a fish trap may be strategically placed downstream of an obstacle to collect fish that are migrating upstream to spawn. These would then be collected and manually moved upstream of the barrier to continue their spawning migration. The trap would have to be emptied frequently to prevent costs to fish health.

v) Stocking – if the river upstream of a barrier is fish-poor but there is no requirement to remediate any connectivity problems perhaps because no attempted spawning movements were observed downstream of obstacle, then fish could be stocked to bolster the upstream population.

The two studied systems, Grimwith (Figure 4) and Langsett (Figure 5) Reservoirs (locations in Yorkshire shown in Figure 2) and their tributaries are classed as ‘Heavily Modified Water Bodies (HMWB)’ (UKTAG, 2008) and have an ecological status of ‘moderate’, ‘moderate or less’ or ‘poor’. Water bodies identified as being at significant risk of failing to achieve good ecological status because of modifications to their hydromorphological characteristics resulting from past engineering works, including impounding works (UKTAG, 2008). It is recognised in the Directive that physical alterations support the socio-economic use of a water body for a particular purpose (for example, water storage, flood defence or navigation). In this case the water body may be designated as a Heavily Modified water body (HMWB). Artificial Water Bodies (AWBs) are those Water Bodies which have been constructed for a specific use (for example, a reservoir). Any of the surface water body types (rivers, coastal, lake or transitional) can be designated as Heavily Modified or Artificial. AWBs and HMWBs are subject to alternative environmental objective than ordinary Water Bodies hence they have been clearly identified in each RBD and will be classified differently. Ecological Status is classified in all Water Bodies, expressed in terms of five classes (high, good, moderate, poor or bad). These classes are established on the basis of specific criteria and boundaries defined against biological, physico-chemical and hydromorphological elements. Biological assessment uses numeric measures of communities of plants and animals (for example, fish and rooted plants). Physico-chemical assessment looks at elements such as temperature and the level of nutrients, which support the biology. Hydromorphological quality looks at water flow, sediment composition and movement, continuity (in rivers) and the structure of physical habitat (Environment Agency, 2010 and 2011).

The overall Ecological Status of a water body is determined by whichever of these assessments is the poorer. For example, a water body might pass ‘Good Status’ for chemical and physico-chemical assessments, but be classed as ‘Moderate Status’ for the biological assessment: In this case it would be classed overall as ‘Moderate Ecological Status’. To achieve the overall aim of good surface water status, the Directive requires that surface waters be of at least Good Ecological Status and Good Chemical Status. To achieve High Status, the Directive requires that the hydromorphological Quality Elements are also in place. For lower classes, although hydromorphological quality is not explicitly required, it is a supporting element of the biological and in some cases physico-chemical status and must therefore be taken into account.(Environment Agency, 2011). All environmental stakeholders are obliged to target ‘good’ status for their rivers (EC, 2000).

Mitigation measures in both Langsett and Grimwith Reservoir systems are classified as ‘moderate or less’. Fish populations are ‘moderate’ or ‘poor’ (Environment Agency, 2016).

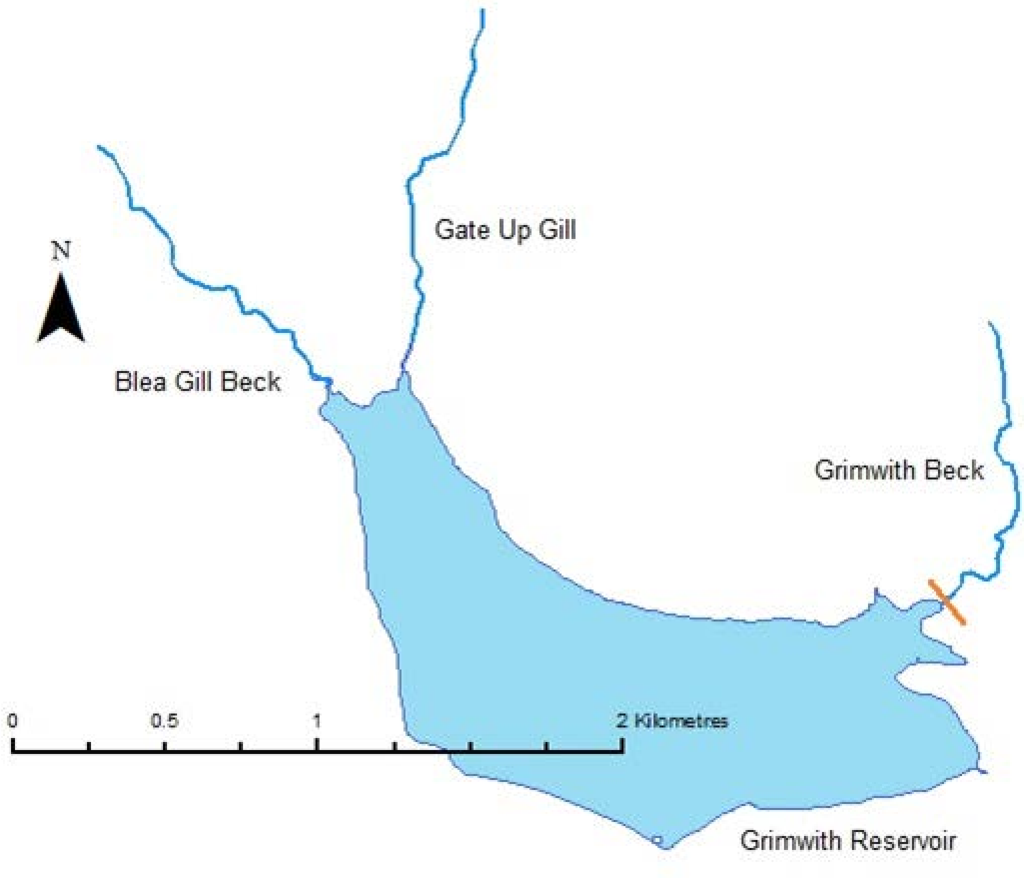


Figure 4. Grimwith Reservoir and tributaries. Here, the orange line marks a weir, a potential barrier to fish.

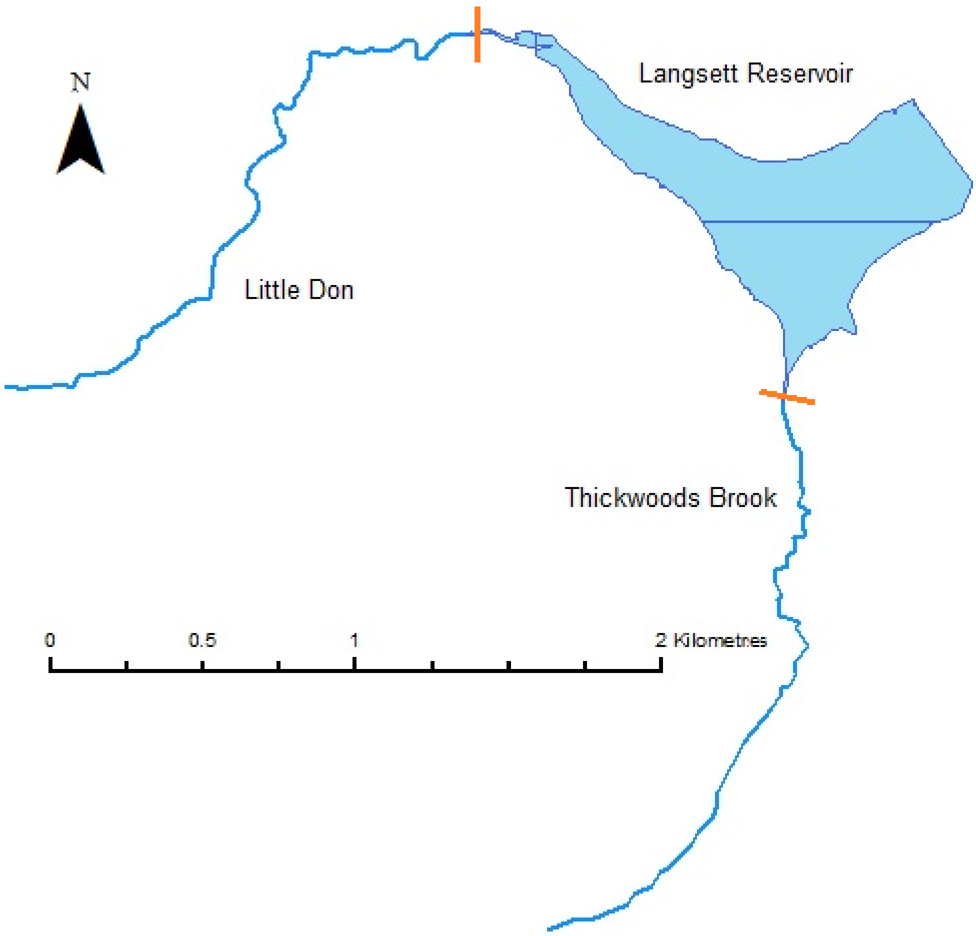


Figure 5. Langsett Reservoir and tributaries. Here, the orange lines mark weirs, potential barriers to fish.

3.1 Fish populations in tributaries upstream of reservoirs

3.1.1 *Sampling methodology*

Fisheries surveys were carried out on tributaries upstream of Langsett and Grimwith Reservoirs in 2014 and 2015 (Figures 6 - 10). Quantitative and semi-quantitative electric fishing strategies involved three operatives (one anode operator and two people netting stunned fish) fishing in an upstream direction, with a fourth operator on the bank supervising safe operation of the electric fishing equipment. A 2 kVA generator powering an Electracatch control box producing a 220 V DC output was employed at accessible sites. At sites with restricted access, backpack electric fishing equipment was used (Electracatch 24 V DC input, 200 – 400 V, 100 W, 50 Hz Pulsed DC, variable pulse width output). Quantitative survey sites (estimates of absolute abundance are based on a three-catch removal method; Carle and Strub, 1979) were isolated by upstream and downstream stop-nets or natural obstacles to ensure no escape from, or migration into, the sampling area, to allow an estimate of numbers present to be derived. During the fishing exercise, as many fish as possible were caught in dip nets by operatives positioned either side, and downstream, of the anode; the process was repeated for each run of the three-catch removal method, with catches kept separate for data collection. Following each survey, individual fish were identified to species level, measured fork length in millimetres, measured and scale samples were removed for ageing purposes (using the appropriate Environment Agency Management System; Britton 2003); the fish were then returned to the river. All electric fishing equipment and modes of operation complied with the EA Health and Safety Regulations. All fish were released at the site of capture following data collection.

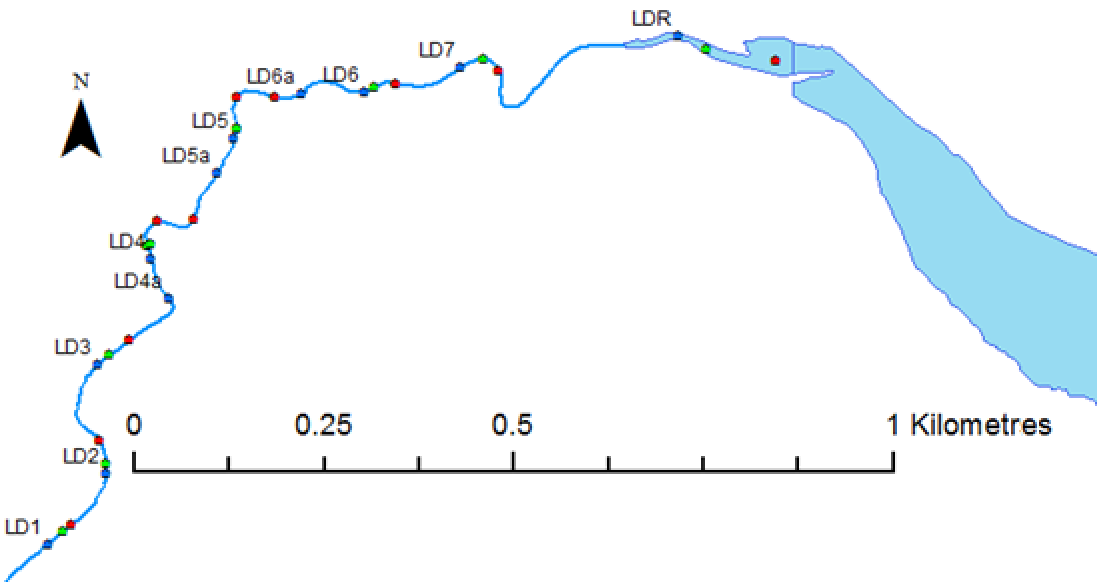


Figure 6. Upstream (blue) and downstream (red) limits of the River Little Don survey sites (LD1 – LD7 and LDR) upstream of Langsett Reservoir and tagged fish release location (green) (tagging methodology in Section 3.2.1). Fish from ‘a’ sites were released at the same location as those from the quantitative site (LD6 and LD6a fish were both released at the LD6 release point). Text labels correspond with upstream limit of the site (blue marker). Sites where two upstream/downstream limits are displayed indicate ‘a’ site limits along with the regular site.

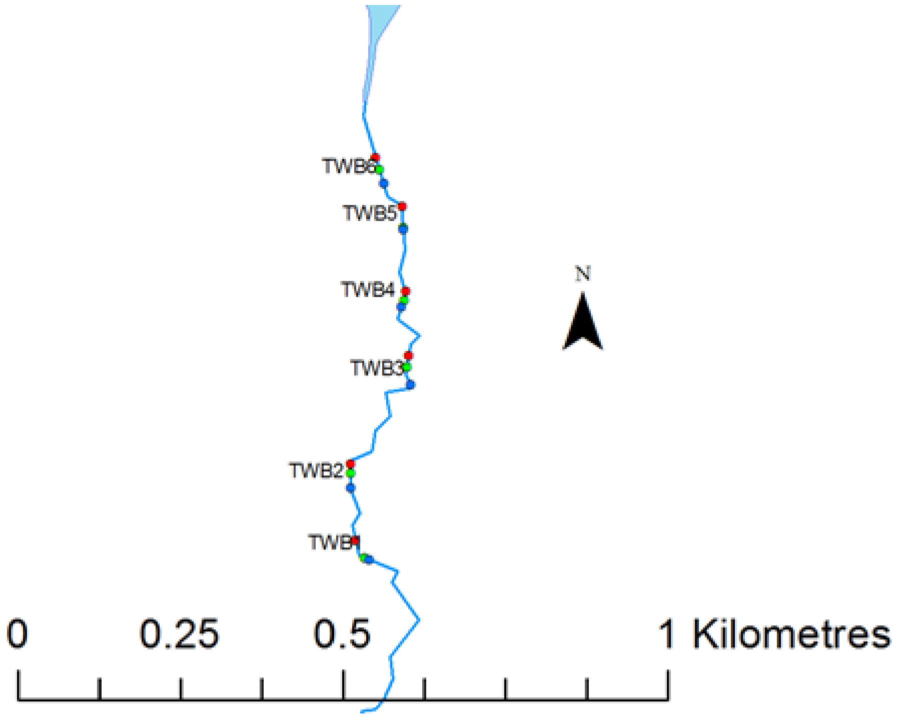


Figure 7. Upstream (blue) and downstream (red) limits of Thickwoods Brook survey sites (TWB1 – TWB6) upstream of Langsett Reservoir and tagged fish release location (green) (tagging methodology in Section 3.2.1). Labels correspond with upstream limit of the site (nearest blue marker). NB. Release site of TWB5 is in very close proximity to the upstream limit.

The River Little Don is the larger of the two tributaries of Langsett Reservoir and the weir present on the River Little Don is larger than that which is present on Thickwoods Brook.

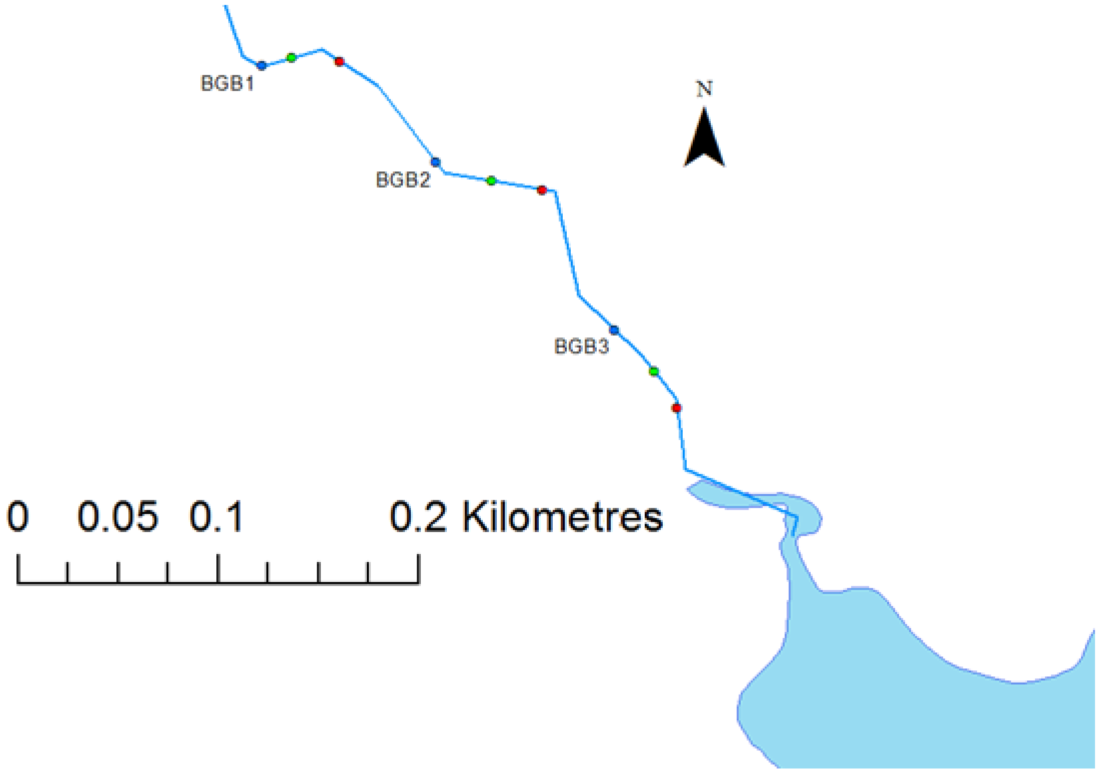


Figure 8. Upstream (blue) and downstream (red) limits of Blea Gill Beck survey sites (BGB1 – BGB3) upstream of Grimwith Reservoir and tagged fish release location (green).

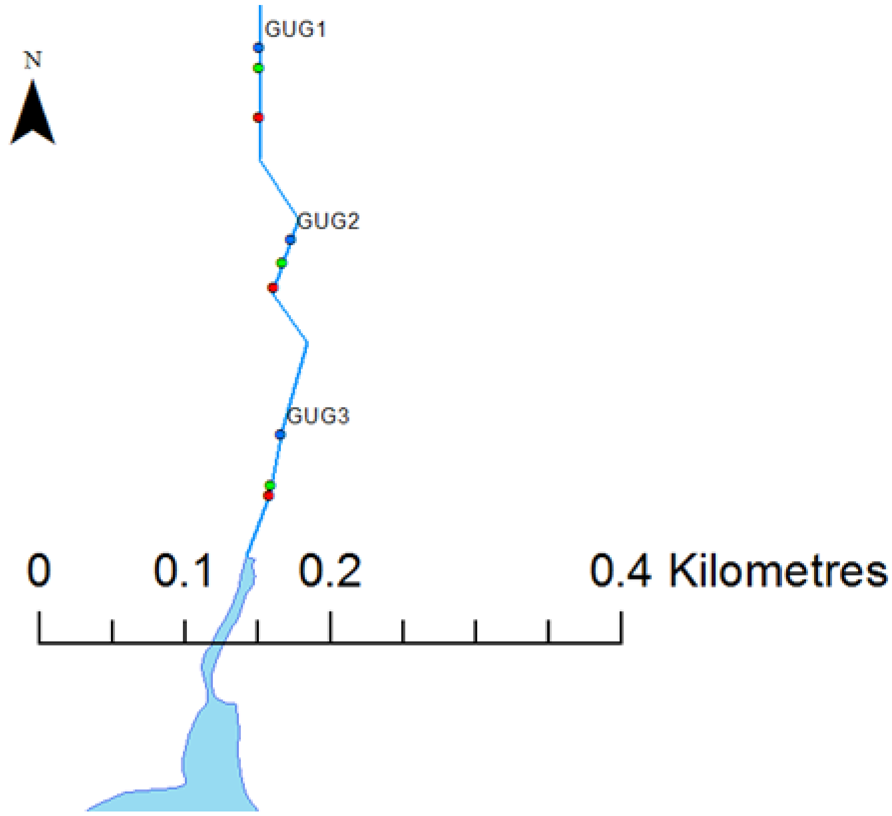


Figure 9. Upstream (blue) and downstream (red) limits of Gate Up Gill survey sites (GUG1 – GUG3) upstream of Grimwith Reservoir and tagged fish release location (green).

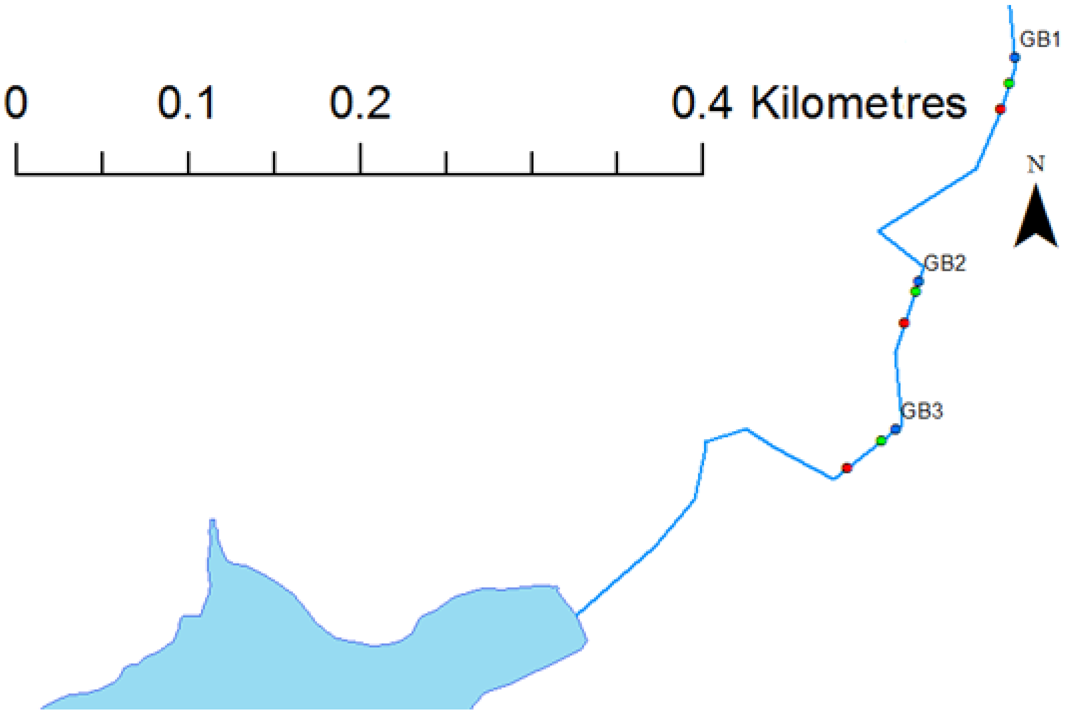


Figure 10. Upstream (blue) and downstream (red) limits of Grimwith Beck survey sites (GB1 – GB3) upstream of Grimwith Reservoir and tagged fish release location (green).

Table 1. Locations (National Grid References (NGR) and Latitude (Lat) and Longitude (Long)) of all surveyed river/reservoir sites.

Reservoir	Site Code and No.	Release NGR	Upstream NGR	Downstream NGR	GPS Release		Upstream GPS		Downstream GPS	
					Lat	Long	Lat	Long	Lat	Long
Grimwith										
	BGB1	SE0481865863	SE0480265860	SE0483965862	54.08865	-1.92784	54.08863	-1.92808	54.08865	-1.92752
	BGB2	SE0491965808	SE0489365815	SE0494465803	54.08816	-1.92629	54.08822	-1.92669	54.08811	-1.92591
	BGB3	SE0499965706	SE0498865781	SE0501465689	54.08724	-1.92507	54.08792	-1.92524	54.08709	-1.92484
	GB1	SE0733165213	SE0733465227	SE0732565196	54.08278	-1.88943	54.08291	-1.88939	54.08263	-1.88953
	GB2	SE0727565095	SE0727765100	SE0727165075	54.08172	-1.89029	54.08177	-1.89026	54.08154	-1.89036
	GB3	SE0725365010	SE0726265015	SE0723664991	54.08096	-1.89063	54.08101	-1.89049	54.08079	-1.89089
	GUG1	SE0535066104	SE0535166117	SE0534766069	54.09082	-1.91970	54.09093	-1.91968	54.09050	-1.91975
	GUG2	SE0536565970	SE0537265986	SE0535965952	54.08961	-1.91947	54.08976	-1.91937	54.08945	-1.91957
	GUG3	SE0536365815	SE0537065853	SE0536265810	54.08822	-1.91951	54.08856	-1.91940	54.08817	-1.91952
Langsett										
	LD1	SK1903699967	SK1901499954	SK1904799978	53.49607	-1.71453	53.49595	-1.71486	53.49616	-1.71436
	LD2	SE1909700057	SE1909100044	SE1909000090	53.49687	-1.71360	53.49676	-1.71369	53.49717	-1.71370

Table 1 (cont.). Locations (NGRs and Latitude/Longitude) of all surveyed river/reservoir sites

Reservoir	Site Code and No.	Release NGR	Upstream NGR	Downstream NGR	GPS Release		Upstream GPS		Downstream GPS	
					Lat	Long	Lat	Long	Lat	Long
Langsett										
	LD4	SE1915300346	SE1916000329	SE1915900390	53.49947	-1.71274	53.49931	-1.71263	53.49986	-1.71265
	LD4a	SE1915300346	SE1918200276	SE1921200379	53.49947	-1.71274	53.49884	-1.71231	53.49976	-1.71185
	LD5	SE1926700500	SE1925600487	SE1926900541	53.50085	-1.71101	53.50073	-1.71118	53.50122	-1.71098
	LD5a	SE1926700500	SE1923300444	SE1932000550	53.50085	-1.71101	53.50035	-1.71153	53.5013	-1.71021
	LD6	SE1944400564	SE1943400562	SE1947700567	53.50142	-1.70834	53.50140	-1.70849	53.50144	-1.70784
	LD6a	SE1944400564	SE1934700557	SE1950100567	53.50142	-1.70834	53.50136	-1.70980	53.50144	-1.70748
	LD7	SE1959200595	SE1956600589	SE1961400566	53.50169	-1.70611	53.50164	-1.70650	53.50143	-1.70578
	LDR	SE1988900608	SE1984900627	SE1997800585	53.50180	-1.70163	53.50197	-1.70223	53.50159	-1.70029
	TWB1	SK2082298721	SK2082298716	SK2080398733	53.48475	-1.68778	53.48475	-1.68769	53.48491	-1.68797
	TWB2	SK2079098839	SK2079098816	SK2079398852	53.48586	-1.68816	53.48565	-1.68816	53.48598	-1.68811
	TWB3	SK2087999000	SK2088698975	SK2088399018	53.48730	-1.68681	53.48708	-1.68670	53.48747	-1.68675

Table 1 (cont.). Locations (NGRs and Latitude/Longitude) of all surveyed river/reservoir sites

Reservoir	Site Code and No.	Release NGR	Upstream NGR	Downstream NGR	GPS Release		Upstream GPS		Downstream GPS	
					Lat	Long	Lat	Long	Lat	Long
Langsett										
	TWB4	SK2086899105	SK2086499096	SK2087499117	53.48825	-1.68697	53.48817	-1.68703	53.48836	-1.68688
	TWB5	SK2087499217	SK2087499213	SK2086899249	53.48925	-1.68687	53.48922	-1.68687	53.48954	-1.68696
	TWB6	SK2084199307	SK2084499284	SK2082999323	53.49007	-1.68736	53.48986	-1.68732	53.49021	-1.68754
Grimwith										
	GR	SK2092599616	N/A	N/A	53.49284	-1.68607	N/A	N/A	N/A	N/A
Langsett										
	LR	SE0652264256	N/A	N/A	54.07419	-1.90182	N/A	N/A	N/A	N/A

Table 2. Fisheries survey site details in 2014 and 2015 (Q = quantitative, T = non-quantitative – fish caught here as insufficient numbers of fish for tagging were caught in quantitative surveys)

Reservoir name	River name	Site code	Survey date	Length (m) / mean width (m) / area (m^2)	Survey method	HABSCORE collected
Grimwith Reservoir	Blea Gill Beck	BGB1	15/10/14	41 / 3.8 / 154	Q	Y
			25/09/15	42 / 1.5 / 62	Q	Y
		BGB2	15/10/14	50 / 3.1 / 154	Q	Y
			25/09/15	50 / 4.0 / 201	Q	Y
		BGB3	15/10/14	50 / 3.1 / 154	Q	Y
			25/09/15	50 / 3.8 / 188	Q	Y
	Gate Up Gill	GUG1	05/10/14	50 / 2.9 / 145	Q	Y
			25/09/15	53 / 3.7 / 193	Q	Y
		GUG2	05/10/14	40 / 4.1 / 163	Q	Y
			25/09/15	40 / 4.4 / 178	Q	Y
		GUG3	05/10/14	38 / 4.9 / 186	Q	Y
			25/09/15	38 / 4.8 / 184	Q	Y
	Grimwith Beck	GB1	10/10/14	38 / 3.2 / 123	Q	Y
			30/09/15	38 / 2.7 / 102	Q	Y
		GB2	08/10/14	30 / 4.1 / 123	Q	Y
			30/09/15	30 / 3.8 / 113	Q	Y
		GB3	08/10/14	42 / 4.0 / 169	Q	Y
			30/09/15	42 / 3.2 / 135	Q	Y
Langsett Reservoir	The River Little Don	LD1	26/09/14	43 / 3.6 / 153	Q	Y
			28/09/15	50 / 4.0 / 199	Q	Y
		LD2	26/09/14	46 / 4.1 / 186	Q	Y
			28/09/15	42 / 5.9 / 246	Q	Y
		LD3	26/09/14	58 / 4.3 / 249	Q	Y
			28/09/15	49 / 4.6 / 225	Q	Y
		LD3a	28/09/15	N/A	T	N
		LD4	26/09/14	63 / 4.7 / 295	Q	Y
			28/09/15	43 / 4.4 / 190	Q	Y
		LD4a	26/09/14	N/A	T	N
			28/09/15	N/A	T	N
		LD5	26/09/14	47 / 5.1 / 241	Q	Y
			28/09/15	58 / 5.3 / 307	Q	Y
		LD5a	26/09/14	N/A	T	N
			28/09/15	N/A	T	N
		LD6	26/09/14	47 / 4.9 / 232	Q	Y
			28/09/15	52 / 4.0 / 210	Q	Y
		LD6a	26/09/14	N/A	T	N
			28/09/15	N/A	T	N
		LD7	17/10/14	48 / 4.6 / 221	Q	N
			28/09/15	50 / 7.3 / 363	Q	Y
		LDR	17/10/14	N/A	T	N
			01/10/15	N/A	T	N
	Thickwoods Brook	TWB1	25/09/14	38 / 1.5 / 57	Q	Y
			29/09/15	42 / 1.5 / 63	Q	Y
		TWB2	25/09/14	38 / 3.1 / 116	Q	Y
			29/09/15	45 / 1.5 / 68	Q	N
		TWB3	25/09/14	49 / 2.1 / 102	Q	Y
			29/09/15	45 / 2.0 / 91	Q	Y
		TWB3a	29/09/15	N/A	T	N
		TWB4	25/09/14	40 / 1.1 / 44	Q	Y
			29/09/15	40 / 1.6 / 64	Q	Y
		TWB4a	29/09/15	N/A	T	N
		TWB5	25/09/14	44 / 2.0 / 88	Q	Y

Table 2 (cont.). Fisheries survey site details in 2014 and 2015 (Q = quantitative, T = non-quantitative – fish caught here as insufficient numbers of fish for tagging were caught in quantitative surveys)

Reservoir name	River name	Site code	Survey date	Length (m) / mean width (m) / area (m^2)	Survey method	HABSCORE collected
Langsett Reservoir	Thickwoods Brook	TWB5	29/09/15	43 / 1.7 / 73	Q	Y
		TWB5a	29/09/15	N/A	T	N
		TWB6	25/09/14	45 / 2.5 / 111	Q	Y
			29/09/15	45 / 2.5 / 111	Q	Y
		TWB6a	29/09/15	N/A	T	N

3.1.2 *Density estimates and abundance categories*

For quantitative sites, estimates of the abundance of 0+ (fish that emerged in the most recent spring and are < 1 year old) and ≥1+ brown trout (fish that emerged in a spring that was prior to the most recent one; are over 1 year old) brown trout and the probability of capture (*P*) were derived using a three-catch Maximum Likelihood removal method (Carle and Strub 1978); the value of *P* was also used to calibrate the survey gear for semi-quantitative surveys. Survey site length (m) and width (m) were measured at each site to calculate the survey site area (m^2) and fish population density, which was expressed as N/100 m^2. Density estimates of 0+ and ≥1+ fish at semi-quantitative sites were derived by gear calibration. The mean *P*, derived from quantitative surveys in the study river, was used to derive relative density (N/100 m^2) as: $N = ((C / P) / A)*100$, where *C* is the total number of fish caught in the single run and *A* is the sampling area (Cowx 1996). Density estimates of 0+ and ≥1+ brown trout were compared between sites and used in the derivation of HABSCORE outputs (Section 4.1.1).

Density estimates from quantitative and semi-quantitative surveys were used to assess the status of brown trout populations according to the matrix procedure adopted by the Environment Agency Fisheries Classification Scheme (EA-FCS, Table 3). The EA-FCS was developed to allow comparison of brown trout monitoring data with a juvenile database derived from over 600 survey sites in England and Wales (Mainstone *et al.* 1994). The classification of brown trout populations is based on a grading scale (A–F) and provides an indication of the status of brown trout populations in study rivers. 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). The population density grades for the EA-FCS are detailed in Table 3.

Table 3. 0+ and ≥1+ brown trout abundance (numbers of fish/100 m^2) classifications used in the Environment Agency Fisheries Classification Scheme (EA-FCS), colours are assigned for clarity in subsequent data analysis.

Species group	Abundance classification					
	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

3.1.3 *HABSCORE data collection and outputs*

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/age combinations – 0+ salmon; >0+ salmon; 0+ trout; >0+ trout <20 cm; >0+ trout >20 cm (Wyatt *et al.* 1995). Using the information from three HABSCORE questionnaires, the software produces a series of outputs, which includes estimates of the expected populations (the Habitat Quality Score, HQS) and the degree of habitat utilisation (the Habitat Utilisation Index, HUI), for each of five salmonid species/age combinations (Wyatt *et al.* 1995).

The effectiveness of HABSCORE and other habitat evaluation methods depends on their ability to explain the spatial component of variance seen in fish population data. Variance analysis of HABSCORE performance shows how the relative importance of spatial and temporal variance alters at different geographical scales, the latter (indicative of synchronous variation) being much more important within small tributaries. Habitat evaluation methods based only on catchment features explain significant proportions of spatial variance, demonstrating their potential in catchment-scale evaluation (Milner *et al*. 1998).

To collect information for HABSCORE analysis, a questionnaire on the habitat found at each fisheries survey site was completed. The methodology of habitat data collection and completion of the relevant form (HABform), along with completion of river catchment information (MAPform) and fisheries information (FISHform) are documented by Barnard and Wyatt (1995).

Data from the three completed forms (HABform, MAPform and FISHform) at each site were entered into the HABSCORE for Windows program and the outputs described below were produced for trout populations (definitions from Wyatt *et al.* (1995)).

Habitat Quality Score (HQS)

The HQS value is a measure of the habitat quality expressed as the expected long-term mean density of fish (n/100 m^2). The HQS is derived from habitat and catchment features, and assumes that neither water quality nor recruitment are limiting 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, n/100 m^2. The confidence limits given should enclose the mean observed density for a site on 90% of occasions. The probability of getting an observed mean density lower than the lower confidence limit by chance alone is therefore 5%.

Habitat Utilisation Index (HUI)

The HUI is a measure of the extent to which the habitat is utilised by salmonids. It is based on the difference between the 'observed' density and that which would be expected under 'pristine' conditions (i.e. the 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.

Log_e HUI

This is the natural logarithm of the HUI. Negative values will represent an observed population less than that which would be expected given the habitat. The data were tabulated from each site and interpreted in relation to the fish population data.

3.1.4 *Length distributions*

Length distributions were constructed for brown trout captured at each site. The methodology involved assigning fish lengths into 5-mm size classes and determining the total number of fish in each size class. Length distributions, supported by ageing of scales from selected length groups, were used to separate 0+ fish from older age groups.

3.1.5 *Length at age and determination of growth rate*

Calculation of growth rates of brown trout was facilitated by the collection of scale samples from a representative number of fish at each site. Determination of the age and growth of fish is an important tool in the assessment of fish population dynamics (Bagenal 1978). The age and growth of brown trout at each site and each year were determined by the interpretation and counting of annual growth checks (annuli) that appear on the scales collected from a sub-sample of the fish (Bagenal and Tesch 1978). These are formed during periods of faster and little or no growth, with the latter generally occurring during the winter months in temperate regions. If large numbers of scale samples were collected in surveys, sub-sampling of a representative size range was carried out according to the EA-AMS (Britton 2003).

Scales from each fish were examined under a microfiche projector and the fish aged by counting the number of annuli, taking care to note any false checks. More than one scale was examined to ensure correct interpretation of the annuli. The total scale radius and scale radius to each annulus were measured from the nucleus to the scale edge. Analysis of the data involved assessment of the relationships between the length of the fish, scale radius to annuli and total scale radius (Dahl-Lea method, Francis (1990)):

$$L_i = (S_i/S_c) \times L_c \qquad \text{(Equation 1)}$$

where, L_i is the length (mm) at year 1, S_i is scale radius at length L_i, L_c the length at capture and *Sc* the scale radius at capture.

For each brown trout, the length at age was back-calculated from the scale radius to each annulus using Equation 1. This calculation was repeated for each fish and the mean length for each age from all fish in the population was calculated. Data were then tabulated for each survey river and compared to national standards (Environment Agency data; Table 4).

Table 4. National standard Back-calculated lengths (mm) at age of brown trout in English and Welsh rivers, including colours assigned to plots.

	Back-calculated lengths (mm)				
Age	Very slow	Slow	Average	Fast	Very fast
1	<53	≥53	≥74	≥95	≥108
2	<102	≥102	≥140	≥174	≥205
3	<149	≥149	≥199	≥238	≥291
4	<193	≥193	≥252	≥291	≥367
5	<234	≥234	≥300	≥334	≥435
6	<273	≥273	≥342	≥369	≥495

3.2 Movements of fish between the reservoirs and their tributaries

3.2.1 *Sampling and tagging procedure*

Brown trout (of sufficient size, i.e. >6 cm; Lucas and Baras, 2000) were PIT-tagged (Ombredane *et al.* 1998) in Langsett (Table 5) and Grimwith (Table 6) Reservoirs and tributaries in 2014 and 2015.

Table 5. Date, number (n), length (mean ± SD (range), mm) and release location (NGR; map in Appendix 2) of PIT-tagged brown trout in Langsett Reservoir and upstream tributaries, in 2014 and 2015.

River / reservoir Site code and No.	Date	n	Fish length (mean fork length ± SD (range), mm)	Release location (NGR)
Thickwoods Brook				
TWB1	29/09/15	10	108.7 ± 21.8 (73 – 135)	SK2080298711
TWB2	25/09/14	10	84.2 ± 7.3 (73 – 96)	SK2079098839
	29/09/15	7	113.6 ± 27.2 (83 – 143)	SK2079098839
TWB3	25/09/14	10	82.7 ± 6.8 (69 – 91)	SK2087999000
	29/09/15	11	105.0 ± 40.7 (79 – 220)	SK2087999000
TWB3a	29/09/15	9	112.1 ± 39.4 (75 – 184)	SK2087999000
TWB4	25/09/14	10	80.2 ± 6.8 (69 – 90)	SK2086899105
	29/09/15	9	118.0 ± 34.1 (71 – 154)	SK2086899105
TWB4a	29/09/15	10	114.7 ± 56.8 (68 – 250)	SK2086899105
TWB5	25/09/14	10	84.1 ± 3.5 (77 – 88)	SK2087499217
	29/09/15	11	132.5 ± 52.4 (74 – 255)	SK2087499217
TWB5a	29/09/15	10	101.5 ± 31.4 (65 – 148)	SK2087499217
TWB6	25/09/14	10	89.8 ± 8.5 (81 – 109)	SK2084199307
	29/09/15	21	121.7 ± 46.7 (77 – 240)	SK2084199307
TWB6a	29/09/15	2	92.0 ± 0 (92)	SK2084199307
The River Little Don				
LD1	26/09/14	1	163	SK1903699967
	28/09/15	3	171.0 ± 28.6 (153 – 204)	SK1903699967
LD2	26/09/14	1	183	SE1909700057
	28/09/15	5	181.4 ± 39.5 (117 – 215)	SE1909700057
LD3	26/09/14	1	167	SE1909700202
	28/09/15	3	145.7 ± 4.0 (142 – 150)	SE1909700202
LD3a	28/09/15	4	159.8 ± 57.9 (82 – 222)	SE1909700202
LD4	26/09/14	2	170.5 ± 23.3 (154 – 187)	SE1915300346
	28/09/15	11	197.3 ± 77.6 (91 – 340)	SE1915300346
LD4a	26/09/14	8	164.9 ± 23.1 (110 – 178)	SE1915300346
	28/09/15	10	223.2 ± 93.7 (144 – 380)	SE1915300346
LD5	26/09/14	4	160.3 ± 11.8 (145 – 171)	SE1926700500
	28/09/15	19	131.2 ± 37.9 (83 – 200)	SE1926700500
LD5a	26/09/14	6	128.7 ± 37.5 (79 – 162)	SE1926700500
	28/09/15	22	178.5 ± 61.8 (102 – 365)	SE1926700500
LD6	26/09/14	5	105.2 ± 4.3 (102 – 112)	SE1944400564
	28/09/15	7	148.3 ± 30.3 (100 – 191)	SE1944400564
LD6a	26/09/14	4	99.5 ± 5.1 (93 – 104)	SE1944400564
	28/09/15	16	158.4 ± 39.0 (95 – 239)	SE1944400564
LD7	17/10/14	18	118.3 ± 26.7 (89 – 167)	SE1958000605
Langsett Reservoir				
LR	13/10/14	37	287.4 ± 57.9 (96 – 391)	SE0652264256
	01/10/15, 28-30/10/15	30	161.0 ± 98.1 (90 – 385)	SE0652264256
LDR	17/10/14	13	274.8 ± 108.7 (157 – 468)	SE1988900608
	01/10/15	56	107.3 ± 57.8 (73 – 405)	SE0652264256

Table 6. Date, number (n), length (mean ± SD (range), mm) and release location (NGR; map in Appendix 2) of PIT-tagged brown trout in Grimwith Reservoir and upstream tributaries, in 2014 and 2015

River / reservoir Site code and No.	Date	n	Fish length (mean fork length ± SD (range), mm)	Release location (NGR)
Grimwith Beck				
GB1	10/10/14	16	101.2 ± 20.8 (74 – 133)	SE0733165213
	30/09/15	33	100.0 ± 33.4 (67 – 190)	SE0733165213
GB2	08/10/14	17	96.2 ± 24.0 (75 – 143)	SE0727565095
	30/09/15	33	97.1 ± 38.3 (64 – 215)	SE0727565095
GB3	08/10/14	17	91.9 ± 22.9 (67 – 135)	SE0725365010
	30/09/15	34	98.0 ± 33.3 (65 – 183)	SE0725365010
Blea Gill Beck				
BGB1	15/10/14	17	109.8 ± 37.3 (74 – 202)	SE0481865863
	25/09/15	19	121.4 ± 32.2 (77 – 187)	SE0481865863
BGB2	15/10/14	17	102.6 ± 28.4 (75 – 183)	SE0491965808
	25/09/15	38	94.5 ± 30.0 (70 – 162)	SE0491965808
BGB3	15/10/14	16	108.1 ± 35.8 (73 – 197)	SE0499965706
	25/09/15	43	99.6 ± 34.4 (63 – 163)	SE0499965706
Gate Up Gill				
GUG1	05/10/14	16	102.8 ± 23.5 (78 – 148)	SE0535066104
	25/09/15	33	103.1 ± 34.5 (69 – 215)	SE0535066104
GUG2	05/10/14	17	97.8 ± 23.7 (76 – 152)	SE0536565970
	25/09/15	34	94.4 ± 34.9 (71 – 199)	SE0536565970
GUG3	05/10/14	17	96.2 ± 18.8 (77 – 134)	SE0536365815
	25/09/15	33	99.9 ± 31.5 (66 – 170)	SE0536365815
Grimwith Reservoir				
GR	15/10/14	50	200.2 ± 37.1 (133 – 290)	SK2092599616
	30/09/15	80	183.4 ± 40.7 (96 – 295)	SK2092599616

All brown trout tagged in tributaries were caught using electric fishing, whereas all brown trout tagged in reservoirs in 2014, and in Grimwith Reservoir only in 2015, were caught using a seine net (approximately 150 m x 4 m; 20 mm stretch mesh) set from a boat in a rectangle parallel to the bank and hauled ashore. In 2015, the water level at Langsett Reservoir was low and seine netting dredged up large quantities of mud, potentially compromising fish health. Therefore, four double fyke nets (10, 14 & 17 mm mesh size, 53 cm ring size, 2.75 m net length, 6 m 'leader' net attached to both) were deployed from a boat, weighted at the offshore end, secured at the nearshore end with metal stakes and checked daily. Captured fish were transferred to water-filled containers. Prior to tagging in the field, fish were anaesthetised using buffered tricaine methanesulphonate (MS-222); the only anaesthetic licensed, in the UK, for fish that may enter the human food chain. When anaesthetised, the fork length (mm) was measured and recorded. 12 mm PIT-tags (12.0 mm long x 2.1 mm diameter, 0.1 g weight in air) were inserted into the body cavity, anterior to the muscle bed of the pelvic fins, using a pre-loaded sterile needle. After tagging, all fish were the held in a recovery tank until they regained balance and were actively swimming before being returned to the river/reservoir at the site of capture. All fish were treated in compliance with the UK Animals in Scientific Procedures Act 1986 under Home Office licence number PPL 60/4400.

3.2.2 *Monitoring*

The PIT antenna stations were cross-channel pass-over loop antennae, full-duplex systems, powered by two 110 Ah deep-cycle lead-acid batteries connected in parallel and charged by adjacent solar panels. Two loops were located in each tributary, upstream and downstream, of the weir delimiting the upstream limit of access of fish in afferent tributaries of each reservoir, enabling direction of movement to be recorded. The loops were located upstream and downstream of the weir in tributaries upstream of Langsett Reservoir (Figures 5 – 7; Table 7), and approximately 10 metres apart in the tributaries of Grimwith Reservoir (Figures 4, 8 – 10; Table 7), there were no barriers to span in Blea Gill Beck or Gate Up Gill and the weir on Grimwith Beck becomes passable when the reservoir level approaches capacity, so was not thought to present a complete barrier and, as such, Grimwith Beck was investigated in the same manner as the other tributaries at Grimwith Reservoir, rather than those at Langsett Reservoir.

Table 7. Location of PIT antennae on studied rivers. Italics indicate that a weir is present in the study area of that tributary.

River	Upstream or downstream	NGR	Latitude	Longitude
Grimwith Beck	U/S	SE0719564997	54.045105	-1.532944
	D/S	SE0719265000	54.045115	-1.532960
Blea Gill Beck	U/S	SE0505665643	54.051205	-1.552710
	D/S	SE0506165644	54.051208	-1.552683
Gate Up Gill	U/S	SE0533565729	54.051482	-1.551174
	D/S	SE0533365718	54.051446	-1.551185
Thickwoods Brook	U/S	SK2082799365	53.490525	-1.687650
	D/S	SK2081399440	53.491261	-1.687774
The River Little Don	U/S	SE1955300578	53.501538	-1.706694
	D/S	SE1981300610	53.501816	-1.702773

The tag detection range (20-40 cm above the river bed) was tested during installation and each site visit (approximately once a month) to ensure the read range of the interrogated water column had not decreased. Tag detections on each loop consisted of date, time, detection period, unique tag ID and loop number, and were stored on to a SD card located in the data logger, which were manually downloaded during site visits. Water depth (cm) and temperature (°C) were recorded at 15-minute intervals in each tributary to Langsett and Grimwith Reservoirs using fixed-locations loggers (Wireless Wildlife, South Africa). Another logger was co-located in one secure box at both Grimwith and Langsett Reservoir and the quarter-hourly pressure data in (mBar) was subtracted from that of the probes in the rivers to provide a depth value (1 mBar is equal to 1 cm of water depth). Values from the loggers were collated to discern daily average values, which were used to calculate 'exceedance values', i.e. the value which is exceeded x% of the time. The value is known as 'Qx'. Q25 is the value which 25% of the time is exceeded. Q10, Q25, Q50 and Q75 will be used. Q0 is the maximum value; Q100 the minimum (US Geological Survey, 2008). A similar method was employed using Q values and water temperature data.

3.3 Movement and habitat use of fish in Grimwith Reservoir

3.3.1 Sampling and tagging procedure

Twenty brown trout (of sufficient size; >100 g) were caught at Grimwith Reservoir using a seine net (approximately 150 m x 4 m; 20 mm stretch mesh) and acoustic tagged (Table 8). Prior to tagging in the field, fish were anaesthetised. When anaesthetised, the fork length (mm) was measured and recorded. For each fish, an acoustic V8 transmitter (20.5 mm long, 8 mm diameter, 2.0 g weight in air; manufacturing inconsistencies may cause slight variations in dimensions) was tested with a hand-held detector, disinfected with betadine and rinsed with distilled water prior to insertion into the body cavity. It was inserted through a ventro-lateral incision made with a scalpel, anterior to the muscle bed of the pelvic fins; the incision was then closed with an absorbable monofilament suture. After tagging, all fish were the held in a recovery tank until they regained balance and were actively swimming before being returned to the river/reservoir at the site of capture (Appendix 2). All fish were treated in compliance with the UK Animals in Scientific Procedures Act 1986 under Home Office licence number PPL 60/4400.

Table 8. Length (mean ± SD (range), mm), mass (mean ± SD (range), g), ratio of tag to total body weight (%) of tag weight of brown trout acoustically tagged at Grimwith

Reservoir on 15/10/2014 (*n* = 7) and 21/10/2014 (*n* = 13). Fish mass was not possible to measure on 15/10/2014 due to highly adverse conditions.

Date	N	Fish length (mean fork length ± SD (range), mm)	Fish mass (mean ± SD (range), g)	Tag / body wt ratio (mean (range), %)
15/10/2014	7	262.6 ± 15.6 (237 – 283)	N/A	N/A
21/10/2014	13	248.7 ± 29.2 (203 – 296)	176.8 ± 66.4 (100 – 325)	1.27 (0.62 – 2.00)

3.3.2 *Monitoring*

An array of 34 acoustic receivers (VEMCO, Halifax, Canada) and six reference tags were distributed around Grimwith Reservoir (Figure 11 and Table 9) on 8-9 October 2014 to determine the 2D location (using triangulation; VEMCO Positioning System (VPS)) of acoustic tagged fish, and thus enable behaviour and habitat use to be studied. Receivers and reference tags were cable tied to a threaded bar, which was attached to a concrete slab and a length of rope to a black buoy (an unobtrusive colour at the request of Yorkshire Dales Sailing Club, based at the reservoir) at the water surface. A synchronisation tag (sync tag) was also attached to each receiver to determine receiver performance and correct for 'clock drift' – a broad term for several phenomena where two similar clocks may not run at exactly the same time. When three or more receivers detect the same tag a 2-Dimensional position can be triangulated (hence the significance of correcting for 'clock drift' – if the times of the receivers were to vary unchecked, this triangulation would be undermined). Six reference tags with the same strength as tags inserted into fish were distributed around the reservoir at known locations to validate array performance. The first data downloads were carried out on 20-22 January and 6 February 2015, sent to VEMCO for processing on 18 February 2015 and returned on 24 April 2015. The receiver battery life should exceed 12 months, but batteries were changed on 3-6 August 2015 during the second data download, which was sent to VEMCO for processing on 9 August 2015 and returned on 7 October.

It was expected that the tagged fish would move into the tributaries to spawn in October – January, and that this would be evident from the tracking data.

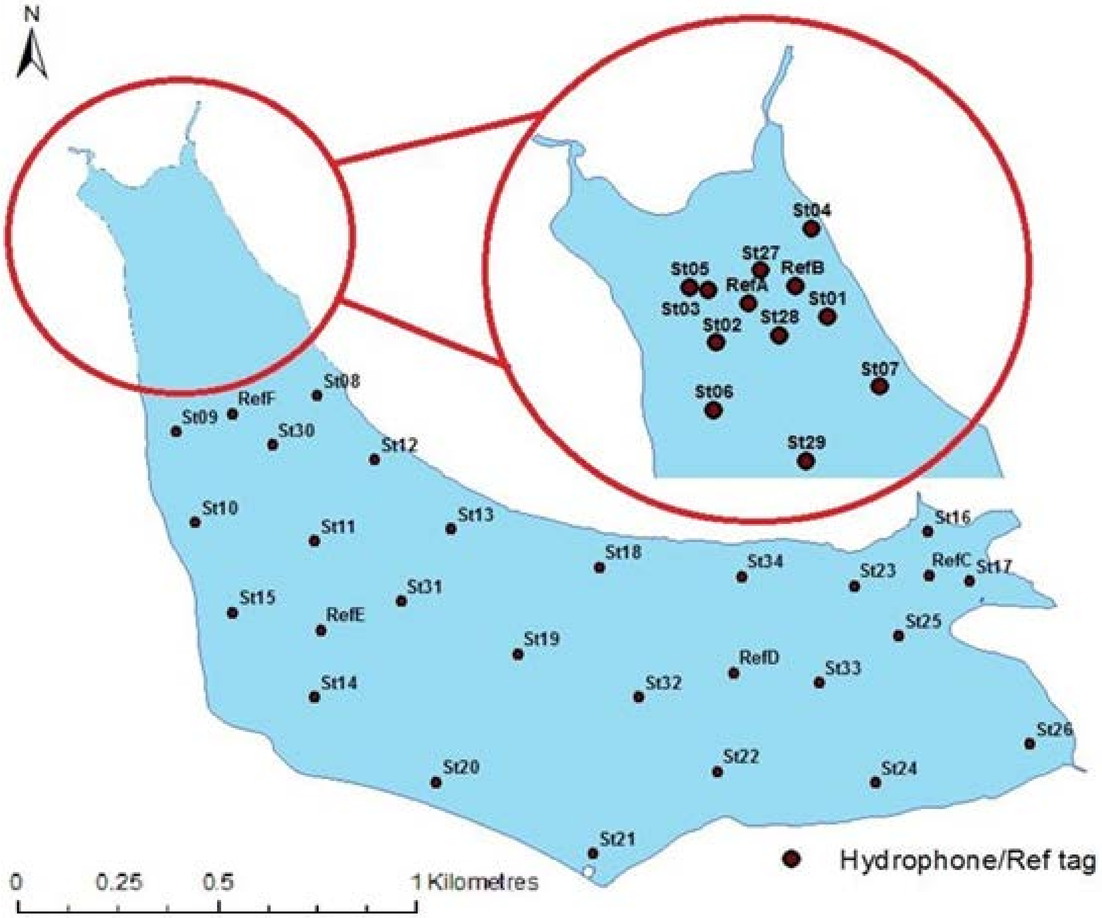


Figure 11. The location of acoustic receivers (St1-St34) and reference tags (RefA-RefF) in Grimwith Reservoir, when initially located.

After the array was installed in the reservoir, a 'tag-drag' was carried out. A tag which emitted its 'ping' to the same level of the same strength as the tags that were surgically implanted into the fish, but with a far larger battery and a frequency of 1 'ping' per second rather than one every 3 – 5 minutes, was suspended in front of the boat (to reduce noise from the boat). A route (10.1 km) around the reservoir was undertaken (Figure 12), recorded using a Garmin 64s GPS receiver and downloaded using Garmin's Basecamp software.

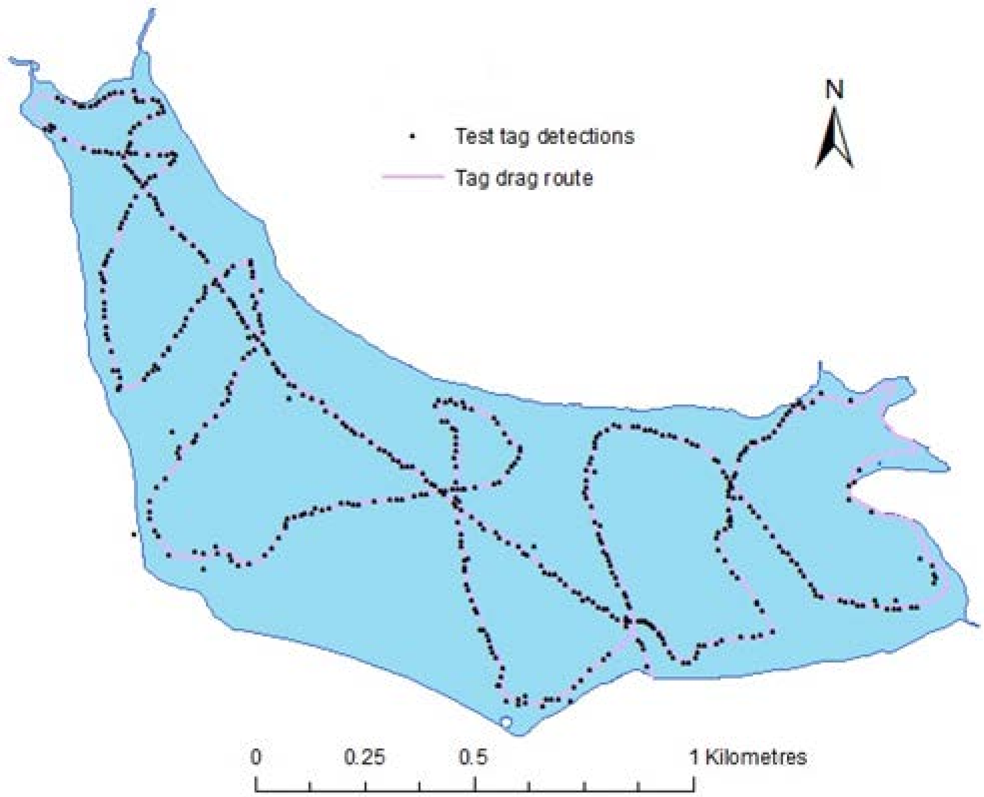


Figure 12. ArcGIS map of the route taken (pink line) of the tag-drag and detected positions (black circles) confirmed by VEMCO at the array in Grimwith Reservoir.

When the data were returned from VEMCO, the points (n = 510) could be added to the ArcGIS layer to ascertain the accuracy of the array and identify any areas where detections may be compromised, such as around the north-eastern corner of the reservoir (Figure 12). These difficulties were confirmed when data were returned by VEMCO and showed co-located sync tags to be consistently incorrectly positioned (Figure 13) – especially of concern is the erroneous values that have low associated error values, which indicate that VEMCO's positioning calculations are fallible in this corner of the reservoir. It was postulated that this was a result of the reservoir's bathymetry, as steep shelves result in stations which, from the water surface, appear to have a line-of-sight to be blind of each other and, as such, triangulation of detections is negatively affected.

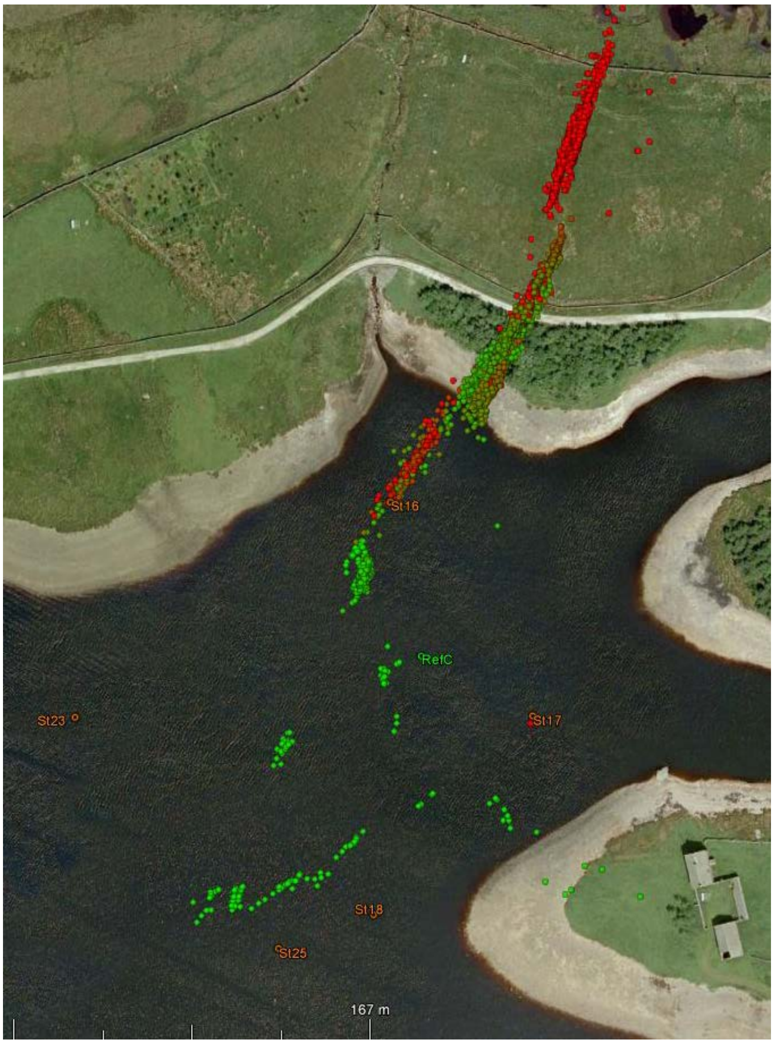


Figure 13. VEMCO returned graphic of the Station 16's co-located sync tag positions (red dots indicate high error value; green dots low error value).

Receivers logged an average of 564,601 detections (79.6 per hour) from sync tags and fish tags combined. On average, an individual sync tag was detected 415,392 times across all receivers. Each transmission was detected on average ~11 times. Overall, 91.7% of sync tag transmissions were logged on three or more receivers. A total of 1,144,932 sync tag positions and 193,388 fish positions were calculated by the VPS (VEMCO Positioning System). Positions were calculated for all 20 fish in the study and a test tag, yields ranged from 495 positions (fish 20559) to 14,279 (fish 20556), after data cleaning (removal of impossible or highly erroneous positions).Three fish (20547, 20549 and 20556) were detected sufficiently to give a home range for all ten months concerned in this study. Two fish (20542 and 20559) were detected sufficiently in just one month (both October). On average, home range was calculable for five months for each fish. Continuity in detection was 89%, in that of the 87 fish with calculable home ranges for months post-October 2014, 77 of these followed successful calculations the prior month. For example, every fish of calculable home range in January also had home range calculated for December. Note that positions are used when describing this data, rather than detections, due to the tag's ping having to be detected by three or more receivers and this data being processed to yield a position of the fish.

Table 9. VEMCO recommended co-ordinates and the co-ordinates at deployment of the acoustic receiver array in Grimwith Reservoir – some positions were impractical due to the reservoir's bathymetry, so dynamic amendments were made on deployment.

VEMCO ORIGINAL			ACTUAL DEPLOYMENT		
Station	Latitude	Longitude	Station	Latitude	Longitude
RefA	54.08532	-1.92233	RfA1	54.08483	-1.92062
RefB	54.08581	-1.91984	RfB1	54.08503	-1.91969
RefC	54.07898	-1.89628	RfC1	54.07890	-1.89620
RefD	54.07683	-1.90255	RfD1	54.07700	-1.90267
RefE	54.07782	-1.91635	RfE1	54.07784	-1.91637
RefF	54.08209	-1.91924	RfF1	54.08207	-1.91927
St01	54.08602	-1.92009	S01a	54.08468	-1.91908
St02	54.08532	-1.92162	S02a	54.08438	-1.92124
St03	54.08497	-1.92214	S03a	54.08498	-1.92138
St04	54.08564	-1.91931	S04a	54.08569	-1.91939
St05	54.08560	-1.92015	S05a	54.08501	-1.92174
St06	54.08361	-1.92164	S06a	54.08361	-1.92129
St07	54.08388	-1.91814	S07a	54.08388	-1.91806
St08	54.08241	-1.91632	S08a	54.08242	-1.91647
St09	54.08174	-1.92117	S09a	54.08173	-1.92116
St10	54.07995	-1.92044	S10a	54.07995	-1.92051
St11	54.07954	-1.91642	S11a	54.07958	-1.91656
St12	54.08107	-1.91443	S12a	54.08117	-1.91456
St13	54.07990	-1.91208	S13a	54.07982	-1.91205
St14	54.07648	-1.91660	S14a	54.07653	-1.91656
St15	54.07819	-1.91925	S15a	54.07819	-1.91928
St16	54.07979	-1.89620	S16a	54.07975	-1.89625
St17	54.07863	-1.89490	S17a	54.07878	-1.89487
St18	54.07901	-1.90721	S18a	54.07906	-1.90714
St19	54.07715	-1.90982	S19a	54.07737	-1.90985
St20	54.07488	-1.91253	S20a	54.07487	-1.91254
St21	54.07354	-1.90739	S21a	54.07347	-1.90734
St22	54.07493	-1.90328	S22a	54.07507	-1.90324
St23	54.07877	-1.89851	S23a	54.07869	-1.89871
St24	54.07483	-1.89818	S24a	54.07484	-1.89802
St25	54.07774	-1.89721	S25a	54.07771	-1.89723
St26	54.07561	-1.89284	S26a	54.07559	-1.89290
St27	54.08531	-1.92294	S27a	54.08521	-1.92039
St28	54.08447	-1.92010	S28a	54.08447	-1.92002
St29	54.08303	-1.91960	S29a	54.08303	-1.91948
St30	54.08138	-1.91796	S30a	54.08146	-1.91796
St31	54.07847	-1.91369	S31a	54.07840	-1.91370
St32	54.07644	-1.90576	S32a	54.07652	-1.90584
St33	54.07678	-1.89976	S33a	54.07680	-1.89988
St34	54.07878	-1.90237	S34a	54.07888	-1.90243

Data from VEMCO were quality controlled by removing the fish positions with error values above the 95th percentile of known reference tag positions (11,351 points out of 105,173), and also by removing any impossible positions that were outside of the reservoir when plotting data on ArcGIS (a further 4,257). 89,565 (85.16%) data points remained. Grimwith Reservoir was split into 1 m x 1 m squares and positions falling into these squares grouped. Kernel density, a non-parametric indicator of density probability of a random variable, was used to evaluate home range size in the reservoir, as it was found to be the most appropriate method for analysing data of this type by Knight *et al.* (2009). Twenty-three northern pike (*Esox lucius* Linnaeus, 1758) were used to examine efficiency of home range and travel estimators. Kernel analysis was found to be better than ellipses or peripheral polygons. Cluster analyses are best for range cores in usable habitat and as an indicator of range fragmentation (Knight *et al.* 2009). This method was also employed by Hawley *et al.* (2016). In this study, data were plotted using ArcGIS.

Each point was assigned a number using Microsoft Excel's 'RAND()' function, sorted into monthly categories and put into numerical order via the random number. The first 54 points were used to calculate the individual fish's monthly home ranges in ArcGIS and two outputs created in the form of heat maps – 'k50' and 'k95' values (50% and 95% probability distribution zones ergo where the area in which the fish resides 50/95% of the time), adapted from Hawley *et al.* (2016). Plotting these points enables comparison between individual fish movements. Comparisons such as between individuals in the tagged population, and between range of occupation in an individual fish across different months.

3.4 Further data analysis methods

Detection data from PIT-tagged fish at all sites were interrogated in the following manner:

- Individual's fork length (mm) of individuals that were detected making movements upstream (from the reservoirs) or downstream (from tributaries) were compared with the fork length (mm) of those which were never detected doing so (so likely remained where they were released) was tested for normal distribution via a Shapiro-Wilk's test, if data were not normally distributed then the data were natural logged and tested again with Shapiro-Wilk's test. If they were still not normally distributed then Mann-Whitney U test was used.
- However if data were normally distributed (either logged or non-logged), an unpaired t-test was used, following a Levene's tests to inform whether or not the variances of the compared data were equal.

Similar methods were employed using PIT detection data from antennae below the two weirs at Langsett Reservoir when comparing the mean total number of days until fish moved from the reservoirs into tributaries and number of different days individual fish were detected on each antennae downstream of the weirs.

These comparisons might allow a tributary of preference to be postulated. The tributary which had the shorter time between release and first detection may be the more attractive tributary to brown trout migrating upstream. The tributary on which tagged fish were detected on more days could be the tributary best able to sustain brown trout which are making upstream migrations. It could also be attractive to the extent that the fish are willing to spend more time and energy attempting to make progress further upstream, the fish are willing to make repeated attempts to migrate upstream despite being thwarted. These characteristics would give any mitigation measures a greater chance of success due to fish making more attempts to use a fish passage or be more likely to be caught for 'Trap-and-transport'. Fish with a higher level of fitness, through migrating upstream in a river that incurs fewer energetic costs, would be more likely to be successful in surmounting a barrier via fish passage or via being translocated.

The number of days until individual fish that were tagged/released upstream of the weir were detected for the first time on the antennae upstream of the weirs in Langsett Reservoir was analysed to see if either population made downstream migrations and if so, if any trends could be discerned. The data for either tributary was compared to see if any significant difference was present, again in a similar way to that which was previously listed.

Water depth and temperature data that was recorded on probes in each river of study was analysed using Q values, mentioned in Section 3.2.2. These Q values were derived from daily mean values. Usually Q values are based on water flow data, but in this study, in lieu of this, depth values were used to create exceedance values. Temperature data was analysed in the same manner, which in this case is novel. Q values were used for temperature data to aid comparison with water depth, so it could be estimated whether or not these variables have any discernible similarities when discussed in the context of fish migrations.

4 RESULTS

4.1 Fish populations in tributaries upstream of Langsett and Grimwith Reservoirs

Langsett Reservoir

In 2014, 0+ brown trout were absent from sites LD1-LD5 in the River Little Don and populations were classified as poor at site LD6 and fair/poor at site LD7. In 2015, 0+ brown trout were absent at sites LD1-3 as in 2014. However, 0+ brown trout were present at sites LD4 and LD5, with densities of 0.53 and 2.74 fish per 100 m^2, respectively, both in the ‘poor’ density range. 0+ brown trout densities at sites LD6 and 7 were also classed as poor with 0.48 and 3.03 fish per 100 m^2, respectively, with lower densities than in 2014 (Table 10). In 2014, ≥1+ brown trout densities in the River Little Don varied from 0.40 to 7.24 fish per 100 m^2 and populations were classified as poor at sites LD1-LD4, fair/poor at site LD5 and average at sites LD6 and LD7 (Table 10). Densities of ≥1+ brown trout were higher in 2015 than 2014 at sites LD1-5, while densities were lower in 2015 than 2014 at sites LD6 and LD7. At LD1, LD3 and LD5, population classifications were the same in 2014 and 2015. ≥1+ brown trout populations at site LD2 improved from poor to fair/poor and at site LD4 they improved from poor to average (Table 10).

In 2014, 0+ brown trout densities in Thickwoods Brook ranged from 8.60 to 31.50 fish per 100 m^2, and populations were classified as good at sites TWB1 and TWB3-TWB5, and average at sites TWB2 and TWB6 (Table 10). However, densities of 0+ brown trout were lower at sites TWB1-5 compared to 2014, with populations at sites TWB1, TWB4 and TWB5 decreasing by grades (good to fair/poor). 0+ brown trout populations at sites TWB2 (average to fair/poor) and TWB3 (good to average) decreased by one grade. 0+ brown trout densities at sites TWB6 improved from 10.80 to 11.71 0+ fish per 100 m^2, but remained in the same classification bracket (average) (Table 10).

In Thickwoods Brook, ≥1+ brown trout densities ranged from 0.86 to 9.09 fish per 100 m^2, and populations were classified as average at sites TWB1 and TWB4, fair/poor at sites TWB5 and TWB6, and poor at sites TWB2 and TWB3 (Table 10). An improvement in ≥1+ brown trout populations between 2014 and 2015 was observed at every survey site in Thickwoods Brook. In particular, the ≥1+ brown trout population at site TWB2 improved by two grades, from poor to average. ≥1+ brown trout populations at sites TWB3 (poor to fair/poor), TWB4 (average to good) and TWB5 and 6 (fair/poor to average) improved by one grade (Table 10).

Table 10. 0+ and ≥1+ brown trout density (numbers of fish per 100 m^2) and abundance classification at survey site locations for Langsett and Grimwith Reservoirs in 2014 and 2015.

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

River Name	Site identifier	0+ brown trout		≥1+ brown trout	
		2014	2015	2014	2015
The River Little Don	LD1	0	0	1.30	1.51
	LD2	0	0	1.07	2.04
	LD3	0	0	0.40	1.77
	LD4	0	0.53	1.02	5.78
	LD5	0	2.74	2.49	4.11
	LD6	2.15	0.48	6.90	3.33
	LD7	6.34	3.03	7.24	3.58
Thickwoods Brook	TWB1	31.50	4.81	8.77	11.22
	TWB2	8.60	4.49	0.86	5.99
	TWB3	23.50	8.80	1.96	4.40
	TWB4	25.00	7.81	9.09	12.50
	TWB5	18.20	5.47	4.55	10.94
	TWB6	10.80	11.71	4.51	10.81
Blea Gill Beck	BGB1	9.75	3.52	3.30	7.54
	BGB2	18.18	16.16	3.25	5.05
	BGB3	21.43	17.01	2.60	9.28
Gate Up Gill	GUG1	6.21	18.97	12.41	5.80
	GUG2	10.43	31.55	13.39	8.33
	GUG3	24.17	14.46	14.50	12.72
Grimwith Beck	GB1	22.03	54.76	7.34	11.53
	GB2	28.46	33.77	13.01	10.39
	GB3	20.69	30.19	13.00	8.84

Grimwith Reservoir (control)

In 2014, 0+ brown trout densities in Blea Gill Beck varied from 9.75 to 21.43 fish per 100 m^2, and were classified as good at sites BGB2 and BGB3 and average at site BGB1 (Table 10). In 2015, 0+ brown trout density was lower at all sites (BGB1-3) than in 2014. 0+ brown trout populations decreased by one grade at sites BGB1 (average to fair/poor) and BGB2 (good to average), while at site BGB3 populations remained 'good'. ≥1+ brown trout densities in Blea Gill Beck varied from 2.60 to 3.30 fish per 100 m^2; ≥1+ brown trout populations were fair/poor at sites BGB1 and BGB2, but poor at site BGB3 (Table 10). Densities of ≥1+ brown trout increased, in 2015. At sites BGB1 and BGB2 (fair/poor to average), ≥1+ brown trout densities improved by one grade between 2014 and 2015, while at site BGB3, ≥1+ brown trout densities increased from 2.60 to 9.28 fish per 100 m^2 (poor to average) between 2014 and 2015.

In 2014, 0+ brown trout densities in Gate Up Gill varied from 6.21 to 24.17 fish per 100 m^2, and populations were classified as good at site GUG3, average at site GUG2 and fair/poor at site GUG1 (Table 10). In 2015, 0+ brown trout densities were higher than in

2014 at GUG1 (improving from fair to good) and GUG2 (improving from average to good). However, at site GUG3, 0+ brown trout densities decreased from 24.17 fish per 100 m^2 in 2014 (good) to 14.46 fish per 100 m^2 (average) in 2015. ≥1+ brown trout densities in 2014 varied from 12.41 to 14.50 fish per 100 m^2; ≥1+ brown trout densities were classified as good at all sites (Table 10). ≥1+ brown trout densities at sites at GUG1-3 were lower in 2015 than 2014; all sites were classified as good in 2014, but GUG1 and 2 were average in 2015; and GUG3 remained in the good bracket.

In 2014, 0+ brown trout densities in Grimwith Beck varied from 20.69 to 28.46 fish per 100 m^2, and populations were classified as good at all sites (Table 10). 0+ brown trout were more abundant at all sites in 2015 compared to 2014. 0+ brown trout populations were good at site GB1 in 2014 and excellent in 2015, whilst populations at sites GB2 and GB3 were good in both years (Table 10). ≥1+ brown trout densities in 2014 varied from 7.34 to 13.01 fish per 100 m^2; ≥1+ brown trout populations were classified as good at sites GB2 and GB3, and average at site GB1 (Table 10). Densities of ≥1+ brown trout were lower in 2015 than 2014 at sites GB2 and GB3, decreasing from good to average. At site GB1, the ≥1+ brown trout population was average in both years, with a marginal increase in density between 2014 and 2015 (Table 10).

4.1.1 *HABSCORE*

HABSCORE is a predictive tool commonly used in the assessment of stream habitat features statistically linked to population estimates of brown trout. The model was used at all sites surveyed in the tributaries to Langsett and Grimwith Reservoirs to compare the observed densities, predicted densities and habitat utilisation by trout (see Section 3.1.3 for definitions of the outputs). Full HABSCORE outputs are provided in Appendix 4 (Tables 30 – 35) with summary tables of findings in 2014 and 2015 provided in Tables 10 to 12 within this section.

In 2014, densities of 0+ brown trout, were significantly lower than predicted by the Habitat Quality Score (HQS) for all sites on the River Little Don amd TWB1 on Thickwoods Brook as the HUI upper CLs were <1 (Tables 11 and 30). Sites TWB2-6 on Thickwoods Brook and the upstream site on both Blea Gill Beck (BGB1) and Gate Up Gill (GUG1) were also lower than predicted by the HQS, suggesting poorer populations than expected. Densities of 0+ brown trout at all sites on Grimwith Beck, the two downstream-most sites on Blea Gill Beck (BGB2 and BGB3) and Gate Up Gill (GUG2 and GUG3) were higher than predicted from the HQS suggesting better populations than expected (Tables 11 and 30).

In 2015, densities of 0+ brown trout were lower than predicted by HQS for all sites on the River Little Don and all sites on Thickwoods Brook apart from TWB6; 0+ brown trout densities were significantly lower than expected at LD1-4, LD6 and TWB5 (Tables 11 and 31). Densities were also lower than predicted, at BGB1, the only site on the tributaries of Grimwith Reservoir for which this was the case. 0+ brown trout densities at sites BGB2 and BGB3, GUG1-3 and GB1-3 were all higher than predicted (HQS) (Tables 11 and 27).

In 2014, populations of >0+ trout (<20 cm) were significantly lower than predicted at sites LD1-LD4 and TWB2-TWB6 (Tables 12 and 32). Populations of >0+ trout (<20 cm) were also lower than predicted at sites LD5-6, TWB1 and BGB1-3 (Tables 12 and 32). >0+ trout (<20 cm) populations were higher than predicted at sites GUG1-3 and GB1-3.

In 2015, densities of >0+ brown trout (<20 cm), were lower than predicted at all sites on the tributaries of Langsett Reservoir, LD1-7 and TWB 1-6, but were only significantly lower at sites LD1 and LD2 (Tables 12 and 32). >0+ trout (<20 cm) densities on all tributaries of Grimwith Reservoir were higher than predicted (HQS) (Tables 12 and 33).

Populations of >0+ trout (>20 cm) at sites LD5, LD6, TWB4, GUG2 and GB2 were higher than predicted from the HQS in 2014, but the HUI lower CL was <1 (Tables 12 and 30). The observed density of >0+ trout (>20 cm) was significantly lower than expected at TWB6, while remaining sites held densities lower than predicted from the HQS, suggesting poorer populations than expected.

In 2015, densities of >0+ trout (>20 cm) were lower than expected at all sites (LD1-3, 5-7; TWB1-6; BGB1-3; GUG1-3; GB1-3) except LD4 where populations were higher than predicted (Tables 13 and 35). Densities of >0+ trout (>20 cm) were significantly lower than predicted at sites TWB4 and BGB1-3.

Table 11. HABSCORE outputs for 0+ brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2014 and 2015. Shaded areas indicate that the observed population was significantly lower (red) than expected under pristine conditions. Densities here are fish per 100 m^2.

Reservoir / River name	Site	2014 Observed density (fish/100 m^2)	HQS (density) (fish/100 m^2)	HUI	HUI lower CL	HUI upper CL	Ln (HUI)	2015 Observed density (fish/100 m^2)	HQS (density) (fish/100 m^2)	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir													
The River Little Don	LD1	0	20.12	0.03	0.00	0.21	-3.51	0	12.41	0.04	0.01	0.27	-1.31
	LD2	0	17.61	0.03	0.00	0.20	-3.51	0	4.29	0.10	0.02	0.65	-0.43
	LD3	0	13.48	0.03	0.00	0.20	-3.51	0	12.60	0.04	0.01	0.24	-1.43
	LD4	0	15.92	0.02	0.00	0.14	-3.91	0.54	6.99	0.08	0.01	0.51	-0.67
	LD5	0	12.34	0.03	0.00	0.2	-3.51	0.90	7.32	0.12	0.02	0.80	-0.22
	LD6	2.17	18.38	0.12	0.02	0.77	-2.12	1.06	14.08	0.08	0.01	0.50	-0.69
	LD7	-	-	-	-	-	-	3.34	4.97	0.67	0.10	4.40	1.48
Thickwoods Brook	TWB1	27.48	31.82	0.06	0.13	0.67	-2.81	12.83	27.58	0.47	0.07	3.06	1.12
	TWB2	16.67	24.48	0.60	0.10	4.45	-0.51	7.29	19.00	0.38	0.06	2.52	0.92
	TWB3	24.48	26.33	0.93	0.14	6.14	-0.07	15.70	17.55	0.89	0.14	5.90	1.77
	TWB4	20.62	57.95	0.36	0.05	2.34	-1.02	6.03	22.22	0.27	0.04	1.80	0.59
	TWB5	18.29	29.35	0.62	0.09	4.11	-0.48	11.82	44.10	0.27	0.04	1.82	0.60
	TWB6	11.09	20.25	0.55	0.08	3.56	-0.60	11.13	9.48	1.17	0.18	7.60	2.03
Grimwith Reservoir													
Blea Gill Beck	BGB1	9.83	14.01	0.70	0.11	4.53	-0.36	5.01	4.17	1.20	0.18	7.99	2.08
	BGB2	17.89	13.77	1.30	0.20	8.48	0.26	14.57	4.12	3.54	0.54	23.05	3.14
	BGB3	22.30	13.44	1.66	0.25	10.80	0.51	16.75	5.75	2.91	0.44	19.13	2.95
Gate Up Gill	GUG1	5.90	14.89	0.40	0.06	2.60	-0.92	8.47	5.08	1.67	0.26	10.79	2.38
	GUG2	10.56	9.15	1.15	0.18	7.60	0.14	17.87	4.22	4.23	0.65	27.45	3.31
	GUG3	25.31	9.45	2.68	0.41	17.59	0.99	19.40	5.36	3.62	0.55	23.86	3.17
Grimwith Beck	GB1	21.21	9.55	2.22	0.34	14.34	0.80	37.69	9.75	3.86	0.60	24.86	3.21
	GB2	29.54	10.92	2.70	0.42	17.42	0.99	31.99	7.11	4.50	0.70	28.88	3.36
	GB3	22.67	9.50	2.39	0.37	15.41	0.87	27.89	12.79	2.18	0.34	14.08	2.64

Table 12. HABSCORE outputs for >0+<20 cm brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2014 and 2015. Shaded areas indicate that the observed population was significantly lower (red) than expected under pristine conditions. Densities here are fish per 100 m^2.

Reservoir / River name	Site	2014						2015					
		Observed density (fish/100 m^2)	HQS (density) (fish/100 m^2)	HUI	HUI lower CL	HUI upper CL	Ln (HUI)	Observed density (fish/100 m^2)	HQS (density) (fish/100 m^2)	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir													
The River Little Don	LD1	0.65	6.97	0.09	0.02	0.55	-2.41	1.00	7.81	0.13	0.02	0.54	-0.62
	LD2	0.54	11.06	0.05	0.01	0.29	-3.00	0.86	6.87	0.13	0.02	0.72	-0.33
	LD3	0.41	4.75	0.09	0.01	0.51	-2.41	1.33	6.55	0.12	0.02	0.71	-0.34
	LD4	0.70	7.21	0.10	0.02	0.57	-2.30	3.26	6.95	0.27	0.05	1.60	0.47
	LD5	1.14	5.65	0.20	0.03	1.18	-1.61	2.02	6.95	0.29	0.05	1.71	0.54
	LD6	5.21	8.44	0.62	0.10	3.63	-0.48	4.35	7.89	0.55	0.09	3.27	1.18
	LD7	-	-	-	-	-	-	3.40	3.15	1.08	0.18	6.36	1.85
Thickwoods Brook	TWB1	6.11	16.24	0.38	0.06	2.24	-0.97	9.24	22.53	0.41	0.07	2.42	0.88
	TWB2	1.67	17.60	0.09	0.02	0.56	-2.41	2.66	12.47	0.21	0.04	1.27	0.24
	TWB3	1.02	12.12	0.08	0.01	0.50	-2.53	1.96	11.92	0.16	0.03	0.97	-0.03
	TWB4	4.12	35.48	0.12	0.02	0.69	-2.12	1.99	20.96	0.10	0.02	0.57	-0.56
	TWB5	2.29	20.86	0.11	0.02	0.65	-2.21	5.53	20.74	0.27	0.04	1.63	0.49
	TWB6	3.41	24.89	0.14	0.02	0.81	-1.97	5.63	10.31	0.55	0.09	3.18	1.16
Grimwith Reservoir													
Blea Gill Beck	BGB1	2.61	6.59	0.40	0.07	2.36	-0.92	3.79	3.72	1.02	0.17	6.16	1.82
	BGB2	3.19	3.36	0.35	0.16	5.76	-1.05	3.44	2.49	1.38	0.23	8.24	2.11
	BGB3	2.70	2.96	0.91	0.15	5.51	-0.09	4.31	5.21	0.83	0.14	4.97	1.60
Gate Up Gill	GUG1	10.49	7.94	1.32	0.23	7.76	0.28	6.52	3.75	1.74	0.29	10.48	2.35
	GUG2	12.42	3.15	3.96	0.65	23.82	1.38	9.96	3.45	2.89	0.48	17.19	2.84
	GUG3	15.19	4.48	3.39	0.58	19.84	1.22	14.10	4.14	3.40	0.57	20.33	3.01
Grimwith Beck	GB1	7.07	5.14	1.38	0.23	8.14	0.32	9.98	4.87	2.05	0.34	12.31	2.51
	GB2	13.50	4.36	3.10	0.53	18.23	1.13	11.49	4.32	2.66	0.45	15.82	2.76
	GB3	14.25	3.19	4.46	0.74	26.75	1.50	11.96	5.83	2.05	0.35	12.22	2.50

Table 13. HABSCORE outputs for >0+>20 cm brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2014 and 2015. Shaded areas indicate that the observed population was significantly lower (red) than expected under pristine conditions. Densities here are fish per 100 m^2.

Reservoir / River name	Site	2014						2015					
		Observed density (fish/100 m^2)	HQS (density) (fish/100 m^2)	HUI	HUI lower CL	HUI upper CL	Ln (HUI)	Observed density (fish/100 m^2)	HQS (density) (fish/100 m^2)	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir													
The River Little Don	LD1	0.65	0.91	0.71	0.23	2.15	-0.34	0.50	1.19	0.48	0.16	1.44	0.36
	LD2	0.54	1.36	0.40	0.13	1.20	-0.92	1.29	1.55	0.83	0.28	2.49	0.91
	LD3	0	0.87	0.47	0.16	1.43	-0.76	0.44	1.02	0.43	0.14	1.32	0.28
	LD4	0.35	0.93	0.34	0.13	1.14	-1.08	2.72	1.46	0.83	0.28	2.52	0.92
	LD5	1.14	0.66	1.74	0.58	5.28	0.55	0.64	1.44	0.45	0.14	1.35	0.30
	LD6	1.74	1.02	1.70	0.56	5.14	0.53	0.95	1.23	0.77	0.26	2.35	0.85
	LD7	-	-	-	-	-	-	0.66	0.86	0.77	0.25	2.36	0.86
Thickwoods Brook	TWB1	1.53	2.32	0.66	0.21	2.02	-0.42	1.75	3.92	0.45	0.15	1.35	0.30
	TWB2	0	2.86	0.54	0.19	1.73	-0.62	0	3.50	0.38	0.12	1.16	0.15
	TWB3	1.02	2.01	0.51	0.17	1.56	-0.67	1.13	2.54	0.45	0.15	1.35	0.30
	TWB4	4.12	3.33	1.24	0.41	3.77	0.22	1.15	4.87	0.24	0.08	0.73	-0.31
	TWB5	2.29	2.42	0.94	0.31	2.69	-0.06	2.09	3.22	0.65	0.20	2.07	0.73
	TWB6	0.85	3.08	0.24	0.09	0.84	-1.43	1.26	3.46	0.36	0.12	1.10	0.10
Grimwith Reservoir													
Blea Gill Beck	BGB1	0.65	0.87	0.75	0.25	2.30	-0.29	0.49	1.93	0.25	0.08	0.77	-0.26
	BGB2	0	1.09	0.59	0.19	1.82	-0.53	0	1.78	0.27	0.09	0.84	-0.17
	BGB3	0	0.79	0.86	0.27	2.70	-0.15	0	3.15	0.16	0.05	0.49	-0.71
Gate Up Gill	GUG1	1.31	1.46	0.90	0.30	2.72	-0.11	0.73	1.43	0.51	0.17	1.53	0.43
	GUG2	1.24	1.08	1.15	0.36	3.62	0.14	0.84	1.40	0.60	0.20	1.81	0.59
	GUG3	0	1.46	0.38	0.13	1.18	-0.97	0	1.58	0.37	0.12	1.10	0.10
Grimwith Beck	GB1	0	1.13	0.70	0.23	2.14	-0.36	0	1.77	0.54	0.18	1.64	0.49
	GB2	0	0.82	1.02	0.34	3.12	0.02	0.87	1.18	0.73	0.24	2.21	0.79
	GB3	0	0.91	0.72	0.23	2.24	-0.33	0	1.30	0.57	0.19	1.71	0.54

4.1.2 *Age and growth*

In 2014, Back-calculated lengths at age 1 were average at all sites in both the headwater tributaries and reservoirs at Langsett and Grimwith when compared with the national standard (Tables 2 and 14). The Back-calculated lengths at age 2 in reservoir tributaries were average or slow in 2014, while growth in the River Little Don (flowing into Langsett Reservoir) and Grimwith Reservoir was fast, and growth in Langsett Reservoir was very fast. Back-calculated lengths at age 3 varied from slow to very fast in the study sites, being slow in the tributaries of Langsett (Thickwoods Brook only) and Grimwith Reservoirs, fast in Grimwith Reservoir and very fast in the River Little Don (reaches upstream and downstream of the main weir) and Langsett Reservoir (Table 18). Larger brown trout aged >4 years old were caught only in low numbers in 2014 and resulted in variable back calculated growth.

Back-calculated lengths at age 1 in 2015 was similar to 2014, with all tributaries of Langsett and Grimwith Reservoirs and the reservoirs themselves remaining in the same growth category in both years (Table 14). Back-calculated growth of brown trout at age 2 was average or slow in 2015, with changes in grade occurring in Thickwoods Brook, the River Little Don (flowing into the reservoir), Langsett Reservoir, Grimwith Beck and Grimwith Reservoir (Table 18). Back-calculated length of brown trout at age 3 were lower in 2015 than 2014 in the sites surveyed for the Langsett study. Growth was slower in Grimwith Reservoir in 2015 than 2014. Larger brown trout, aged >4 years old, were caught in low numbers in 2015 and resulted in variable back calculated growth.

Table 14. Back-calculated lengths at age (mm ± S.D. (*n*)) for brown trout from study rivers and reservoirs in 2014 and 2015. Colours represent growth rate compared with the national standard: orange – slow; yellow – average; green – fast; blue – very fast.

Study reservoir (year)	River / reservoir name	Back-calculated lengths at age (mm ± S.D. (*n*))					
		1	2	3	4	5	6
Langsett (2014)	The River Little Don	85±15 (66)	160±21 (17)	308 (1)			
	Thickwoods Brook	88±14 (19)	166±14 (5)				
	The River Little Don (Reservoir)	89±13 (54)	189±42 (16)	312±42 (7)	405±64 (5)		
	Langsett Reservoir	90±16 (36)	210±28 (35)	292±28 (28)	346±24 (7)		
Langsett (2015)	The River Little Don	85±12 (74)	161±18 (25)	242±20 (8)	280±5	342 (1)	
	Thickwoods Brook	76±7 (48)	137±11 (5)	180(1)			
	The River Little Don (Reservoir)	76±14 (14)	172±33 (2)	255±64 (2)			
	Langsett Reservoir	89±11 (31)	159±19 (20)	224±29 (20)	275±22 (6)	337±14 (6)	358 (1)
Grimwith (2014)	Blea Gill Beck	82±11 (87)	149±27 (11)	197 (1)			
	Gate Up Gill	78±13 (89)	144±20 (53)	180±17 (6)			
	Grimwith Beck	82±18 (89)	136±21 (35)				
	Grimwith Reservoir	79±16 (102)	185±26 (101)	255±112 (32)			
Grimwith (2015)	Blea Gill Beck	77±8 (34)	131±9 (6)				
	Gate Up Gill	80±10 (38)	146±14 (5)				
	Grimwith Beck	74±8 (30)	146±8 (5)				
	Grimwith Reservoir	80±14 (45)	148±8 (26)	203±12 (8)	223±13 (2)		

4.1.3 *Other species*

During fish surveys in 2014 and 2015, a species other than brown trout was recorded at some sites. Common minnow (*Phoxinus phoxinus* Linnaeus, 1758) were caught in BGB3 and GUG3 (sites on tributaries of Grimwith Reservoir) in 2014 but also observed in tributaries of Grimwith Reservoir in 2015 without capture.

4.2 **Movements between reservoirs and tributaries**

Sizes and release locations of the tagged brown trout have been detailed in Tables 5 and 6.

4.2.1 *Langsett Reservoir*

2014 tagging cohort in 2014/15

Thirty-six (72%) and twenty-one (42%) of the brown trout PIT-tagged in Langsett Reservoir were detected on the antennae downstream of weirs on the River Little Don and Thickwoods Brook, respectively (Table 15), with the majority of detections occurring between 15/10/14 and 18/01/15 (Figures 14 and 15). Brown trout PIT-tagged in Langsett Reservoir and detected (mean fork length ± SD = 301.5 ± 65.7 mm) by antennae downstream of weirs on The River Little Don and Thickwoods Brook were significantly larger than undetected PIT-tagged fish (243.7 ± 74.8 mm) (MWU test: Z = -2.244, n = 50, P = 0.025), i.e. larger fish approached the weirs and smaller fish remained in the reservoir. No brown trout PIT-tagged in Langsett Reservoir were detected on PIT antennae upstream of the study weirs. All but one of the brown trout PIT-tagged in Langsett Reservoir detected on the Thickwoods Brook lower antenna were also detected on the River Little Don lower antenna. Thirteen PIT-tagged fish of reservoir origin were not detected on any antennae.

Table 15. Number (proportion, %) of brown trout PIT-tagged in Langsett Reservoir (downstream of the weirs), The River Little Don and Thickwoods Brook (upstream of the weirs), in 2014, detected on antennae upstream and downstream of weirs in The River Little Don and Thickwoods Brook in the spawning period, 2014/15.

Antenna location	Release location		
	Langsett Reservoir	The River Little Don	Thickwoods Brook
The River Little Don upstream	0 (0%)	15 (30%)	0 (0%)
The River Little Don downstream	36 (72%)	5 (10%)	1 (2%)
Thickwoods Brook upstream	0 (0%)	0 (0%)	3 (6%)
Thickwoods Brook downstream	21 (42%)	0 (0%)	3 (6%)

The total number of days until fish were detected moving from the reservoir into the tributaries were (mean time ± SD) 51 ± 41 days (Thickwoods Brook) and 34 ± 28 days (the River Little Don); the River Little Don was the tributary generally accessed more quickly but the difference was not significant (t test: n = 55, P = 0.076).

The total number of different days individual fish tagged in Langsett Reservoir were detected on the antenna downstream of the weir on the River Little Don (mean time ± SD 10 ± 9 days) was lower than in Thickwoods Brook (12 ± 24 days) (t test: n = 55, P = 0.628), but not significantly so.

The mean number of days until the first detection of individual fish in the River Little Don (mean time ± SD) 108 ± 139 days was lower than that in Thickwoods Brook (258 ± 99 days) (MWU test: Z = -1.279 n = 10, P = 0.257), but not significantly so.

Fifteen (30%) of the fish tagged in the River Little Don (caught/tagged/released upstream of the antenna) were detected on the antenna upstream of the weir and a third of these were subsequently detected on the antenna downstream of the weir (Table 15), with downstream movements occurring during periods of elevated river level (Figures 14 and 15). Three (6%) of the fish tagged in Thickwoods Brook were detected on the antenna upstream of the weir and all were subsequently detected on the antenna downstream of the weir. The fish detected moving downstream (mean fork length ± SD = 120.2 ± 32.7 mm) from The River Little Don were significantly smaller than those not detected (139.9 ± 32.3 mm) (t-test: n = 50, P = 0.045). Brown trout PIT-tagged in the River Little Don were largely detected moving downstream towards the reservoir on the antennae upstream of the weir between 28/03/15 and 02/07/15.

Of the brown trout PIT-tagged in headwater tributaries that moved into Langsett Reservoir, one fish from Thickwoods Brook was subsequently detected in the River Little Don.

2014 tagging cohort in 2015/16

Sixteen (32%) and thirteen (26%) of the brown trout PIT-tagged in Langsett Reservoir in 2014 were detected on the antennae downstream of weirs on the River Little Don and Thickwoods Brook, respectively (Table 16), with the majority of detections occurring between 31/10/15 and 06/01/16 (Figures 14 and 15). Brown trout PIT-tagged in Langsett Reservoir and detected (mean fork length ± SD = 279.7 ± 96.1 mm) by antennae downstream of weirs on the lower The River Little Don and Thickwoods Brook were not of a significantly different size (when tagged) from undetected PIT-tagged fish (286.5 ± 60.2 mm) (MWU test: Z = -0.492, n = 50, P = 0.623). No brown trout PIT-tagged in Langsett Reservoir were detected on PIT antennae upstream of the study weirs. All but one of the brown trout PIT-tagged in Langsett Reservoir detected on Thickwoods Brook antenna downstream of the weir were also detected on the antenna downstream of the weir in the River Little Don. Four PIT-tagged brown trout detected on The River Little Don were detected only there, not being recorded on the antenna downstream of the weir at Thickwoods Brook. Very few brown trout PIT-tagged in the tributaries of Langsett Reservoir in 2014 were detected making downstream movements (2% in either tributary).

Table 16. Number (proportion, %) of brown trout PIT-tagged in Langsett Reservoir in 2014, The River Little Don and Thickwoods Brook detected on antennae upstream and downstream of weirs in The River Little Don and Thickwoods Brook in the spawning period, 2015/16.

Antenna location	Release location		
	Langsett Reservoir	The River Little Don	Thickwoods Brook
The River Little Don upstream	0 (0%)	1 (2%)	0 (0%)
The River Little Don downstream	16 (32%)	1 (2%)	1 (2%)
Thickwoods Brook upstream	0 (0%)	0 (0%)	1 (2%)
Thickwoods Brook downstream	13 (26%)	1 (2%)	1 (2%)

The mean number of different days fish tagged in Langsett Reservoir were detected on the antenna downstream of the weir on the River Little Don (mean time ± SD = 16 ± 10 days) was lower than Thickwoods Brook (19 ± 38 days; SW test = 0.000), but not significantly so (t test: n = 30, P = 0.764).

2015 tagging cohort in 2015/16

Thirteen (15%) of the brown trout PIT-tagged in Langsett Reservoir in 2015 were detected on each of the antennae downstream of weirs on the River Little Don and Thickwoods Brook, respectively (Table 17), with the majority of detections occurring between 31/10/15 and 06/01/16 (Figures 14 and 15). Brown trout PIT-tagged in Langsett Reservoir and detected (mean fork length ± SD = 268.4 ± 89.5 mm) by antennae downstream of weirs on the lower The River Little Don and Thickwoods Brook were significantly larger than undetected PIT-tagged fish (128.0 ± 74.2 mm) (t test: n = 100, P = 0.000), i.e. larger fish approached the weirs and smaller fish remained in the reservoir. No brown trout PIT-tagged in Langsett Reservoir were detected on PIT antennae upstream of the study weirs. Eight of the brown trout PIT-tagged in Langsett Reservoir were detected on both downstream antennae. Five individual brown trout were only detected on the antenna downstream of Thickwoods Brook and a further five were only detected on the antenna downstream of the weir on the River Little Don.

Table 17. Number (proportion, %) of brown trout PIT-tagged in Langsett Reservoir in 2015, The River Little Don and Thickwoods Brook detected on antennae upstream and downstream of weirs in The River Little Don and Thickwoods Brook in the spawning period, 2015/16.

Antenna location	Release location		
	Langsett Reservoir	The River Little Don	Thickwoods Brook
The River Little Don upstream	0 (0%)	4 (4%)	0 (0%)
The River Little Don downstream	13 (15%)	1 (1%)	1 (1%)
Thickwoods Brook upstream	0 (0%)	0 (0%)	4 (4%)
Thickwoods Brook downstream	13 (15%)	1 (1%)	1 (1%)

Four brown trout tagged in each tributary of Langsett Reservoir were detected moving downstream (Table 17). Brown trout moving downstream in Thickwoods Brook were larger (mean fork length ± SD = 123.0 ± 78.4 mm) than those not detected (110.5 ± 40.4 mm) (MWU test: Z = -0.158, n = 100, P = 0.874) but there was no statistically significant difference. Brown trout moving downstream in the River Little Don were larger (mean fork length ± SD = 238.5 ± 99.1 mm) than those not detected (165.5 ± 58.2 mm) (MWU test: Z = -2.120, n = 100, P = 0.034).

The mean number of days until the first detection in the River Little Don (mean time ± SD = 67 ± 39 days) was higher than Thickwoods Brook (44 ± 27 days), however due to equipment damage at the monitoring site upstream of the weir at the River Little Don during a December 2015 flood event, the significance and accuracy of this is highly dubious.

The mean total number of different days fish tagged in Langsett Reservoir were detected on the antenna downstream of the weir on the River Little Don (mean time ± SD = 17 ± 12 days) was significantly higher than Thickwoods Brook (10 ± 13 days) (MWU test: Z = -2.425, n = 32, P = 0.015).

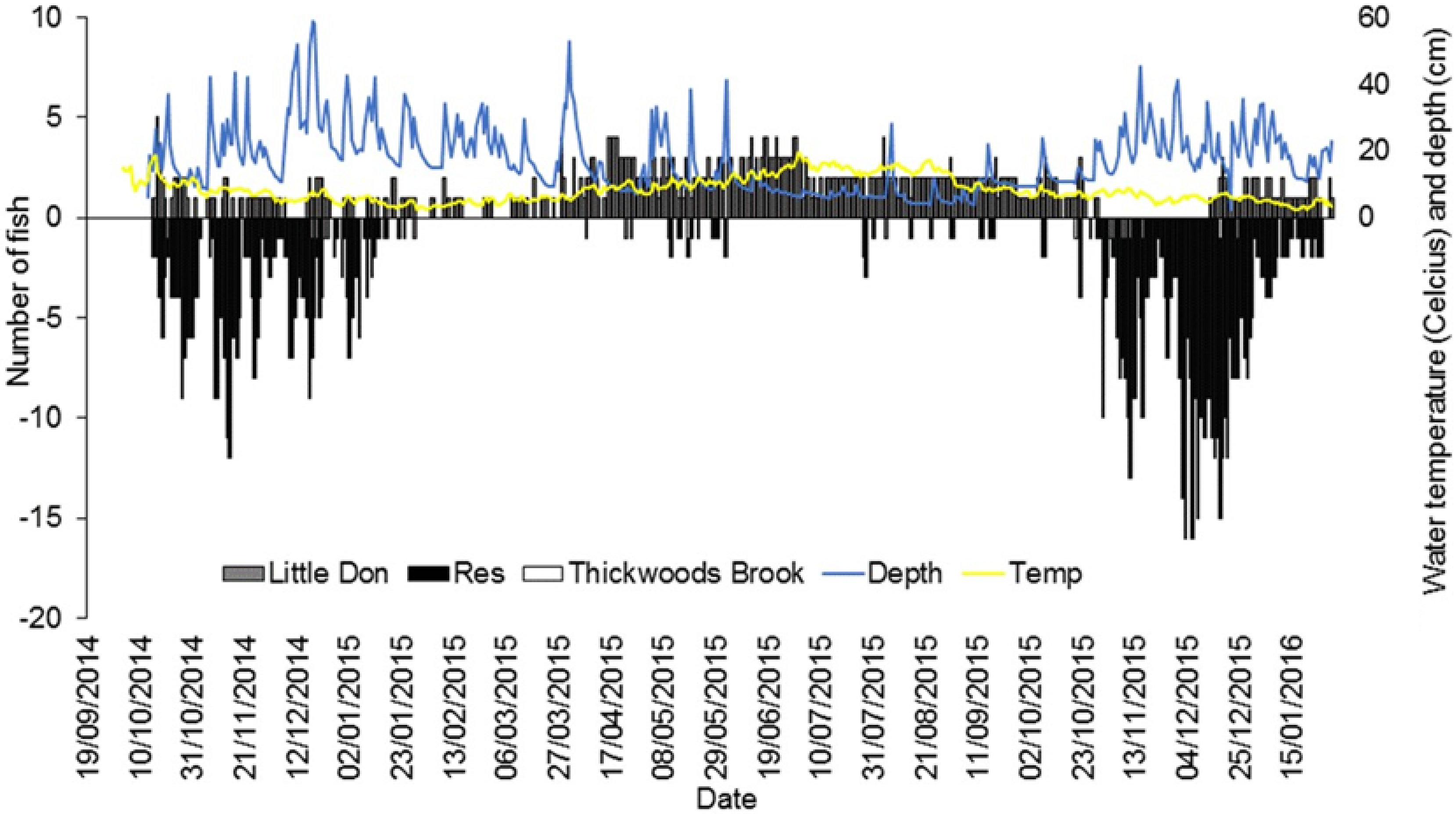


Figure 14. Number of PIT-tagged brown trout released in Langsett Reservoir (black bar), The River Little Don (grey bar) and Thickwoods Brook (white bar) subsequently detected on PIT antennae upstream (positive values) and downstream (negative values) of the weir on the River Little Don. Temperature (°C) and depth (cm) are plotted on the secondary axis.

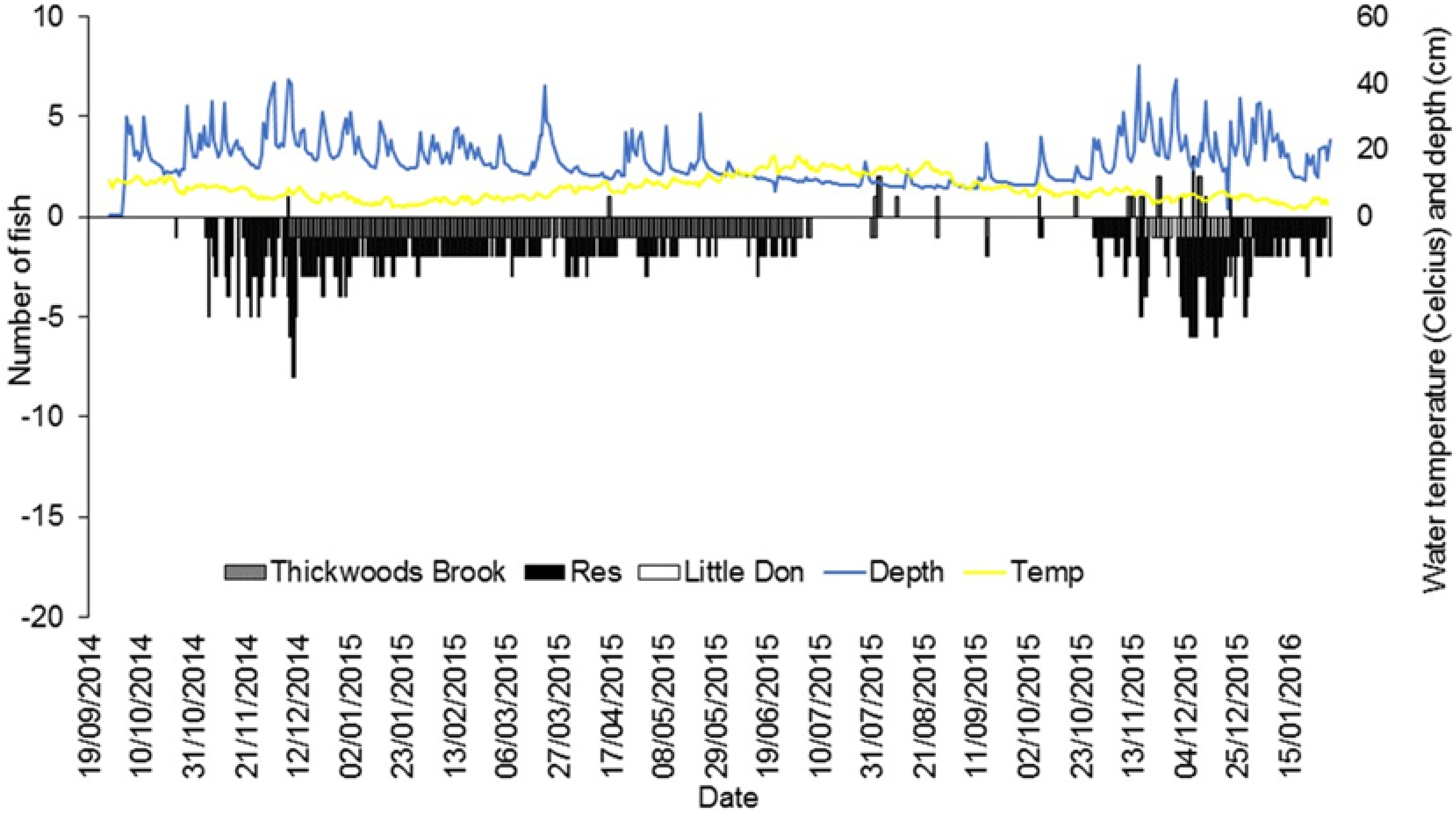


Figure 15. Number of PIT-tagged brown trout released in Langsett Reservoir (black bar), Thickwoods Brook (grey bar) and The River Little Don (white bar) subsequently detected on PIT antennae upstream (positive values) and downstream (negative values) of the weir on the Thickwoods Brook. Temperature (°C) and depth (cm) are plotted on the secondary axis.

There were more detections in total of fish recorded on the antenna downstream of the weir on the River Little Don (A4) than on the antenna downstream of the weir at Thickwoods Brook (A2). There were more detections at A4 than A2 every hour apart from the tenth of the day (Figure 16). The 5 hours of the day in which the highest number of detections at A4 were recorded were consecutive from 18 to 22. The fewest detections were seen around the 12th and 14th hours of the day at both sites.

The mean number of days until the first detection of fish tagged in Langsett Reservoir on the antenna on the River Little Don (mean time ± SD = 27 ± 23 days) was fewer than in Thickwoods Brook (92 ± 90 days) (MWU test: Z = -2.150, n = 32, P = 0.032).

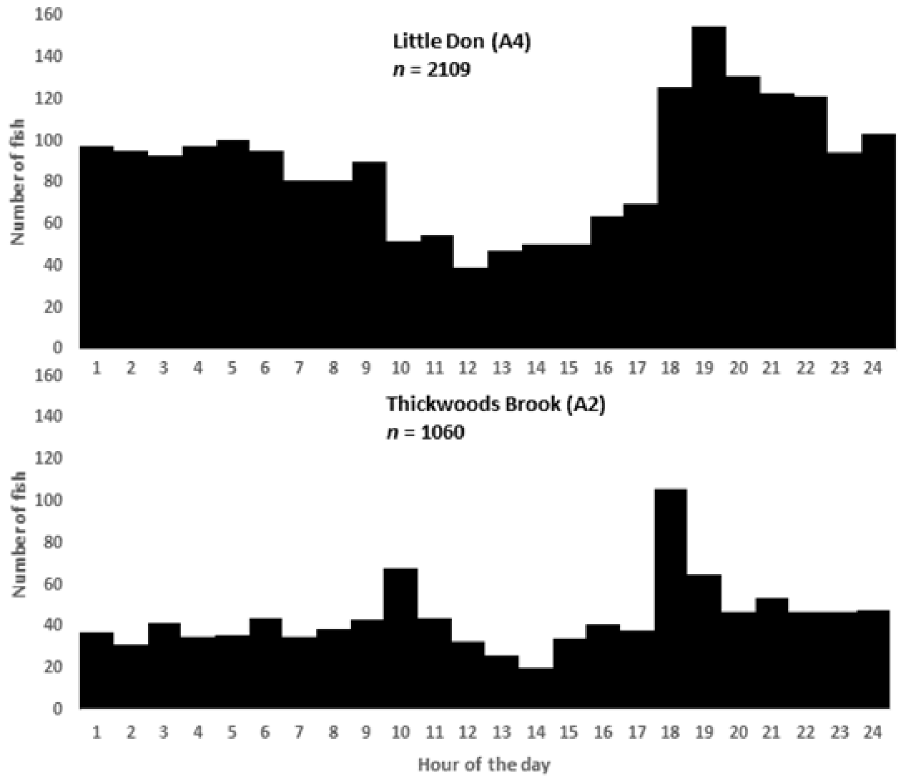


Figure 16. Hour of the day in which fish were detected on PIT antennae downstream of weirs at Langsett Reservoir.

4.2.2 *Grimwith Reservoir*

2014 tagging cohort

Six (12%) of the brown trout PIT-tagged in Grimwith Reservoir were detected on either Blea Gill Beck or Gate Up Gill PIT antennae between 30/11/14 and 31/01/15 (Figures 17 – 19), with two fish entering both (Table 18). Brown trout PIT-tagged in Grimwith Reservoir detected (mean fork length ± SD = 222.0 ± 45.0 mm) in tributaries were larger than undetected fish (197.2 ± 35.5 mm), although the difference was not significant (MWU test: Z = -1.225, n = 50, P = 0.221).

Thirteen (26%), twelve (24%) and twelve (24%) of the brown trout PIT-tagged in Blea Gill Beck, Gate Up Gill and Grimwith Beck, respectively, were detected moving downstream towards the reservoir predominantly in October–November and in April–May (Table 18). The fish detected moving downstream (mean fork length ± SD = 107.9 ± 27.7 mm) from the tributaries at Grimwith Reservoir were significantly larger than those which were not detected (98.1 ± 30.0 mm) (MWU test: Z = -2.311, n = 150, P = 0.021).

Table 18. Number (proportion, %) of brown trout PIT-tagged in Grimwith Reservoir, Grimwith Beck, Blea Gill Beck and Gate Up Gill in 2014, detected on antennae in Grimwith Beck, Blea Gill Beck and Gate Up Gill, in 2014.

Antenna location	Release location			
	Grimwith Reservoir	Grimwith Beck	Blea Gill Beck	Gate Up Gill
Grimwith Beck	0 (0%)	12 (24%)	0 (0%)	0 (0%)
Blea Gill Beck	4 (8%)	0 (0%)	13 (26%)	0 (0%)
Gate Up Gill	4 (8%)	0 (0%)	4 (8%)	12 (24%)

Ten (20%) of the brown trout PIT-tagged in Grimwith Reservoir were detected on Grimwith Beck, Blea Gill Beck or Gate Up Gill PIT antennae between 01/11/15 and 31/01/16 (Figures 17 – 19), with some fish entering multiple tributaries (Table 18). Brown trout PIT-tagged in Grimwith Reservoir detected (mean fork length ± SD = 207.7 ± 28.7 mm) in tributaries were larger than undetected fish (198.3 ± 39.0 mm), although the difference was not significant (MWU test: Z = -0.849, n = 50, P = 0.396).

Seven (14%), four (8%) and seven (14%) of the brown trout PIT-tagged in Blea Gill Beck, Gate Up Gill and Grimwith Beck, respectively, were detected moving downstream towards the reservoir predominantly in October–November and in April–May (Table 19). The fish detected moving downstream (mean fork length ± SD = 99.1 ± 21.1 mm) from the tributaries at Grimwith Reservoir were smaller than those which were not detected (100.7 ± 27.3 mm) but it was not significant (MWU test: Z = -0.508, n = 150, P = 0.612).

Table 19. Number (proportion, %) of brown trout PIT-tagged in Grimwith Reservoir, Grimwith Beck, Blea Gill Beck and Gate Up Gill in 2014, detected on antennae in Grimwith Beck, Blea Gill Beck and Gate Up Gill, in 2015.

Antenna location	Release location			
	Grimwith Reservoir	Grimwith Beck	Blea Gill Beck	Gate Up Gill
Grimwith Beck	4 (8%)	4 (8%)	0 (0%)	0 (0%)
Blea Gill Beck	2 (4%)	1 (2%)	4 (8%)	0 (0%)
Gate Up Gill	7 (14%)	2 (4%)	3 (6%)	4 (8%)

2015 tagging cohort

Twenty-five (31%) of the brown trout PIT-tagged in Grimwith Reservoir in 2015 were detected on PIT antennae in the three tributaries between 01/10/14 and 31/01/15 (Figures 17 – 19), some fish were detected on multiple antennae. Brown trout PIT-tagged in Grimwith Reservoir detected (mean fork length ± SD = 222.9 ± 41.6 mm) in tributaries were significantly larger than the remaining undetected tagged fish (196.1 ± 38.5 mm) (MWU test: Z = -2.642, n = 80, P = 0.008).

Twenty-three (23%), twenty-six (26%) and twenty-one (21%) of the brown trout PIT-tagged in Blea Gill Beck, Gate Up Gill and Grimwith Beck, respectively, were detected moving downstream towards the reservoir between October 2015 and January 2016 (Table 20). The fish detected moving downstream (mean fork length ± SD = 102.2 ± 29.5 mm) from the tributaries at Grimwith Reservoir were larger than the remaining undetected tagged fish (100.0 ± 34.9 mm) (t test = 0.939, n = 300), but not significantly so.

Table 20. Number (proportion, %) of brown trout PIT-tagged in Grimwith Reservoir, Grimwith Beck, Blea Gill Beck and Gate Up Gill, 2015 detected on antennae in Grimwith Beck, Blea Gill Beck and Gate Up Gill, in 2015.

Antenna location	Release location			
	Grimwith Reservoir	Grimwith Beck	Blea Gill Beck	Gate Up Gill
Grimwith Beck	12 (15%)	21 (21%)	0 (0%)	3 (3%)
Blea Gill Beck	7 (9%)	3 (3%)	23 (23%)	5 (5%)
Gate Up Gill	12 (15%)	4 (4%)	4 (4%)	26 (26%)

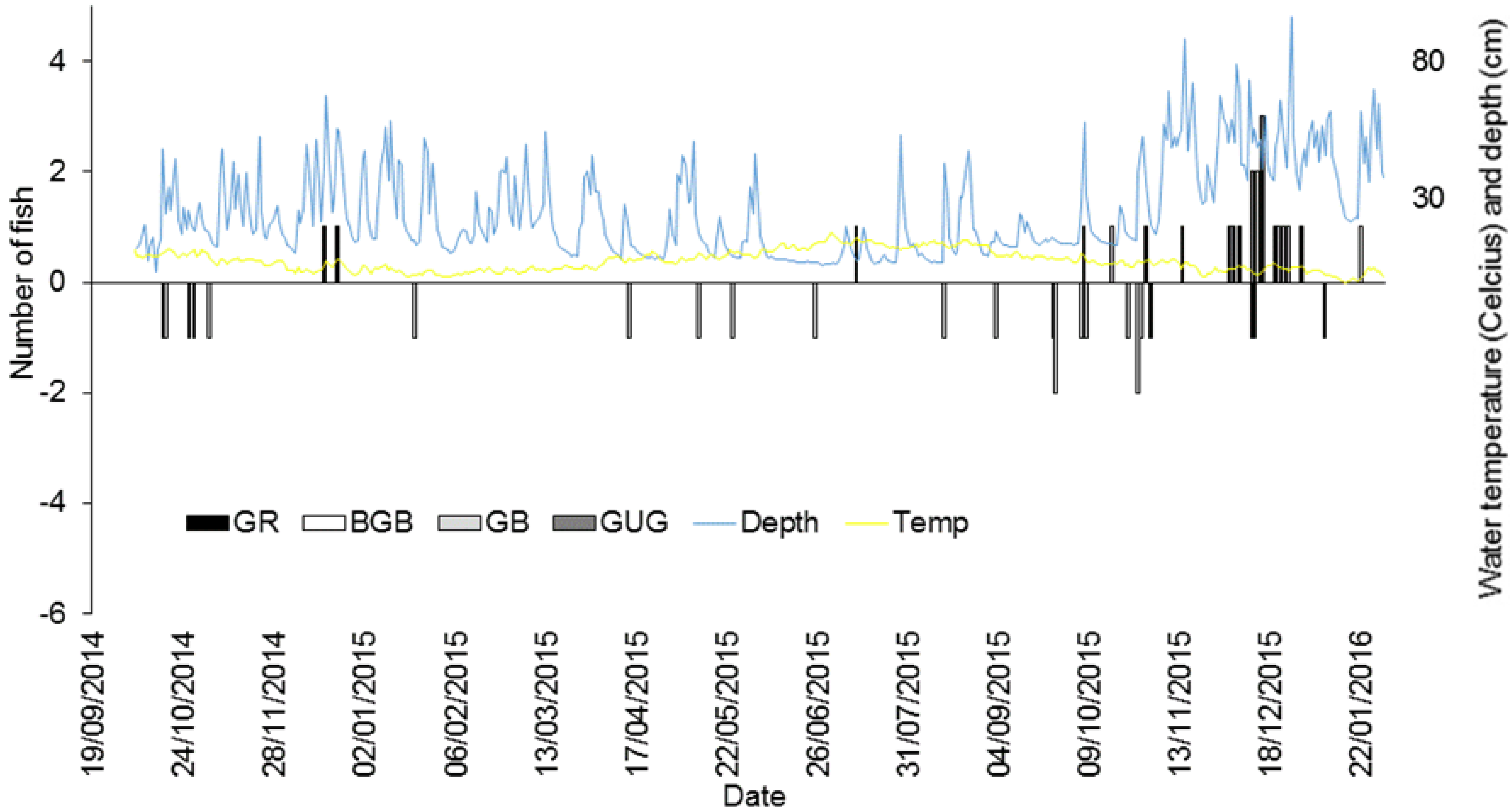


Figure 17. Number of PIT-tagged brown trout released in Grimwith Reservoir (black bar) and headwater tributaries (Blea Gill Beck white bar; Grimwith Beck light grey bar and Gate Up Gill dark grey bar) detected moving upstream (positive values) and downstream (negative values) in Blea Gill Beck, September 2014 – January 2016. Temperature (°C) and depth (cm) are plotted on the secondary axis.

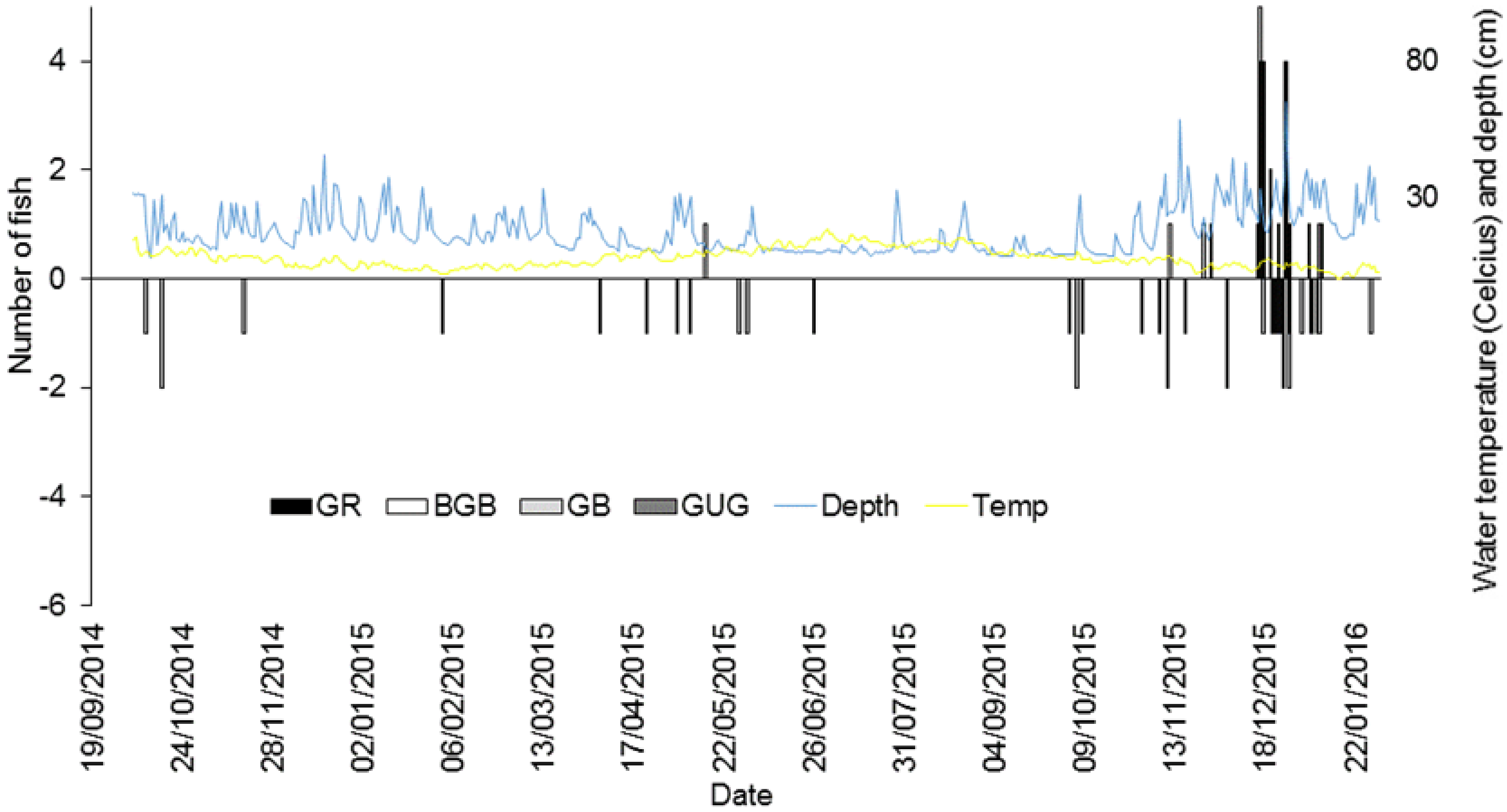


Figure 18. Number of PIT-tagged brown trout released in Grimwith Reservoir (black bar) and headwater tributaries (Blea Gill Beck white bar; Grimwith Beck light grey bar and Gate Up Gill dark grey bar) detected moving upstream (positive values) and downstream (negative values) in Grimwith Beck, September 2014 – January 2016. Temperature (°C) and depth (cm) are plotted on the secondary axis.

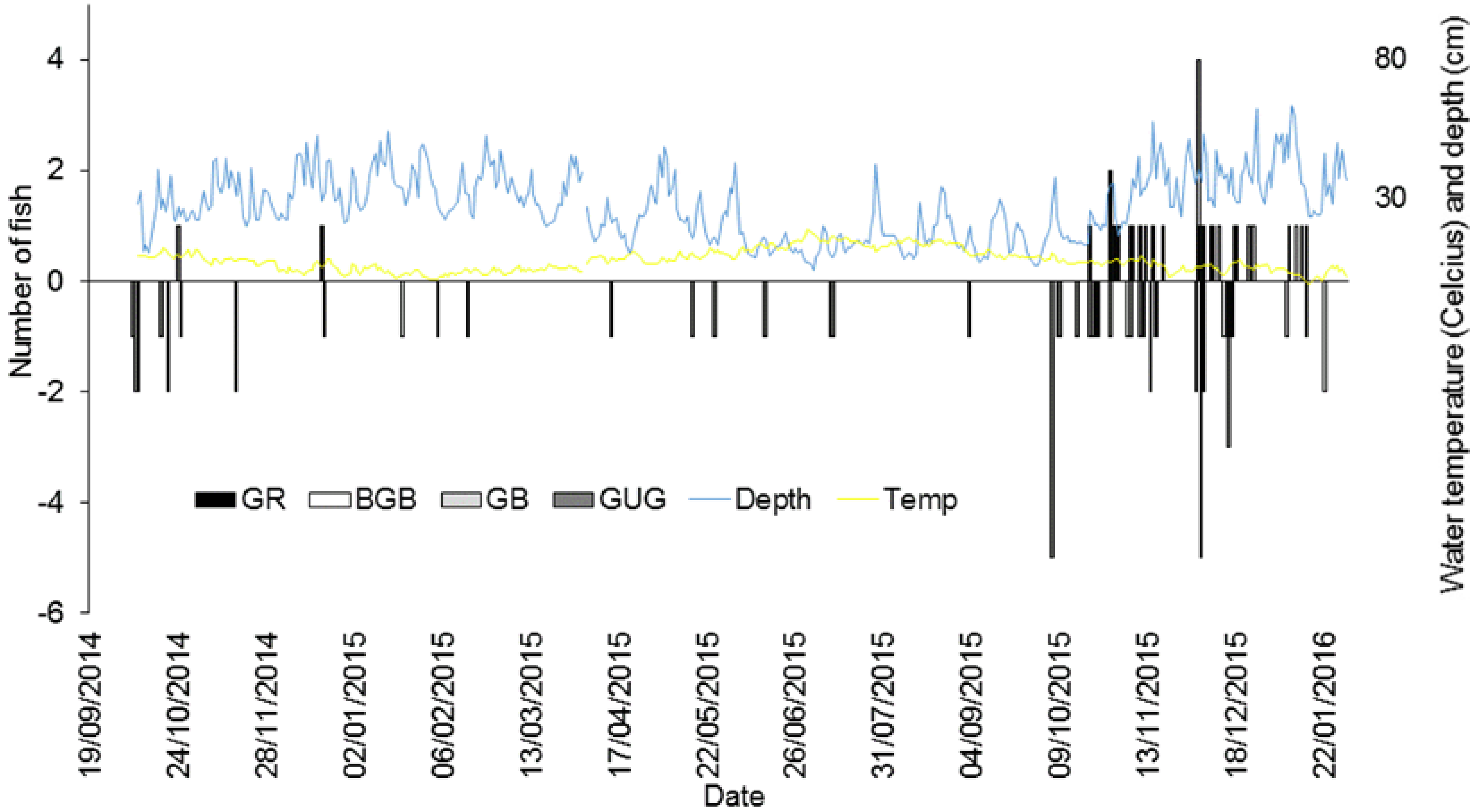


Figure 19. Number of PIT-tagged brown trout released in Grimwith Reservoir (black bar) and headwater tributaries (Blea Gill Beck white bar; Grimwith Beck light grey bar and Gate Up Gill dark grey bar) detected moving upstream (positive values) and downstream (negative values) in Gate Up Gill, September 2014 – January 2016. Temperature (°C) and depth (cm) are plotted on the secondary axis.

4.2.3 *Q values and movements*

Water depth

The percentage of fish detected moving was greater than the exceedance percentage at all levels at all locations apart from Q10 on Blea Gill Beck and Gate Up Gill (Table 21). This trend is most marked on the tributaries of Langsett Reservoir, only 1.2% (the River Little Don) and 3.1% (Thickwoods Brook) of detections occurred when the river was at its shallowest 25%. 86.1% of detections on Grimwith Beck occurred during Q50 or greater depth (Table 22), no studied tributary recorded greater percentages of fish detections at Q50, Q25 or Q10 than Grimwith Beck.

Table 21. A comparison of daily average flow exceedance values with daily number of unique fish detections of brown trout tagged in Langsett Reservoir on PIT antennae A2 and A4 (downstream of the respective weirs) and Grimwith Reservoir on PIT antennae 02, 04 and 06, located in each of the tributaries.

Reservoir	Langsett				Grimwith					
Tributary	The River Little Don		Thickwoods Brook		Grimwith Beck		Blea Gill Beck		Gate Up Gill	
	n	%	n	%	n	%	n	%	n	%
Q75	825	98.8	413	96.9	33	91.7	23	92.0	50	89.3
Q50	701	84.0	336	78.9	31	86.1	13	52.0	41	73.2
Q25	374	44.8	190	44.6	22	61.1	8	32.0	15	26.8
Q10	181	21.7	69	16.2	12	33.3	1	4.0	5	8.9

Water temperature

Water temperature Q values did not correlate with fish detections in the same way as flow values did. As a result, different combinations of Q values were dynamically investigated, in particular, Q75-25 (detections at temperatures between the 25th and 75th centiles) and Q75-50 (detections at temperatures between the 50th and 75th centiles) (Table 23). Detections were most frequent on the River Little Don and Thickwoods Brook when temperature was between Q75-50 (49.2% and 41.1%, respectively). A concentration towards the lower quarter was not repeated at the tributaries of Grimwith Reservoir, values recorded for Q25 being 22.2%, 32.0% and 41.5% (Table 22).

Table 22. A comparison of daily average temperature exceedance values with daily number of unique fish detections of brown trout tagged in Langsett Reservoir on PIT antennae A2 and A4 (downstream of the respective weirs).

Reservoir	Langsett				Grimwith					
Tributary	The River Little Don		Thickwoods Brook		Grimwith Beck		Blea Gill Beck		Gate Up Gill	
	n	%	n	%	n	%	n	%	n	%
Q75	678	81.2	280	65.7	27	75	21	84.0	36	87.8
Q50	267	32.0	105	24.6	17	47.2	18	72.0	31	75.6
Q25	67	8.0	19	4.5	8	22.2	8	32.0	17	41.5
Q10	5	0.6	11	2.6	1	2.8	1	4.0	3	7.3
Q75-25	611	73.2	261	61.3	19	52.8	13	52.0	19	46.3
Q75-50	411	49.2	175	41.1	10	27.8	3	12.0	5	12.2

4.3 Movements of fish in Grimwith Reservoir

All fish positions were plotted in ArcGIS (Figure 20), and a general predilection for littoral areas of the reservoir was evident. The blue areas (those where positions were most dense) are all close to shore (nowhere more than 150 m from shoreline) and there is an area in the middle of the reservoir where there were no positions at all. Areas near the tributaries that are also position-free are most likely to be due to array coverage being poorest.

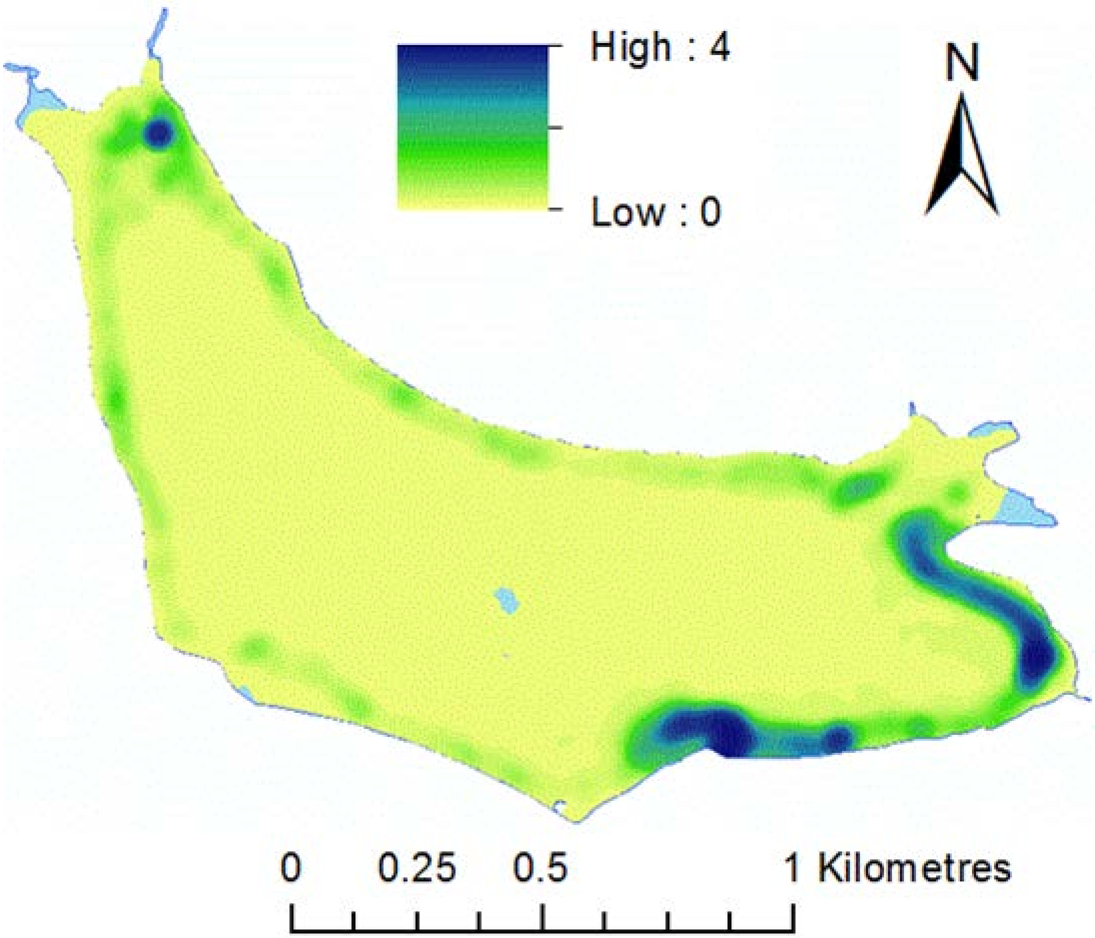


Figure 20. Colour coded heat map of all fish positions in Grimwith Reservoir, October 2014 – July 2015, the areas where the highest number of fish were positioned are coloured in dark blue; the fewest is in yellow. Scale is in arbitrary units for demonstrative purposes. Where the blue of the reservoir can be seen, in the midde and at the periphery in the north-west and –eastern corners, no fish were positioned.

4.3.1 *Spatial variations in habitat use*

Acoustically tagged fish in the reservoir largely occupied the littoral zone, but not necessarily near the tributaries, and very few occupied the middle of the reservoir (Figure 20). Many more positions occurred in the eastern portion of the reservoir than the west.

4.3.2 *Temporal variations in home range size between individuals*

A large amount of variability in home range size was found between fish (Table 23), although even with this there was temporal variability. For example, Fish 20557 had the largest home range in a month (June: k50 113.73 ha) and Fish 20546 the largest under k95 (132.81 ha in April) scenarios and were detected in many parts of the reservoir throughout the period (Table 23).

Table 23. Fish ID number, length and monthly k95 and k50 home range sizes (ha) of fish acoustic tagged in Grimwith Reservoir, October 2014 – July 2015, and mean home range (ha, k95 and k50, *n*).

Fish	Length	October		November		December		January		February		March		April	
Number	(mm)	k95	k50	k95	k50	k95	k50	k95	k50	k95	k50	k95	k50	k95	k50
20542	254	21.36	15.36	-	-	-	-	-	-	-	-	-	-	-	-
20543	272	127.50	102.67	37.70	11.32	-	-	-	-	-	-	-	-	-	-
20544	283	16.99	11.35	3.33	2.43	6.47	4.26	0.09	0.06	0.18	0.09	-	-	78.44	41.90
20545	237	10.19	5.26	26.07	13.12	1.03	0.80	0.10	0.06	12.02	8.91	-	-	-	-
20546	237	2.66	0.98	1.71	1.17	2.64	1.78	0.24	0.14	0.63	0.33	1.43	0.60	132.81	88.12
20547	268	28.73	18.05	1.74	1.26	3.95	2.35	5.91	3.68	0.43	0.26	1.07	0.54	1.58	1.21
20548	252	100.89	71.53	2.11	1.56	63.88	45.13	-	-	0.32	0.16	-	-	-	-
20549	272	1.19	0.92	11.83	5.30	92.92	57.93	0.14	0.10	1.56	0.96	8.51	6.29	4.77	3.08
20550	242	1.78	1.08	1.46	1.11	0.50	0.36	0.01	0.01	0.23	0.14	0.33	0.25	0.30	0.24
20551	296	2.04	0.80	96.53	28.04	6.26	2.77	-	-	-	-	-	-	-	-
20552	236	73.34	45.74	21.16	10.99	69.60	48.55	42.61	27.22	1.90	1.16	8.80	5.44	118.94	91.37
20553	252	26.13	18.68	5.15	2.64	2.07	1.10	4.00	3.07	-	-	-	-	-	-
20554	270	0.66	0.43	0.58	0.42	0.33	0.20	-	-	-	-	-	-	-	-
20555	261	6.54	3.43	7.49	4.07	0.45	0.10	-	-	2.87	1.16	0.11	0.07	-	-
20556	226	2.27	1.57	0.72	0.51	0.85	0.60	0.16	0.11	0.25	0.19	0.65	0.45	0.31	0.24
20557	227	8.31	3.30	1.33	0.44	0.32	0.20	0.17	0.13	-	-	-	-	-	-
20558	213	4.49	2.50	68.90	44.33	4.36	2.36	-	-	-	-	-	-	-	-
20559	282	53.03	25.53	-	-	-	-	-	-	-	-	-	-	-	-
20560	203	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20561	288	1.29	0.83	6.52	1.68	17.01	9.44	-	-	-	-	-	-	-	-
Mean		25.76	17.37	17.31	7.67	17.04	11.12	5.34	3.46	2.04	1.34	2.99	1,95	48.16	32.31
Standard Deviation		37.50	28.16	27.17	11.83	29.81	19.84	13.26	8.46	3.62	2.70	3.90	2.69	60.17	41.98

Table 23 cont. Fish ID number, length and monthly k95 and k50 home range sizes (ha) of fish acoustic tagged in Grimwith Reservoir, October 2014 – July 2015, and mean home range (ha, k95 and k50, *n*).

Fish	Length	May		June		July		Mean (±SD), *n*	
Number	(mm)	k95	k50	k95	k50	k95	k50	k95	k50
20542	254	-	-	-	-	-	-	21.36, 1	15.36, 1
20543	272	-	-	-	-	-	-	55.07 ± 65.50, 2	38.00 ± 56.30, 2
20544	283	-	-	130.43	112.53	-	-	33.70 ± 50.92, 7	24.66 ± 41.46, 7
20545	237	-	-	-	-	-	-	9.88 ± 10.50, 5	5.63 ± 5.51, 5
20546	237	-	-	127.50	98.67	51.37	28.87	35.67 ± 56.02, 9	24.52 ± 40.20, 9
20547	268	4.63	2.82	87.52	53.12	117.03	75.10	25.26 ± 42.00, 10	15.84 ± 26.48, 10
20548	252	-	-	-	-	-	-	41.80 ± 49.24, 4	29.59 ± 34.89, 4
20549	272	0.49	0.27	9.22	5.46	4.54	2.47	13.51 ± 28.19, 10	8.28 ± 17.59, 10
20550	242	-	-	59.33	13.25	5.06	2.69	7.67 ± 19.44, 9	2.13 ± 4.26, 9
20551	296	-	-	-	-	-	-	34.94 ± 53.38, 3	10.53 ± 15.19, 3
20552	236	41.37	15.69	-	-	-	-	47.21 ± 38.90, 8	30.77 ± 30.15, 8
20553	252	-	-	-	-	-	-	9.34 ± 11.27, 4	6.37 ± 8.25, 4
20554	270	-	-	-	-	1.77	1.03	0.83 ± 0.64, 4	0.52 ± 0.36, 4
20555	261	-	-	-	-	-	-	3.49 ± 3.40, 5	1.77 ± 1.88, 5
20556	226	21.72	2.49	51.74	22.39	131.48	95.28	21.01 ± 42.20, 10	12.38 ± 29.92, 10
20557	227	-	-	124.74	113.73	2.81	1.34	22.94 ± 49.96, 6	19.86 ± 46.00, 6
20558	213	-	-	-	-	-	-	25.92 ± 37.32, 3	16.40 ± 24.19, 3
20559	282	-	-	-	-	-	-	53.03, 1	25.53, 1
20560	203	-	-	114.20	89.78	56.91	28.98	85.55 ± 40.51, 2	59.38 ± 42.99, 2
20561	288	-	-	-	-	-	-	8.27 ± 8.01, 3	3.98 ± 4.75, 3
Mean		17.04	5.32	88.09	63.62	46.37	29.47		
Standard Deviation		18.64	7.01	44.30	45.59	53.07	36.76		

February was the month with smallest mean home range size (k50 – 1.34 ha and k95 – 2.04 ha; n = 10), whereas June was the month with the largest mean home range size (k50 – 63.62 ha and k95 – 88.09 ha; n = 8) (Tables 23 and 24). Expected movement towards and aggregation at spawning tributaries in October to January was generally not seen.

Table 24. Areas occupied by fish in February (month of smallest average home range) and June (month of largest home range) in Grimwith Reservoir. Dark blue areas indicate k95 home range, lighter blue areas inside indicate k50 home range. Empty cells in the table (grey) indicate that the number of times the fish was positioned in the month was insufficient to accurately map their home range.

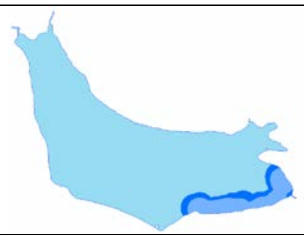
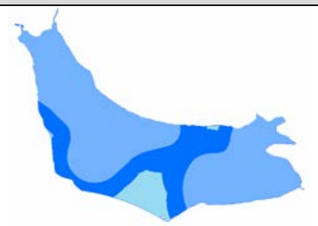
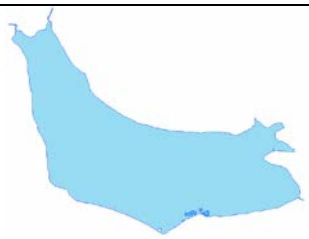
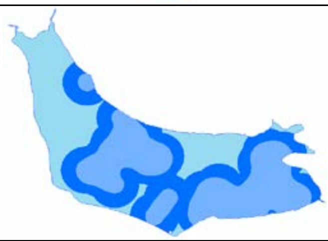
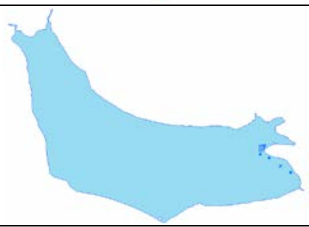
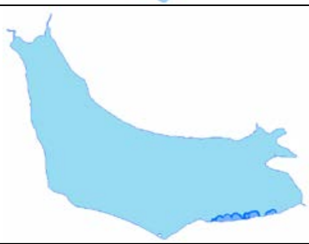
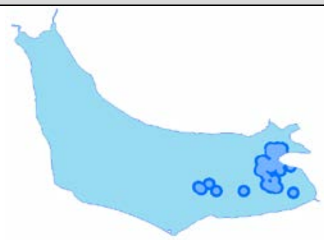
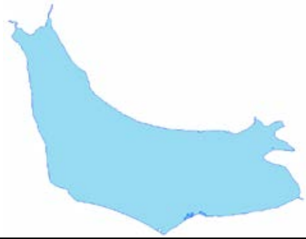
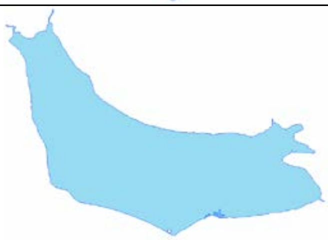
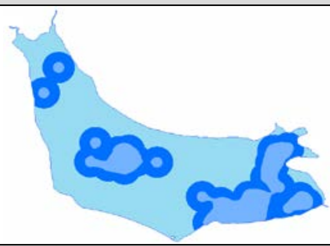
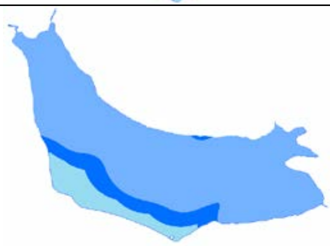
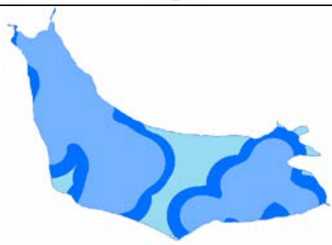
Fish ID	February 2015	June 2015
20544		
20545		
20546		
20547		
20548		
20549		

Table 24 cont. Areas occupied by fish in February (month of smallest average home range) and June (month of largest home range) in Grimwith Reservoir. Dark blue areas indicate k95 home range, lighter blue areas inside indicate k50 home range. Empty cells in the table (grey) indicate that the number of times the fish was positioned in the month was insufficient to accurately map their home range.

Fish ID	February 2015	June 2015
20550		
20552		
20555		
20556		
20557		
20560		

Individual fish displayed differing reservoir occupational tendencies throughout the study period. Fish 20554, though only positioned sufficiently for four months occupied a very small area (home range <1.03 ha; k50), in the south eastern portion of the reservoir – always nearshore.

By contrast, data collected for Fish 20552 yielded home ranges in eight months, October-May; rather than remaining in broadly the same place it was highly mobile. Only in February (k95 1.90 ha) and March (k95 8.80 ha) was the k95 home range less than 10 ha. K95 home range area in the 'mobile months' was 21.16 – 118.94 ha (Table 23).

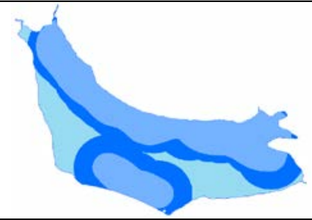
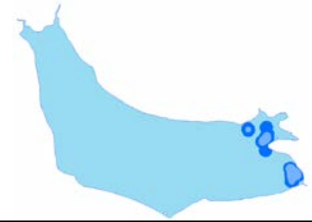
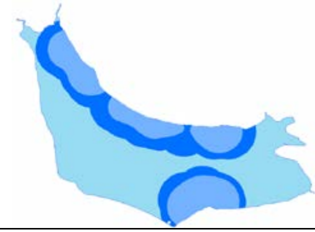
4.3.3 *Variations in individual fish*

By contrast, Fish 20550 and 20556 appeared to remain in broadly the same area from October to April (k95 home range <2.5 ha), only moving out of these small areas in June (Fish 20550) and May – July (Fish 20556) (Table 23).

One of the fish that yielded home range data for all ten months, Fish 20556, was very limited in its home range from October to April (k95 <2.27 ha), yet 'adventurous' in the next three months. This was particularly the case in July (k95 131.48 ha; almost the full extent of the reservoir – the largest of any fish of any month in the study) (Table 23).

This contrast can be seen in Table 25, Fish 20548 was highly mobile during October and December but relatively sedentary during November. The opposite was true for Fish 20551 and 20558.

Table 25. Comparison of calculated home range sizes for Fish 20548, 20551 and 20558 for the months of October – December 2014 inclusive. Dark blue areas indicate k95 home range, lighter blue areas inside indicate k50 home range.

Fish ID	October 2014	November 2014	December 2014
20548			
20551			
20558			

4.3.4 *Variations in array performance*

Nineteen fish were positioned in October, the highest number of fish that were detected sufficiently to produce the sufficient number of positions required for accurate home range calculation, of any month in the study. Four fish were positioned in May, the fewest. On average, home range was calculable for eleven fish each month.

The number of positions calculated by the VPS was highly variable, both temporally and between individual fish (Figures 21 and 22). The amount of variation is particularly stark when compared with the relatively homogeneous ref- and sync tags (Figure 23 and Tables 27 – 29).

The majority of fish positions occurred in October (19.9%) and November (49.7%); by way of comparison, during these months respectively 8.2% and 9.7% of total ref-tag positions occurred, from this it can be inferred that fish behaved in a manner which was different from those tags which were static. The tagged fish occupied different areas of the reservoir and were less likely to be detected at different times. Fish 20560 opposed the trend of more frequently being positioned towards the start of the study because 20.6% and 76.5% of its positions occurred during June and July – this being the only fish that was positioned more frequently (97.1%) than 16% in total in these months.

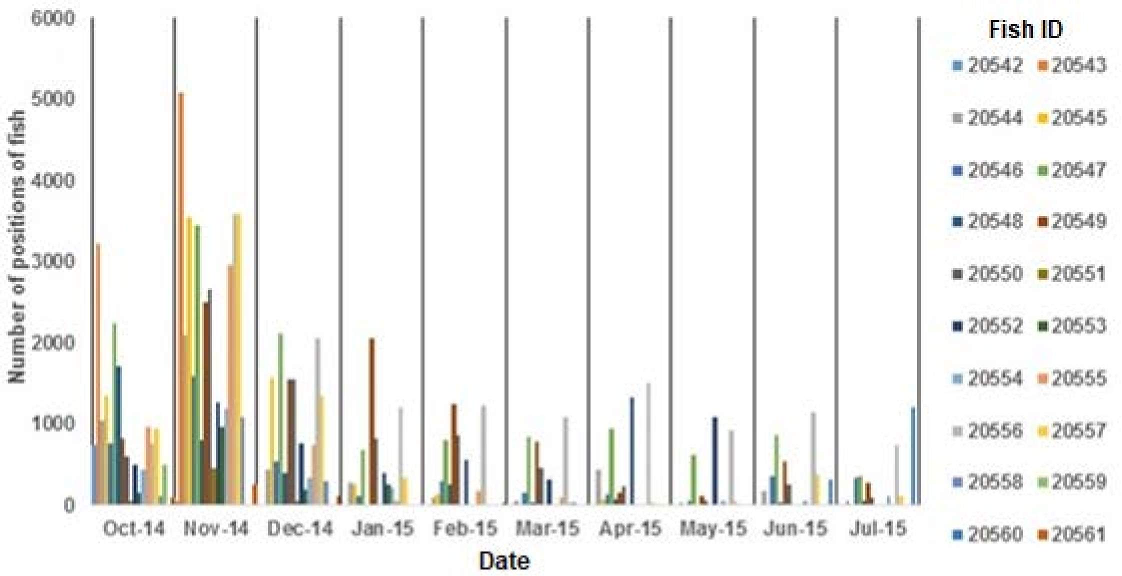


Figure 21. Number of positions per individual acoustic tagged fish per month in Grimwith Reservoir.

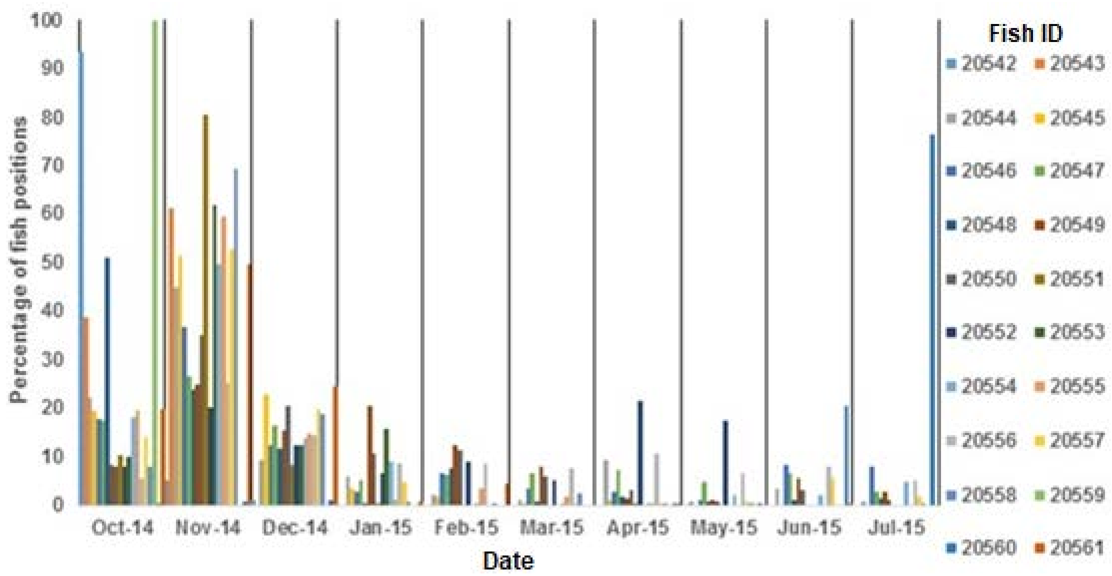


Figure 22. Percentage of positions per individual acoustic tagged fish per month in Grimwith Reservoir.

Most positions were calculated in the first three months (October – December 2014) of the study (Figures 21 and 22; Table 26) except for Fish 20560 which was positioned most in June (20.6%) and July (76.5%).

No fish were positioned for more than 7.8% of their total positions during the whole study in the month of March, the lowest of any month.

Table 26. Number and percentage of positions calculated for each acoustic tagged fish in Grimwith Reservoir. Entries shaded in green indicate a percentage of 10≤*n*≤20% of total detections over the entire study period for the individual fish in the month; yellow indicates >20%. These percentages over 10% have been highlighted because in a ten month study, an equal number of detections each month would equal 10% of detections. Any number over this indicates a month in which a fish was positioned more than expected if detections were equal.

	Oct-14		Nov-14		Dec-14		Jan-15		Feb-15		Mar-15		Apr-15		May-15		Jun-15		Jul-15	
Fish ID	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
20542	746	93.5	42	5.3	10	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20543	3224	38.8	5085	61.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20544	1041	22.3	2090	44.7	432	9.2	271	5.8	96	2.1	51	1.1	439	9.4	40	0.9	168	3.6	43	0.9
20545	1339	19.3	3553	51.3	1568	22.7	250	3.6	129	1.9	2	0.0	80	1.2	0	0	0	0	0	0
20546	769	17.9	1582	36.7	536	12.4	121	2.8	285	6.6	148	3.4	127	2.9	51	1.2	349	8.1	339	7.9
20547	2240	17.4	3440	26.7	2108	16.3	687	5.3	804	6.2	841	6.5	937	7.3	623	4.8	852	6.6	361	2.8
20548	1709	51.1	801	24.0	386	11.5	16	0.5	248	7.4	22	0.7	63	1.9	20	0.6	35	1.0	44	1.3
20549	825	8.2	2493	24.9	1547	15.4	2054	20.5	1239	12.4	781	7.8	156	1.6	113	1.1	537	5.4	272	2.7
20550	597	7.9	2659	35.1	1555	20.5	813	10.7	857	11.3	452	6.0	243	3.2	60	0.8	249	3.3	85	1.1
20551	57	10.2	451	80.5	46	8.2	3	0.5	0	0	0	0	3	0.5	0	0	0	0	0	0
20552	488	7.9	1256	20.3	767	12.4	398	6.4	560	9.0	318	5.1	1325	21.4	1083	17.5	0	0	0	0
20553	156	10.0	962	61.8	194	12.5	245	15.7	0	0	0	0	0	0	0	0	0	0	0	0
20554	429	18.1	1178	49.8	325	13.7	209	8.8	3	0.1	3	0.1	6	0.3	49	2.1	49	2.1	116	4.9
20555	965	19.3	2971	59.5	732	14.7	50	1.0	179	3.6	93	1.9	3	0.1	0	0	0	0	0	0
20556	765	5.4	3598	25.3	2051	14.4	1206	8.5	1220	8.6	1084	7.6	1506	10.6	925	6.5	1139	8.0	740	5.2
20557	950	14.0	3597	52.8	1348	19.8	328	4.8	0	0	26	0.4	30	0.4	42	0.6	370	5.4	119	1.7
20558	121	7.8	1079	69.5	292	18.8	12	0.8	2	0.1	37	2.4	3	0.2	6	0.4	0	0	1	0.1
20559	495	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20560	7	0.4	12	0.8	18	1.1	0	0	0	0	0	0	1	0.1	8	0.5	324	20.6	1204	76.5
20561	99	19.9	247	49.7	122	24.5	3	0.6	23	4.6	0	0	2	0.4	0	0	1	0.2	0	0

These values are in contrast to those recorded for reference tags (Figure 23 and Table 27) and sync tags (Table 28) which were much more homogenous. The percentage of fish positions that occurred in any particular month was extremely variable (range: 0% - 93.5%); sync tags were less so (range: 0% - 26.7%) and reference tag positions even less so (range: 5.5% - 13.3%). This indicates that movements effects ability to detect tags, and sync-tags that were located at the reservoirs periphery were harder to detect than the ref-tags which were located in the centre of the reservoir. This has implications for fish reservoir occupation.

Figure 23. Number of positions per reference tag per month (bar; primary y-axis) and percentage of total positions per month (line; secondary y-axis).

Table 27. Number and percentage of positions calculated for each reference tag in Grimwith Reservoir. Entries shaded in green indicate a percentage of 10%≤*n*≤20% of total detections over the entire study period for the reference tag in the month.

	Oct-14		Nov-14		Dec-14		Jan-15		Feb-15		Mar-15		Apr-15		May-15		Jun-15		Jul-15	
Tag ID	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
RefA	2380	7.8	3142	10.2	3248	10.6	3066	10.0	2877	9.4	3148	10.3	3108	10.1	3186	10.4	3220	10.5	3328	10.8
RefB	2425	7.8	3174	10.3	3251	10.5	3097	10.0	2896	9.4	3235	10.5	3091	10.0	3142	10.2	3244	10.5	3343	10.8
RefC	2457	9.2	3005	11.3	2720	10.2	2675	10.1	2372	8.9	2456	9.2	2153	8.1	2535	9.5	3178	12.0	3019	11.4
RefD	2566	9.0	2856	10.1	3305	11.6	3152	11.1	2736	9.6	3015	10.6	2884	10.2	2826	10.0	2739	9.7	2293	8.1
RefE	1633	6.5	1758	7.0	1386	5.5	1948	7.7	2808	11.2	3126	12.4	3062	12.2	3020	12.0	3083	12.2	3355	13.3
RefF	2433	8.2	2900	9.7	3016	10.1	2963	9.9	2745	9.2	3043	10.2	3028	10.1	3080	10.3	3206	10.7	3436	11.5

Table 28. Number and percentage of positions calculated for each sync tag co-located with each VR2W in Grimwith Reservoir. Entries shaded in green indicate a percentage of 10≤*n*≤20% of total detections over the entire study period for the individual fish in the month; yellow indicates >20%.

	Oct-14		Nov-14		Dec-14		Jan-15		Feb-15		Mar-15		Apr-15		May-15		Jun-15		Jul-15	
Tag ID	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
S01	2206	8.3	2824	10.7	2953	11.2	2702	10.2	2575	9.7	2859	10.8	2891	10.9	2910	11.0	2895	10.9	1669	6.3
S02	2424	8.1	3158	10.6	3296	11.0	3150	10.5	2737	9.1	2972	9.9	2976	9.9	3010	10.1	3045	10.2	3149	10.5
S03	2146	7.5	3046	10.6	3101	10.8	2891	10.1	2630	9.1	2949	10.3	2927	10.2	3014	10.5	2913	10.1	3146	10.9
S04	1891	7.2	2623	10.0	2744	10.5	2504	9.6	2609	10.0	2904	11.1	2864	10.9	2897	11.1	2938	11.2	2218	8.5
S05	506	2.3	513	2.4	663	3.0	1668	7.7	2750	12.6	3112	14.3	3010	13.8	3097	14.2	3145	14.4	3327	15.3
S06	2445	7.9	3320	10.8	3401	11.0	3221	10.5	2790	9.1	3109	10.1	2959	9.6	3142	10.2	3073	10.0	3349	10.9
S07	2526	8.2	3254	10.6	3296	10.7	3120	10.2	2756	9.0	3040	9.9	3074	10.0	3120	10.2	3111	10.1	3399	11.1
S08	2220	8.1	2440	8.9	2712	9.9	2513	9.2	2553	9.3	2904	10.6	2895	10.6	2899	10.6	2983	10.9	3294	12.0
S09	2181	7.6	2526	8.8	2960	10.4	3012	10.5	2665	9.3	2958	10.4	2919	10.2	3030	10.6	3050	10.7	3264	11.4
S10	1696	7.2	1953	8.3	2091	8.9	2372	10.1	2130	9.1	2298	9.8	2640	11.2	2568	10.9	2774	11.8	2999	12.8
S11	2224	7.5	2884	9.8	3107	10.5	3069	10.4	2608	8.8	3010	10.2	3042	10.3	3053	10.3	3204	10.8	3374	11.4
S12	2180	7.7	2705	9.5	2612	9.2	2860	10.1	2563	9.0	2924	10.3	2952	10.4	3006	10.6	3127	11.0	3406	12.0
S13	2049	7.2	2346	8.2	2919	10.2	3012	10.5	2540	8.9	2921	10.2	3029	10.6	3109	10.9	3228	11.3	3412	11.9
S14	1776	7.7	1801	7.8	1479	6.4	1528	6.6	2236	9.7	2418	10.5	2787	12.1	2733	11.9	2972	12.9	3257	14.2
S15	639	3.0	907	4.2	949	4.4	1840	8.5	2431	11.3	2786	12.9	2853	13.3	2890	13.4	3025	14.0	3211	14.9
S16	439	4.9	440	4.9	913	10.1	1625	18.0	1896	21.0	2004	22.2	6	0.1	800	8.9	410	4.5	498	5.5
S17	4	0.1	155	2.6	631	10.5	1152	19.2	1430	23.9	1600	26.7	335	5.6	619	10.3	56	0.9	6	0.1
S18	2367	8.9	3119	11.8	2634	10.0	1292	4.9	2371	9.0	3209	12.1	3118	11.8	3163	12.0	2750	10.4	2429	9.2
S19	1822	7.0	2671	10.2	2279	8.7	1905	7.3	2357	9.0	2500	9.6	2998	11.5	2747	10.5	3209	12.3	3618	13.9
S20	873	4.4	978	5.0	894	4.5	1075	5.5	2350	12.0	2756	14.0	2872	14.6	2479	12.6	2593	13.2	2794	14.2
S21	106	0.7	1107	7.4	1474	9.9	1214	8.2	1857	12.5	1953	13.1	2232	15.0	1822	12.2	2152	14.5	971	6.5
S22	1104	4.1	2257	8.4	2718	10.2	2670	10.0	2780	10.4	2531	9.5	3152	11.8	3133	11.7	3319	12.4	3086	11.5

Table 28 (cont). Number and percentage of positions calculated for each sync tag co-located with each VR2W in Grimwith Reservoir. Entries shaded in green indicate a percentage of 10≤*n*≤20% of total detections over the entire study period for the individual fish in the month; yellow indicates >20%.

	Oct-14		Nov-14		Dec-14		Jan-15		Feb-15		Mar-15		Apr-15		May-15		Jun-15		Jul-15	
Tag ID	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
S23	2341	9.1	3088	12.0	3564	13.8	3401	13.2	2926	11.4	3088	12.0	0	0.0	1232	4.8	2951	11.5	3142	12.2
S24	2143	9.2	2506	10.7	1704	7.3	2128	9.1	2240	9.6	2392	10.2	2499	10.7	2491	10.6	2493	10.7	2799	12.0
S25	1640	7.2	2114	9.2	2092	9.1	2809	12.3	2897	12.6	3041	13.3	3152	13.8	3033	13.2	1720	7.5	421	1.8
S26	1334	21.3	1233	19.7	1151	18.4	677	10.8	0	0	0	0	2	0.0	992	15.9	328	5.2	534	8.5
S27	2342	7.8	3144	10.4	3329	11.1	3143	10.4	2928	9.7	3199	10.6	3116	10.3	3296	10.9	3221	10.7	2397	8.0
S28	2117	7.4	2546	8.9	2682	9.4	2857	10.0	2743	9.6	3038	10.7	3020	10.6	3091	10.9	3081	10.8	3289	11.6
S29	2127	7.4	2604	9.0	2661	9.2	2783	9.6	2742	9.5	3101	10.7	3115	10.8	3145	10.9	3164	11.0	3449	11.9
S30	1902	7.2	2034	7.7	1848	7.0	2196	8.3	2751	10.4	3026	11.4	3077	11.6	3052	11.5	3175	12.0	3427	12.9
S31	1377	5.1	1813	6.8	1921	7.2	2305	8.6	2803	10.4	3251	12.1	3206	11.9	3260	12.1	3333	12.4	3581	13.3
S32	2146	11.5	2585	13.8	2515	13.4	2633	14.1	2753	14.7	2341	12.5	2795	14.9	684	3.6	275	1.5	13	0.1
S33	2569	7.9	3277	10.1	3542	10.9	3250	10.0	2928	9.0	3267	10.0	3383	10.4	3438	10.6	3622	11.1	3267	10.0
S34	1911	8.9	2726	12.8	2802	13.1	2556	12.0	2788	13.0	2548	11.9	1952	9.1	1654	7.7	1858	8.7	577	2.7

5 DISCUSSION

The investigation compared the distribution, spatial ecology and behaviour of brown trout in a reservoir and its headwater tributaries with barriers (Langsett Reservoir) with that at Grimwith Reservoir, which has no permanent barriers to fish movements into its tributaries.

5.1 Brown trout populations upstream of Langsett and Grimwith Reservoirs

Tributaries upstream of Grimwith Reservoir contained average to good 0+ brown trout populations in 2014, but 0+ brown trout densities were mainly lower in Blea Gill Beck in 2015 than 2014. 0+ brown trout densities in Gate up Gill and Grimwith Beck were higher in 2015 than 2014 at two sites. ≥1+ brown trout densities were more variable between sites and between study years with some sites showing improvements in populations and some showing declines. This reduction in fish number could be attributed to unprecedented weather conditions across the catchments of this study in the winter of December 2014 – March 2015, resulting in widespread flooding as reported by Smallwood (2016); floods interfere with red-digging (Bagliniere, 1979) and egg development (Tappel and Bjornn, 1983) and can prove fatal even to adult fish (Young *et al.* 2010). A combination of fewer spawning adults in an already sparsely populated river, and the same river containing poor substrata for egg development could explain the observed reductions in populations at some sites, but with only two years of data it is difficult to assert whether the poorer year was sub-normal or the richer year was extraordinary.

0+ and ≥1+ brown trout populations in the River Little Don were predominantly poor or fishless, with populations generally decreasing with increasing distance upstream of the reservoir. 0+ brown trout populations in Thickwoods Brook were good or average in 2014 but were predominantly fair/poor to average in 2015, while ≥1+ brown trout populations were more variable – the adverse conditions already stated may have had a deleterious effect on the populations in Grimwith Reservoir could also have elicited deleterious effects in Langsett Reservoir and its tributaries.

Importantly, in both years of the study, in both of the tributaries of Langsett Reservoir the observed populations of 0+ and >0+ (<20 cm) brown trout were lower, and in many cases significantly lower, than predicted from the habitat present in the reaches. This indicates that the habitat could support a higher population than it currently does and, as such, causes of, and remedies to, this paucity of fish ought to be explored. These lower than expected population levels were found by Olsson and Greenberg (2004) to dissuade resident brown trout from migrating downstream due to plentiful food and habitat availability. Back-calculated growth of brown trout in the River Little Don was higher than conspecifics in all of the Grimwith tributaries, which all had denser populations than the River Little Don, possibly supporting Olsson and Greenberg's findings.

This possible promotion of residency of large fish could also be linked to further pressures on the population – such as dominance in the system of large piscivorous brown trout, which predate upon juveniles; this was noted by Kennedy and Fitzmaurice (1971), albeit in lakes. It was observed upstream of the weir in the River Little Don in the second year of this study, the largest brown trout caught in either year of the study (over 450 mm) was scanned with the PIT reader and two PIT-tags were detected. Upon further investigation, the codes corresponded with those of two 0+ brown trout tagged the previous year. The large fish had eaten the two smaller fish.

Growth rates of brown trout were predominately average to fast in tributaries of Langsett and Grimwith Reservoirs and the reservoirs themselves, suggesting good food resources and/or low levels of competition for food and habitat, agreeing with Olsson and Greenberg (2004) and Lobón-Cerviá (2009).

Overall it was not possible to determine for certain if the lower than expected trout densities upstream of Langsett Reservoir were caused by the presence of the weirs (Section 5.2), but there is potential to improve the upstream fish populations associated with Langsett Reservoir. At the very least even if the weirs were to be shown not to negatively affect the brown trout populations then further investigation into the weirs need not be pursued and alternative causes investigated and mitigated. Whether it be poor spawning habitat (although Smallwood (2016) judged the gravels and riffles to be sufficient in the River Little Don for brown trout spawning), or over-predation of juveniles by large resident piscivorous brown trout (such as the individual caught in 2015), which could be selectively removed, perhaps even translocated to the reservoir.

5.2 Movement of brown trout between reservoirs and their tributaries

Longitudinal movements (including direction) of PIT-tagged brown trout were investigated at the mouth of the tributaries entering Langsett and Grimwith (control) Reservoirs using fixed-location telemetry (results between October 2014 and January 2016 included in this thesis). The age and size of brown trout that moved, the timing of movements related to flow and temperature and the possible impact (e.g. complete blockage) weirs had on brown trout movements were all considered.

5.2.1 *Downstream movements of brown trout from tributaries towards reservoirs*

In 2014, approximately one quarter (24, 24 and 26%) of the brown trout PIT-tagged in tributaries were detected by PIT antennae moving downstream towards Grimwith Reservoir across a wide range of flows, including some of the lowest flows recorded during the study. A comparable proportion (30%) of the brown trout PIT-tagged upstream of the weir in the River Little Don were detected upstream of the study weir, but only a third these (n = 5) were detected on the antenna downstream of the weir. So it is possible that the weir impeded 66% of brown trout moving downstream from entering Langsett Reservoir; if so, this would correlate with the findings of Aarestrup and Koed (2003), that some smolts abandoned their downstream migration in the presence of weirs (that had a barrier effect). Although, this movement possibly could be coincidental, or the fish may not have attempted to surpass the barrier.

Craig (1982) found that brown trout in the tributaries of Windermere, UK, migrate downstream in their first to third years, and thereafter remain river-resident. If the same happens in the River Little Don, migration up to year three and residency afterwards, then this could further explain residency levels upstream of the barrier, annual efforts being thwarted (66% non-completion of barrier passage) perhaps leading to migration abandonment. Jonsson *et al.* (1999) also found the majority of brown trout migrating downstream into Lake Femund, Norway, being two or three years old, although individuals as old as eight were recorded moving downstream in small number. The was a similarity between the River Little Don and Grimwith tributaries in terms of number of migratory attempts which suggests that they are appropriately comparable in this regard, and this should be borne in mind for future study. Only two (4%) of the PIT-tagged brown trout in Thickwoods Brook were detected upstream of the weir and both were detected downstream of the weir, i.e. they entered Langsett Reservoir – when the reservoir is full the level rises approximately hallway up the weir, so there is no riverine habitat, any fish downstream of that weir is reservoir-resident.

Fewer fish were detected in 2015 than in 2014 despite there being more PIT-tagged brown trout in each study system (assuming that the the previous year's tagged cohort were still alive, with working tags, and still inhabiting the system – this was evidenced by small numbers of recaptured fish). In the River Little Don and Thickwoods Brook, one fish from the 2014 tagging cohort was detected in 2015, on the antenna upstream of the weir and subsequently on the downstream antenna, i.e. the weir did not permanently impede either of these brown trout moving downstream into the reservoir, although it may have caused a delay. Of the 2015 tagged cohort four fish originating upstream of each upstream antenna were detected on the upstream antenna; one of each of these four was subsequently detected on the antenna downstream of the weir. The weirs possibly prevented 75% of the tagged fish migrating downstream, although the sample sizes were too small to conclude with great conifidence. Those that moved were larger than those that were resident, suggesting that the downstream migrations may have been an active choice or that the opportunities available upstream of the weir were insufficient.

Fish moving downstream at Grimwith were very similar in size to those that did not move suggesting factors other than size are possibly more prevalent in driving the behaviours in this system, thereby contradicting findings of Kalleberg (1958) and LeCren (1973). A similar percentage of downstream-moving PIT-tagged brown trout were detected at Grimwith in 2014 (21 – 26%) and 2015 (24 – 26%), this could perhaps be tentatively considered the baseline proportion of fish detected moving downstream, and firmly considered so if it was confirmed in further years.

Downstream movements over the weir on the River Little Don occurred only during periods of elevated flow. The downstream movements generally occurred during autumn and spring, as was reported by Jonsson and Jonsson (2002) and Carlsson *et al.* (2004). The movements may be due to juveniles moving downstream as part of density-dependent dispersal strategies coupled with downstream displacement of juveniles during high flows (a combination of that which has been demonstrated by Landergren (2004) and observed by Ottoway and Clarke (1981)). However, density-dependent dispersal is unlikely as HABSCORE revealed brown trout densities in The River Little Don were lower or significantly lower than predicted and there were locations for brown trout to seek refuge during elevated flows – these circumstances do not fit into Landergren’s or Ottoway and Clarke’s scenario and indicate that the processes involved are highly complex and more investigation must be conducted to understand them.

Furthermore, downstream brown trout movements in Grimwith Reservoir tributaries occurred across a wide range of flows, although over 90% occurred at Q75; a small portion occurred at extremely low flows between Q75-Q100. Brown trout in the River Little Don did not move downstream in February – April during flows of similar or greater magnitude to those that did elsewhere, possibly, the weir is the variable in this instance that prevents them from migrating downstream. In that flows that are sufficient to trigger downstream movements in unobstructed rivers may not be sufficient enough in the River Little Don, or perhaps obstructed weirs generally.

It is concluded that it is most likely that brown trout perform active downstream migration rather than displacement, passive drift or washout, i.e. brown trout move downstream in autumn to seek refuge in deeper water during winter and in spring to access food resources in the summer (similar to the findings of Stuart (1957), Lien (1979) and Jonsson and Jonsson (2011). Indeed, brown trout inhabiting both Grimwith and Langsett Reservoirs experienced first year growth comparable to those that were resident in the streams upstream of the weirs, which could possibly mean that they are from those areas upstream of the weir and are migrants. They experienced increased growth rates after the first year of life compared with those spending multiple years in upstream tributaries – corroborating Frost and Brown (1967). This suggests that brown trout in the reservoir originated from the upstream tributaries and moved downstream after their first summer, agreeing with Craig (1982) and Jonsson et *al*. (1999).

5.2.2 *Upstream movements of brown trout from reservoirs into tributaries*

A dichotomy in upstream brown trout movements from reservoirs into tributaries was found. In Grimwith Reservoir, where brown trout were free to move into two of the tributaries year-round, very few brown trout PIT-tagged in the reservoir were detected entering either Blea Gill Beck, Gate Up Gill or Grimwith Beck (the weir on this tributary is passable by fish when the reservoir is full). By contrast, in Langsett Reservoir, a far larger proportion of brown trout PIT-tagged in the reservoir were detected downstream of weirs in the River Little Don and Thickwoods Brook, but none were detected on PIT antennae upstream. Possibly brown trout were detected less successfully in the tributaries of Grimwith Reservoir than those of Langsett Reservoir, but this seems unlikely as all three sets of PIT loops in this system seemed to be affected by conditions to a similar extent to those in Langsett Reservoir. Most likely was that the tagged brown trout simply did not move into the tributaries there, possibly spawning in the reservoir (as has been reported by Frost and Brown (1967), Klemetsen (1967), Scott and Irvine (2000), Sneider (2000), Brabrand *et al.* (2002), Louhi *et al.* (2008) and Jonsson and Jonsson (2011)) or using the areas of tributary downstream of the most downstream loop (if the monitoring equipment was moved further downstream it would be at high risk of inundation during high flows and when the reservoir was full). The conditions outlined by Brabrand *et al.* (2002; 2006) conceivably present in Grimwith Reservoir, so a lake-spawning theory may be viable, as could one that states that the fish . This necessitates further investigation to see if it is the case. It could also be investigated at Langsett Reservoir to better understand the population downstream of the weirs.

Brown trout detections downstream of the weirs on the tributaries to Langsett Reservoir were almost exclusively during periods of elevated flow between October and January, and thus were probably during an upstream spawning migration (Piecuch *et al.* 2007; Jonsson and Jonsson, 2011). Such disruption to spawning migrations can cause loss of fitness due to repeated attempts to pass impoundments, or increased time spent in suboptimal conditions where the bottleneck occurs (Aarestrup and Jensen, 1998; Gerlier and Roche, 1998). They may also be subject to increased predation pressures if the bottleneck is exposed or predators exploit the weir as a vantage point (Garcia de Leaniz, 2008) or even have to settle for less favourable spawning areas, which may lead to higher egg mortality (Battin, 2004; Thaulow *et al*. 2014). All of these compromise reproductive success and survival. This is doubly deleterious for spawning populations because these spawning fish may either waste their gametes and/or die, when they would have otherwise not done, and, as such, the population also does not benefit from subsequent years that they could have spawned.

The findings in this study, that brown trout migrate upstream to spawn, are concurrent with numerous other reports that brown trout perform spawning movements when flow is increased (Young *et al.* 1997; 2010, Jonsson and Jonsson, 2011), though Carlsson *et al.* (2004) also found immature trout in the migratory population, so spawning may not be the sole driver.

The brown trout populations in the headwater tributaries on Langsett Reservoir hence appear to be upstream of insurmountable barriers and must be sustained by brown trout that do not move downstream over the weirs. Those that do move downstream are likely eliminated from the gene pool of their natal population as they appear to be unable to re-ascend the weir into the River Little Don or Thickwoods Brook. Further, if brown trout cannot spawn in the reservoir itself they ultimately do not contribute to the next generation of brown trout in Langsett Reservoir; Smallwood (2016) noted that the area downstream of the weir on the River Little Don was probably unsuitable for spawning, due to poor spawning-substrata and limited space – so lake spawning (or zero spawning) would appear to be the only options for this below-weir population. Potentially, as a result of this possible isolation, the population could be fragmenting. Due to genes only moving downstream over the weir, genetic diversity is only conserved in that area. The population that remains upstream of the weir will be ever decreasing in genetic variety and, as such, could become vulnerable to inbreeding depression and/or disease.

Most brown trout detected on the antenna downstream of the weir on Thickwoods Brook were also detected on the antenna downstream of the weir on the River Little Don, and this was not the case *vice versa*. This is further evidence that the River Little Don should be prioritised for weir remediation work, given that a higher proportion of brown trout enter this tributary than Thickwoods Brook and, as such, the catchment would probably be improved more with this approach than with the same remediation measures on the weir on Thickwoods Brook. Another reason for this difference could be that the River Little Don is a much larger river than Thickwoods Brook, and the weir on it is also larger than that on Thickwoods Brook, thereby the attraction flow (Arnekleiv and Kraabol, 1996) resulting from water cascading down the weir may be more enticing than that on Thickwoods Brook.

5.3 Movement of brown trout and habitat use in Grimwith Reservoir

Some acoustic tagged brown trout in Grimwith Reservoir occupied a very small home range while others were highly mobile. Schulz and Berg (1992) found similar – that movements in lakes could be divided into two groups i) local movements within a realtively small area and ii) long excursions). Almost all fish exclusively occupied the littoral zone in Grimwith Reservoir, in contrast to the observation of Frost and Brown (1967) that larger adult fish spent all of their time in deeper waters. However this may be the result of not being able to capture any fish from the deeper, central areas of the reservoir for tagging. The behaviour of acoustic tagged fish in Grimwith Reservoir did correlate with the findings of Nettles (1983), who stated that brown trout prefer to be as near to the shore as possible. However, the fish used in this study were all caught in the shallow margins, and there could be larger fish occupying deeper areas, so there may have been some bias in the sample. Further work should therefore be undertaken to expand the sample size and employ varied methods and locations of capture.

Acoustic tagged brown trout did not seem to spend any time near the presumed spawning tributaries of Grimwith Reservoir, which was contrary to the findings of Nettles *et al*. (1987) on Lake Ontario, Canada, who reported a predilection for areas near spawning tributaries and a power plant effluent, possibly due to the in-washing of nutrients and warmer water. It is possible that the needs of the brown trout in Grimwith Reservoir are met without having to employ the feeding behaviours Nettles *et al*. noticed i.e. moving great distances and showing large temporal variability.

Variability brown trout behaviour was observed between months and between individuals. Temporal differences in usage of the reservoir were also found, with fish occupying larger home ranges in April, June and July, perhaps related to feeding behaviour or refuge from warmer water temperatures (Young *et al.* 2010); the implications of this are that for this period the brown trout are not occupying their previous small home ranges, if this is the case then the fish would be having to expend more energy to produce the same results (i.e. food capture) as in other months; this could cause a loss of fitness and make them more vulnerable to disease and death, or at least result in reduced growth as energy is used for feeding (a priority).

Only two acoustic tagged brown trout made movements towards the tributaries, meaning that spawning in the rivers was not likely for the remainder. These fish may well have spawned in the lake, or perhaps they did not spawn at all. Stuart (1953) described a population where 51% did not spawn in a particular year – if lake spawning is not occurring in Grimwith Reservoir then it is possible that 90% of brown trout tagged in Grimwith Reservoir did not spawn. If this is evidence of staggered years of spawning though, it could indicate a level of robustness in the population due to multiple years of complete recruitment failure, and greatly restricted migration from upstream rivers, required to render this population extinct (Lobón-Cerviá and Rincon, 2004). Other studies identified that lake spawning populations of brown trout exist (Brabrand *et al.* 2002, 2006; Thaulow *et al.* 2014 – performed egg searches (Brabrand) and genetic analysis of juveniles (Thaulow) near areas of freshwater upwelling, a crucial requirement for lake-spawning to occur). In theory, this could be happening at Grimwith Reservoir and further studies could attempt to establish this by performing detailed analysis of brown trout tracks at Grimwith Reservoir during the spawning period, analysis of substrata and areas of upwelling in the reservoir using backscatter, and/or performing genetic analysis of prevailing brown trout populations using scales from brown trout already captured.

Some fish were positioned extremely inconsistently and at very low number during this investigation, which could have implications for the strength of the data and, as such, the strength of the conclusions. The tag-drag and information from VEMCO indicate that areas near to shore were insufficiently covered by the array to accumulate many verified positions. For acoustic tags to be reliable detected they need to be inside the array, and, as such, inside triangles (preferably multiple triangles) of receivers. It is therefore possible that fish that were extremely rarely positioned spent much of their time in the littoral areas extremely close to the shore, outside of the array's coverage – if so, the conclusions drawn about habitat use being predominantly nearshore can still be considered valid.

5.4 Mechanisms for improving fish populations upstream of weirs in Langsett Reservoir

Langsett Reservoir offers the best habitat for brown trout in that system in terms of fish growth; growth rates are higher in the reservoir than either of its tributaries. However, the tributaries offer the best spawning habitat, and it is possible that all fish in the reservoir originally resided in the streams upstream of the weirs. As a result, remediation could prove beneficial for the population of brown trout in the system.

Prior to undertaking any remediation work, an acoustic telemetry investigation that triangulates the 2D location of tagged brown trout should be performed at Langsett Reservoir (Section 5.5), as carried out at Grimwith Reservoir. Such an approach would allow a better understanding of the behaviour and habitat use of brown trout in the reservoir prior to compensatory measures being implemented; special focus should be paid to movements during the spawning period, as understanding spawning behaviour of these fish will inform remediation. It would also enable comparison between a population that does not seem to utilise rivers for spawning (Grimwith Reservoir) and one that does (Langsett Reservoir), as suggested by the PIT telemetry component of the investigation. If possible, the investigation should span the spawning period in the years before and after remediation, thus enabling the behaviour and habitat use of the same brown trout to be studied, if remediation work is implemented within a timeframe that would permit this. This data may permit deeper insight into how the remediation measures have affected individual fish, that less-specific studies may not be able to address.

5.4.1 *Fish pass or weir removal*

Fish pass facilities permit both upstream and downstream migrations. Fish pass designs generally fall into one of two categories: 'nature-like' and 'technical'. Both designs intend to allow fish passage whilst minimising delay, but they differ in their approach. Nature-like bypasses are being tested for effectiveness for various species and are the more frequently used of the two types (Jungwirth 1996; Calles and Greenberg 2005; Larinier 2008). Whereas technical bypasses are generally more species and purpose specific, nature-like bypasses rely on creating a pseudo-natural river channel alongside obstructions for its use by a variety of species for both passage and inhabitation (Calles and Greenberg, 2005). In terms of morphology, bypass channels are designed to mimic natural streams (Parasiewicz *et al.* 2009). The ability of fish to be able to find the entrance of fish passes is influenced by the "attraction flow" (Gustavsson *et al.* 2011; Williams *et al.* 2012; Katopodis *et al.* 2001; Wassvik 2006). Logically, it has been highlighted that the ease with which fish are able to locate fish passes, i.e. by detecting the attraction flow, is one of the most important factors to consider with all types of fish pass (Clay 1961; Katopodis 2005; Parasiewicz *et al.* 2009; Roscoe and Hinch 2010; Noonan *et al.* 2012).

Improvements to fish passage at the weir on the River Little Don could allow an increase in the adult trout population upstream of the weir during spawning periods, and thus potentially lead to increased recruitment. Habitat assessments suggest that the spawning areas are suitable to support brown trout egg development and fry emergence, and are comparable to or better than those on the nearby River Loxley, Yorkshire, UK, which supports higher densities of brown trout (Smallwood, 2016).

The weirs on the River Little Don and Thickwoods Brook could either be removed or equipped with fish passes. Prioritisation should be afforded to the River Little Don, given its larger size and poorer fish populations, and thus the likelihood of greater benefit compared with performing remediation to the weir on Thickwoods Brook. There is more of a fish deficit per 100 m^2 in the River Little Don and far more river habitat in which newly migrant fish could spawn and, in which, their progeny could inhabit. Restoring connectivity in this river would permit upstream movement up to a further twenty km (subject to a small weir 2 km upstream of the main weir concerned, that was historically used to divert water to a sheep-dip pool, but is currently in a state of disrepair).

It is recommended that a nature-like fish pass is built onto the weir rather than removing the weir as it has historical heritage value and, upon removal, the release of chemicals in the sediment could be deleterious to aquatic life lower in the system – albeit this is a minor concern in such an upland river. The fish pass design must ensure effective fish passage across the full range of flows when brown trout are likely to approach the weir. The brown trout detected immediately downstream of weirs on Langsett tributaries were significantly larger than undetected brown trout. Notwithstanding this, the brown trout that approached the weirs ranged from a fork length of 150-450 mm, and thus the fish pass should be effective at allowing passage for this size range of brown trout as a minimum. Larger trout are more fecund than smaller trout and as such hold more reproductive value, so if a priority of size must be made, it should be concentrated on larger individuals. Fish of varying sizes were also detected moving downstream throughout the year. Hence, should a fish pass be built, it ought to permit downstream movements, across all flows, for all age/size classes of brown trout that inhabit Langsett Reservoir tributaries, as well as those movements. If a fish pass is installed, the approach, attraction, entrance, exit and passage efficiencies should be investigated for fish moving in both upstream and downstream directions to assess its operational effectiveness and inform future designs.

Fish passage designs are many and varied. The aim of their installation is to reduce the chances of the isolation or fragmentation of populations or alleviate those which have already been isolated or fragmented. Additionally they should also assist fish that make obligatory migrations, sometimes for spawning, to complete said migrations. Fish passes allow passage over/around structures that have elicited negative effects and obstructions upon fish communities (Lucas and Baras, 2000).

5.4.2 *“Trap-and-transport” investigation*

An option for remediating some of the impacts of the weirs upstream of Langsett Reservoir without removing the weirs or constructing fish passes is to trap brown trout downstream of the weirs and transport them upstream, thus potentially increasing numbers of spawning adults in the fish-poor reaches upstream of the weir(s). This is a less preferable option than installing fish passages, due to its temporary nature.

PIT-tagged fish from Langsett Reservoir approached the weirs almost exclusively between October and December, predominately during periods of elevated flow and darkness, and were significantly larger than undetected fish. Brown trout capture should, therefore, occur between October and December, and large fish should be targeted. Ideally, the feasibility of using fyke nets and electric fishing to capture adult brown trout between October and December, should be investigated further. Such an investigation should also determine the timing, duration and extent of upstream migration for those that remain. One of the following may be discovered:

- Brown trout captured only early in the migration window will have sufficient time prior to spawning to become acclimated to the river before resuming their migration. Although this would probably only be necessary if the habitats upstream and downstream of the barrier were unalike.
- Conversely, it may be advantageous to capture fish later in the migration window to increase the likelihood of translocating migratory fish that are undertaking upstream movements to spawn. For instance if fish were demonstrated to assemble downstream of the barrier and wait, it could be most efficient to transport them up in one window to maximise spawning events.

"Trap-and-transport" was adopted by Schmetterling (2003) who found that most of the 42 cutthroat trout (*Oncorhynchus clarki lewisi* Richardson, 1836) and bull trout (*Salvelinus confluentus* Suckley, 1859) transported around Milltown Dam, Montana, continued upstream to spawn, and many migrations exceeded 100 km. Caudron *et al.* (2012) found that brown trout translocated upstream of an impassable barrier increased upstream densities by a factor of 50 or more in three years. DeHanan and Bernall (2013) trapped and transported bull trout too and reported that 27% of bull trout juveniles sampled had at least one parent that had been transported upstream.

5.4.3 *Stocking the river*

In this instance, stocking the river has been discounted as a means of improving the brown trout population due to stocked fish being triploid and, therefore, infertile. In addition they may increase a density-dependent mortality or drive fish that would have been river-resident and contributors to the spawning population downstream into Langsett Reservoir (Bohlin *et al.* 2002; Hansen, 2002; Hansen *et al.* 2009) and, as such, out of the spawning stock.

5.5 Recommendations for further research

This study has shown that the fish populations in Langsett Reservoir and its tributaries are fragmented and potentially isolated by weirs and fish densities are substantially lower than what may be reasonably expected in rivers of their characteristics, and, as such, there is a need for remediation.

5.5.1 *Future monitoring*

Should remediation work upstream of Langsett Reservoir be carried out, brown trout in each tributary (the River Little Don and Thickwoods Brook) should be PIT-tagged to assess upstream and downstream movements and subsequent return using fixed-location PIT telemetry. PIT loops should be installed immediately upstream and downstream, or even in, any fish pass facilities installed. Only if "Trap-and-transport" is employed a sample of the translocated fish should be radio tagged to assess and understand how far they progress upstream, (this would inform future population surveys (in that areas further upstream may need to be surveyed) and potentially allow re-colonisation to be mapped. It may also be possible to deduce spawning locations from these data. If these data do yield information on spawning locations, redd counts could be conducted, as could hatching dispersal monitoring. Redd counts and dispersal monitoring should also be carried out prior to remediation to provide a baseline.

Subsequently, electric fishing and habitat surveys could be conducted for multiple years post-remediation with data yielded by this study used as a baseline, to monitor the continued effect of improved longitudinal connectivity and how the fish population changes as a result. This could also inform future remediation efforts at other locations.

Fish in any acoustic study should also be PIT-tagged so that monitoring of their behaviour *ex*-array can be discerned. Considerable periods of time out of the array were observed in the acoustically tagged fish in Grimwith Reservoir, but no further information could be collected. However if they had been PIT-tagged too, and they entered tributaries, they would be detected by PIT loops and, as such, some of this paucity of information would be elucidated.

Further analysis could be devoted to understanding the minutiae of the acoustic detections. A tag's ping must be detected on three acoustic receivers to be triangulated, but if it was detected on two or just one receiver then that would provide some information on the approximate location of that fish.

5.5.2 *Genetic analysis*

It is recommended that DNA is extracted from scales already collected and stored from brown trout in Grimwith and Langsett Reservoirs and upstream tributaries, and from scales or fin-clips of any caught in the future, to:

- Determine whether the populations in the reservoirs are self-recruiting. If the populations in the reservoir are genetically distinct from those in the tributaries, it could indicate this.
- Estimate the impact of the weirs on possible asymmetric gene flow and its consequences, i.e. identify if populations in the tributaries are genetically distinct, and, if so, identify natal tributary of reservoir trout.
- Relate the findings to movements of tagged individuals, e.g. identify if brown trout return to their natal stream to spawn (Morán *et al*. 1995; Skaala and Solberg, 1997; Laikre, 1999).

The focus should be on Langsett Reservoir but Grimwith Reservoir and its tributaries should be included because this will provide the opportunity to investigate a brown trout population that has an almost unobstructed connection between the reservoir and its tributaries. Further strength could be added through temporal repetition, continuing this study for more time (multiple years), additionally this could identify any changes in populations in the reservoirs and their tributaries that may occur over time.

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APPENDIX 1. LENGTH FREQUENCY DISTRIBUTIONS 2014

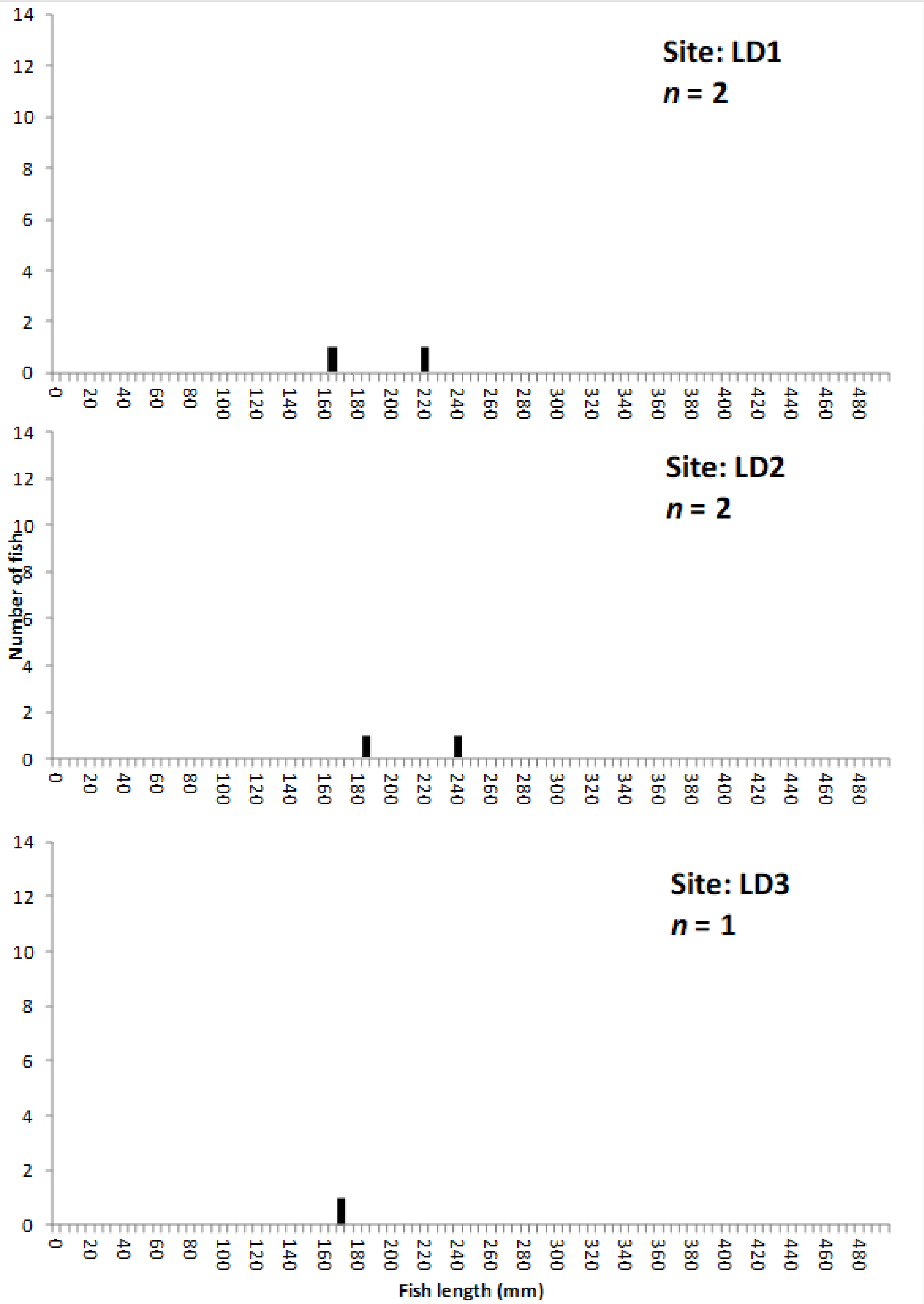


Figure 24. Length frequency histograms of brown trout caught at the River Little Don sites LD1, LD2 and LD3.

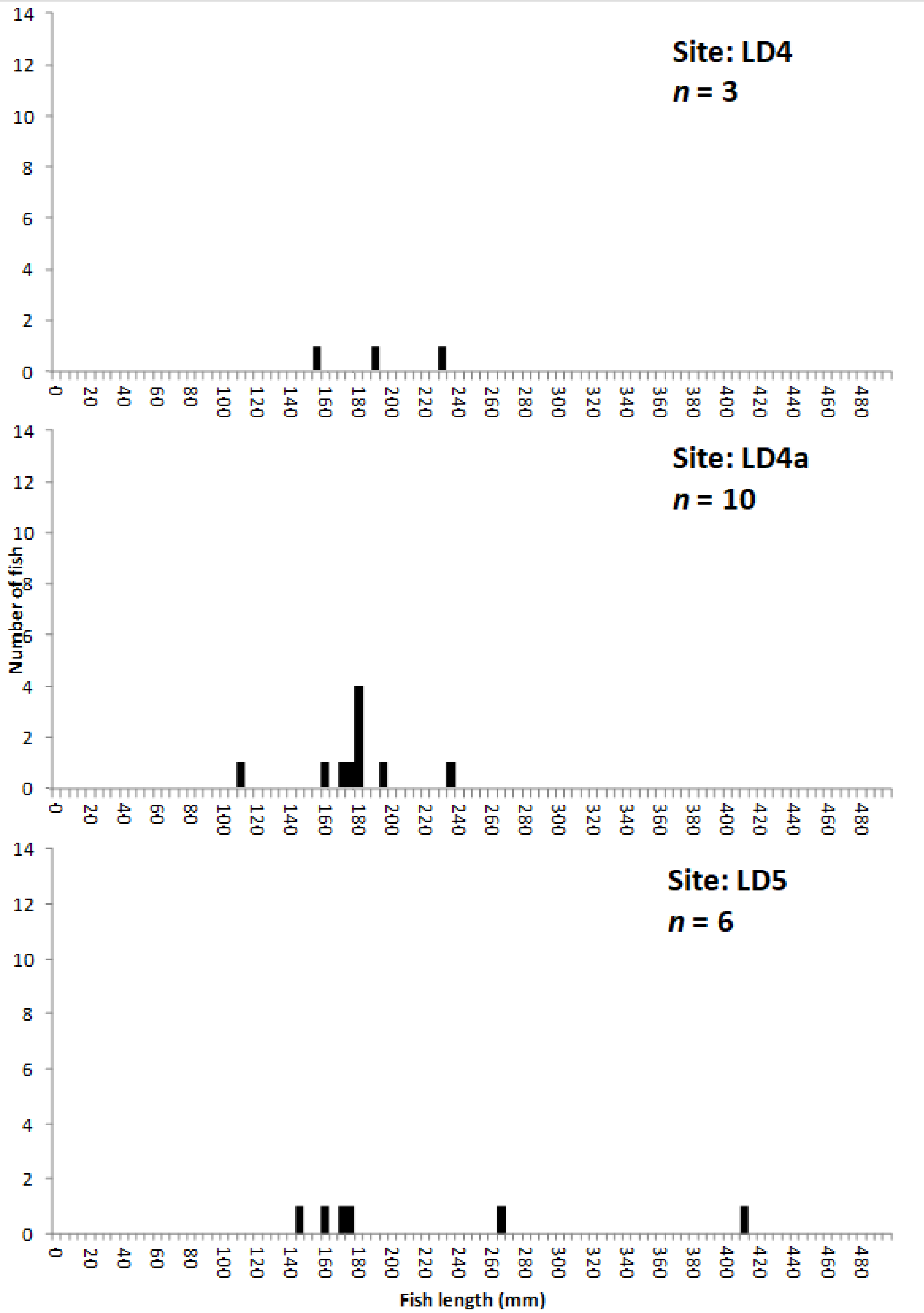


Figure 25. Length frequency histograms of brown trout caught at the River Little Don sites LD4, LD4a and LD5.

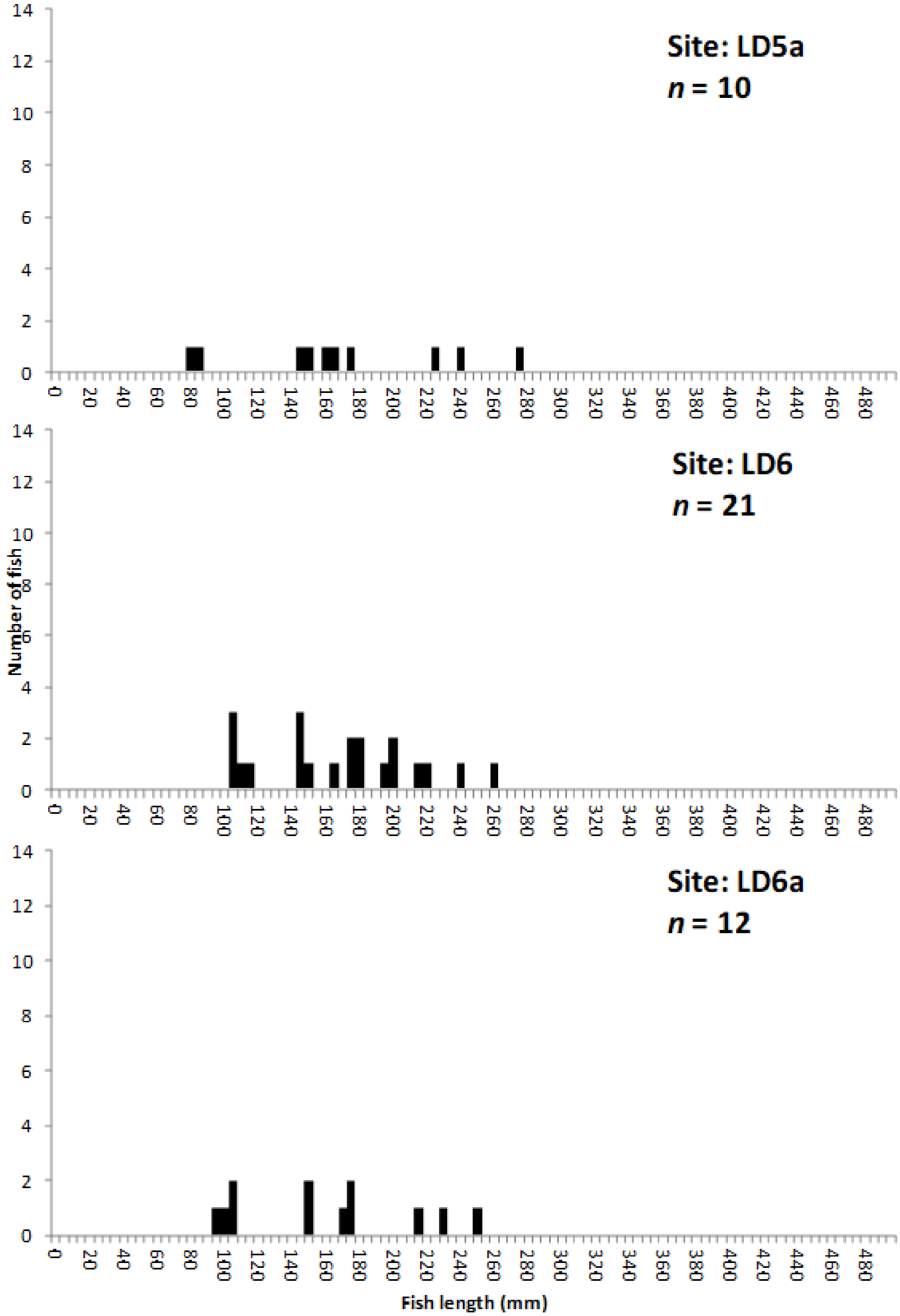


Figure 26. Length frequency histograms of brown trout caught at the River Little Don sites LD5a, LD6 and LD6a.

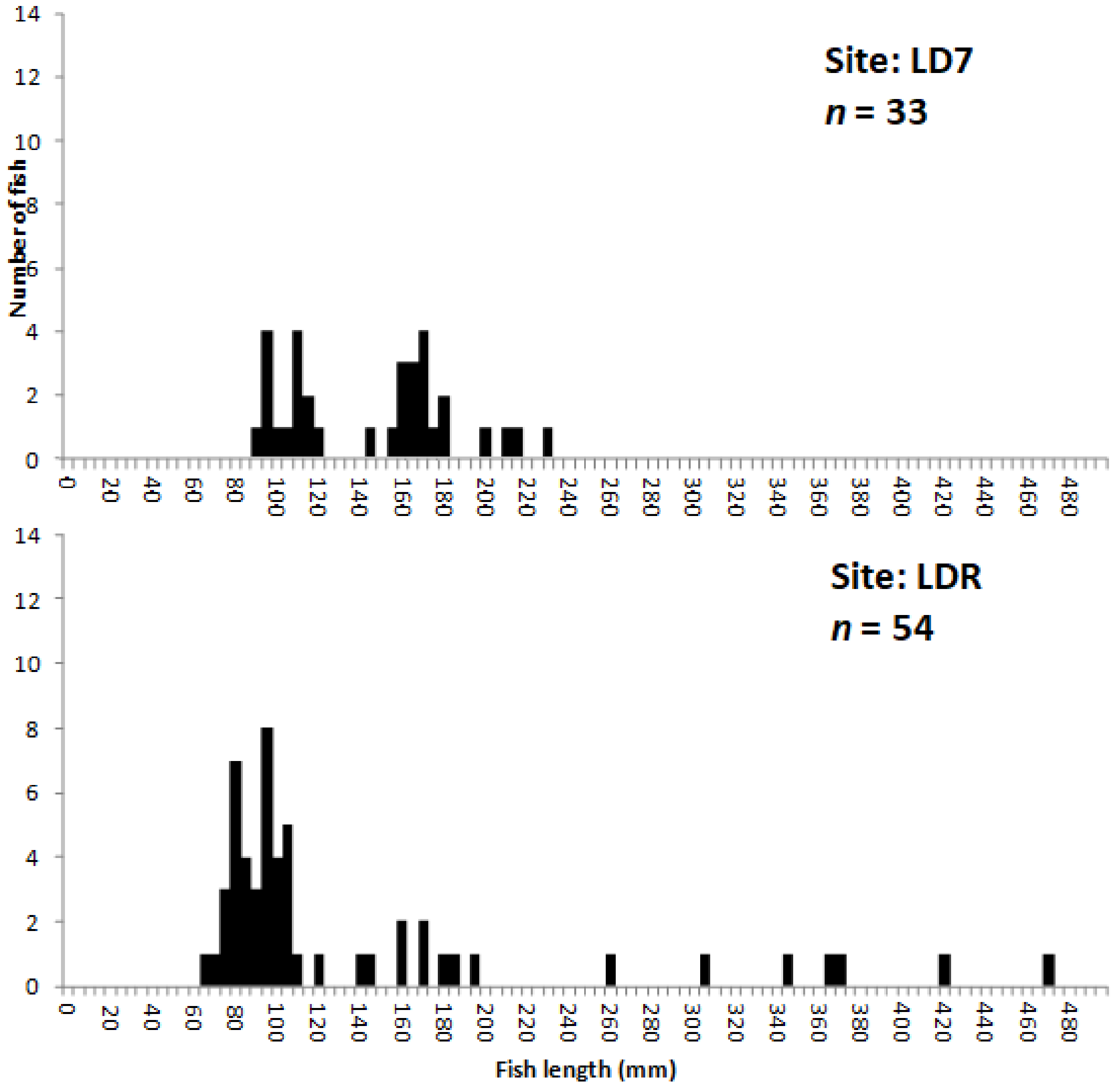


Figure 27. Length frequency histograms of brown trout caught at the River Little Don sites LD7 and LDR.

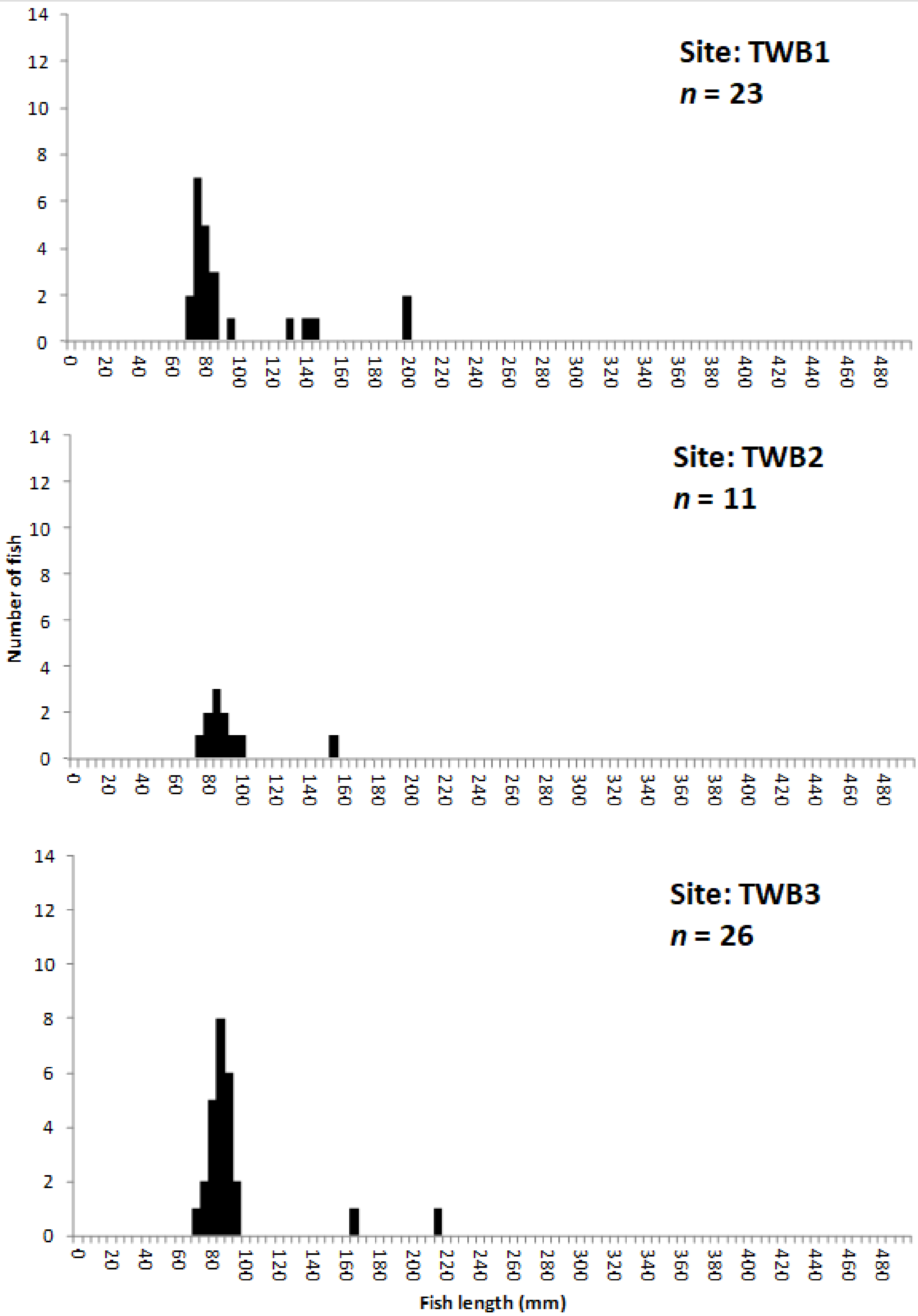


Figure 28. Length frequency histograms of brown trout caught at Thickwoods Brook sites TWB1, TWB2 and TWB3.

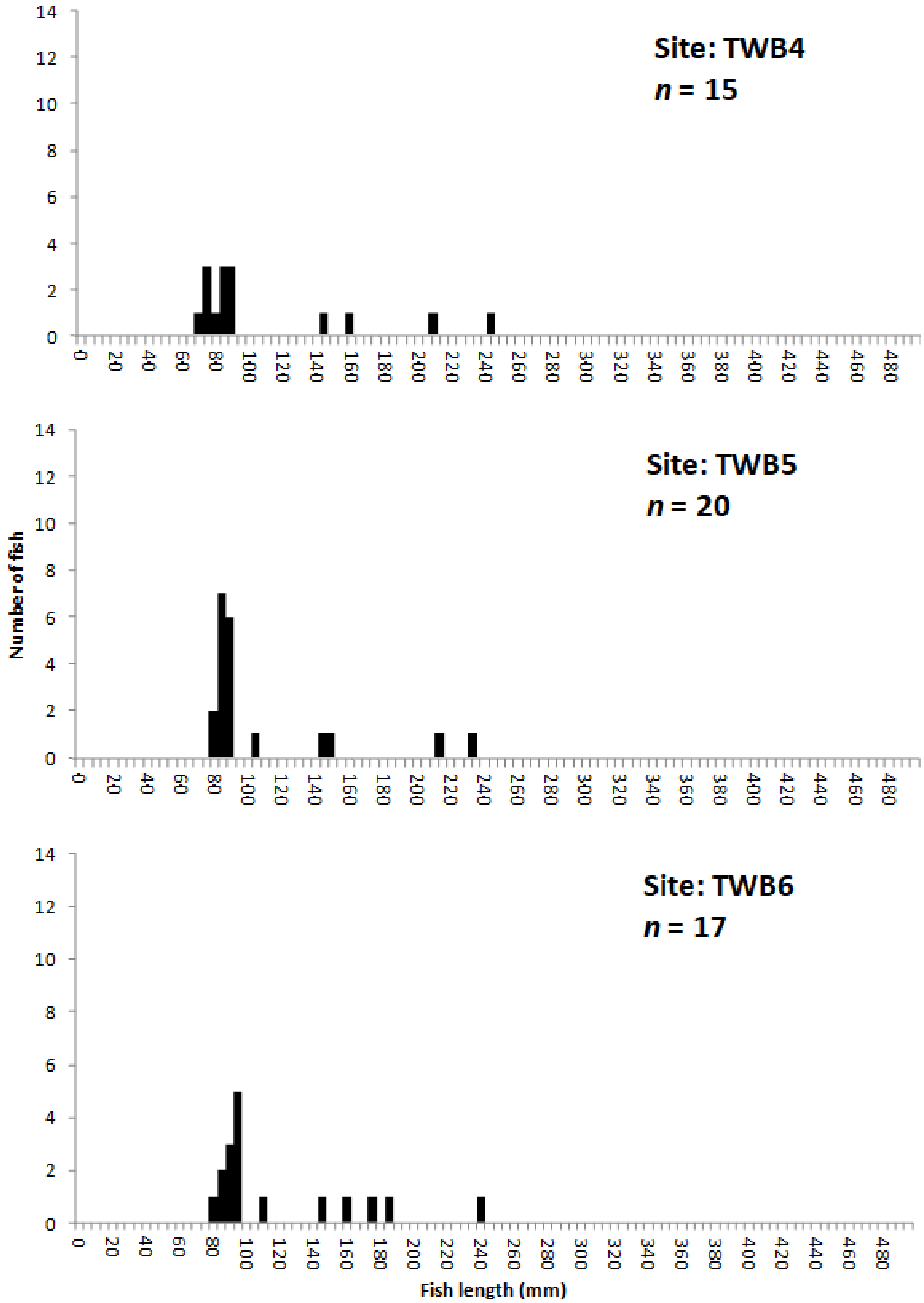


Figure 29. Length frequency histograms of brown trout caught at Thickwoods Brook sites TWB4, TWB5 and TWB6.

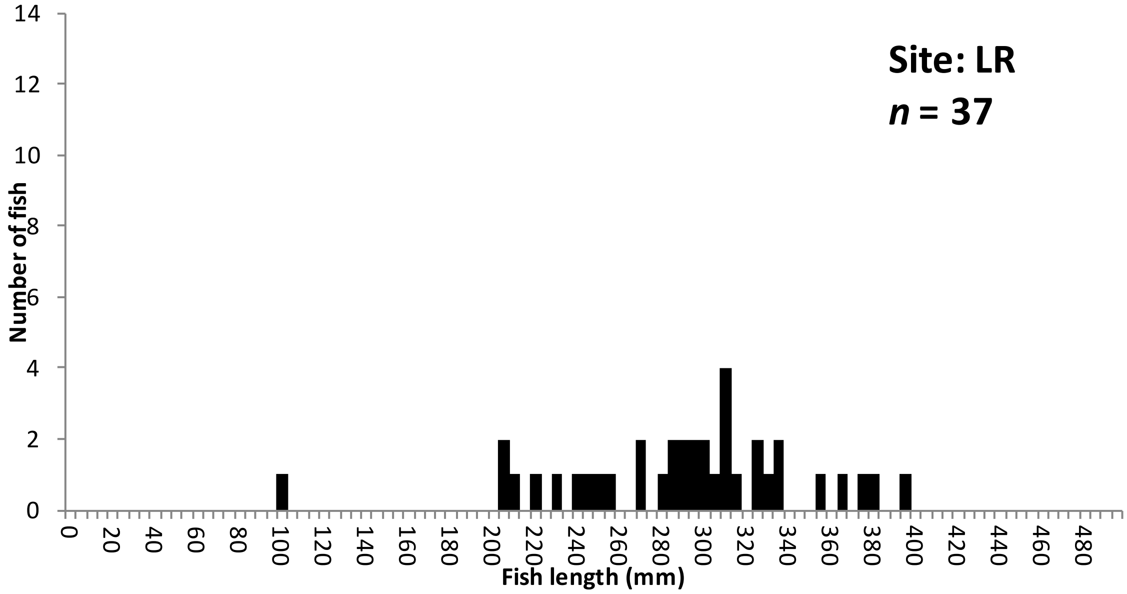


Figure 30. Length frequency histogram of brown trout caught in Langsett Reservoir.

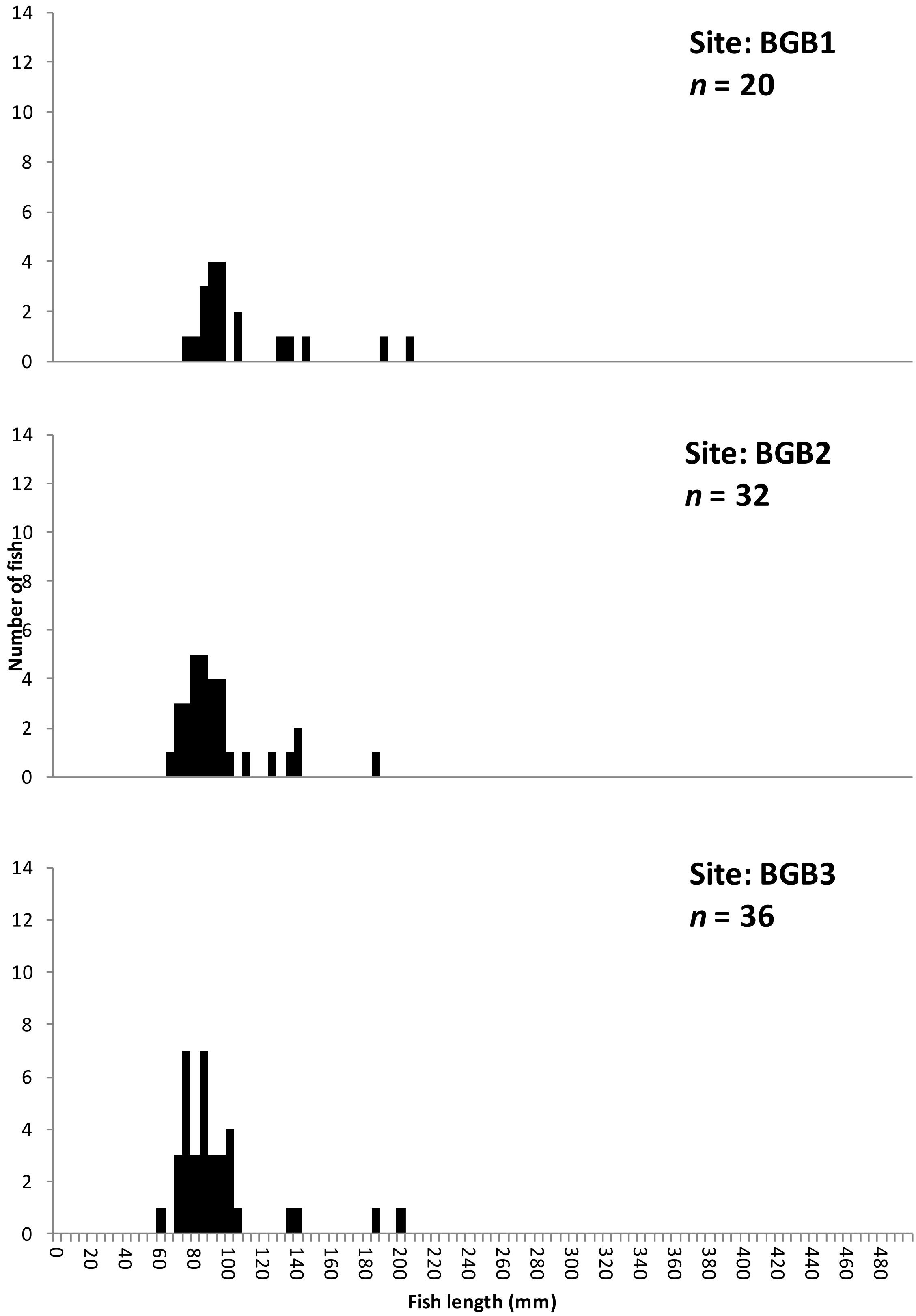


Figure 31. Length frequency histograms of brown trout caught on Blea Gill Beck.

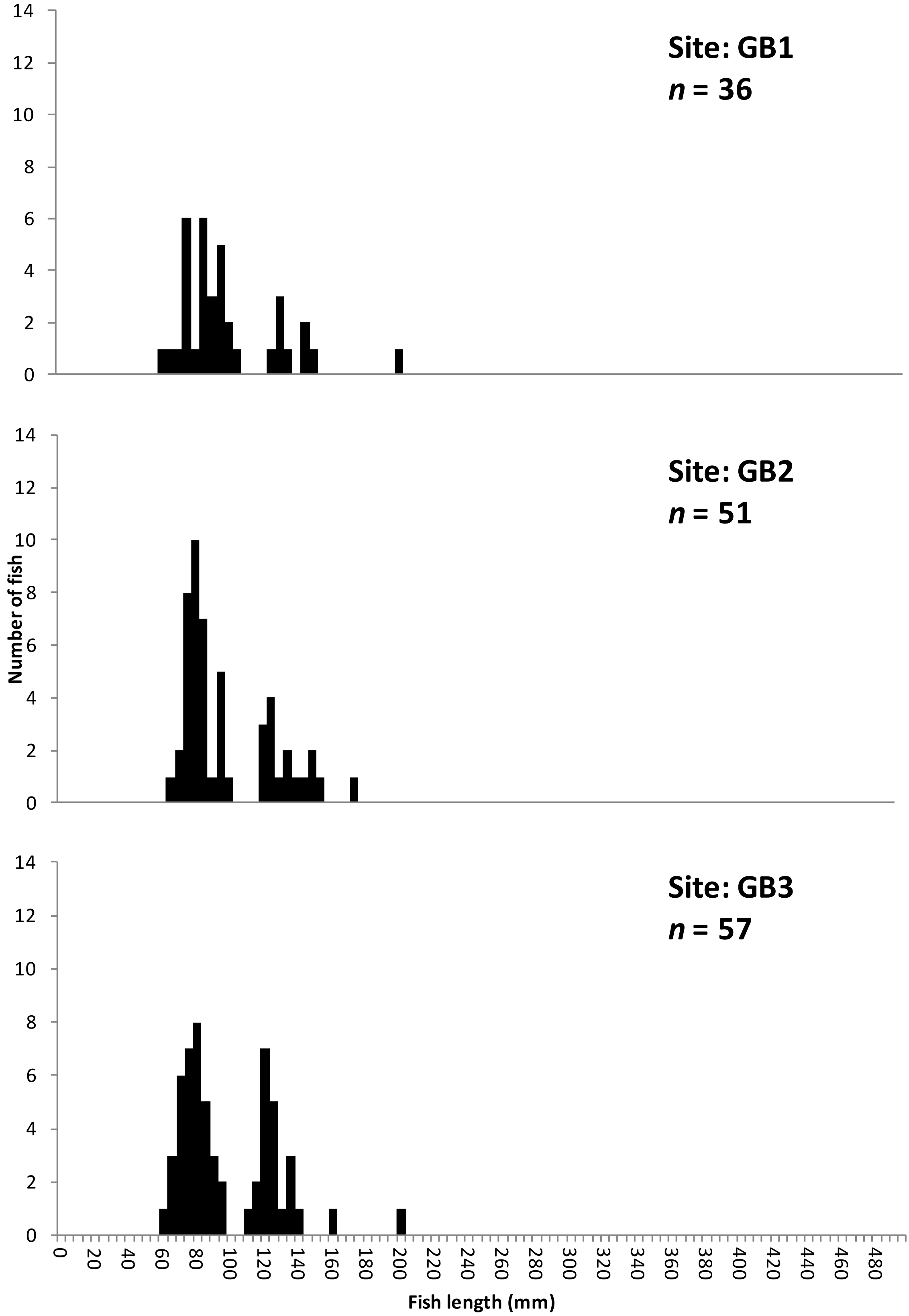


Figure 32. Length frequency histograms of brown trout caught on Grimwith Beck.

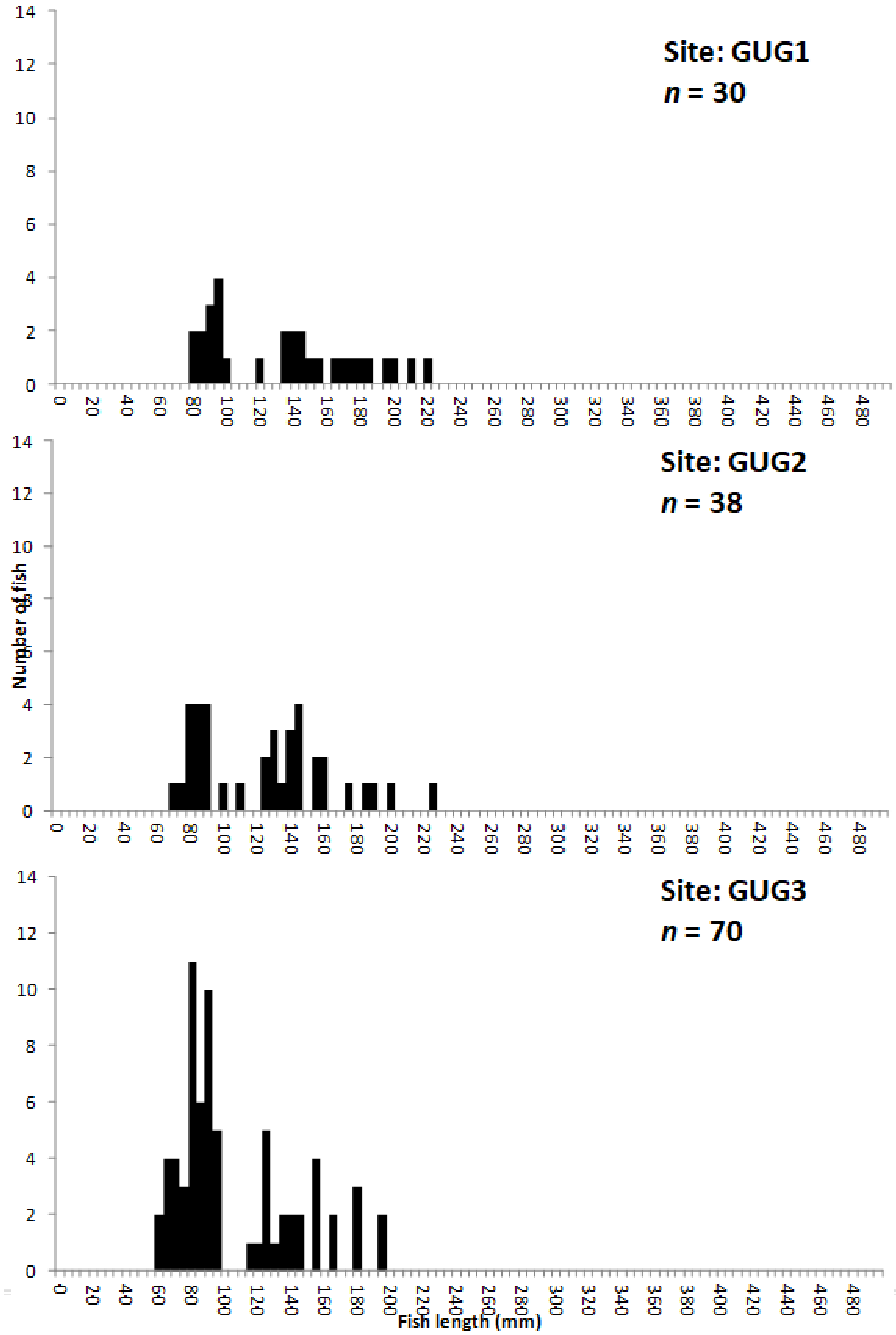


Figure 33. Length frequency histograms of brown trout caught on Gate Up Gill.

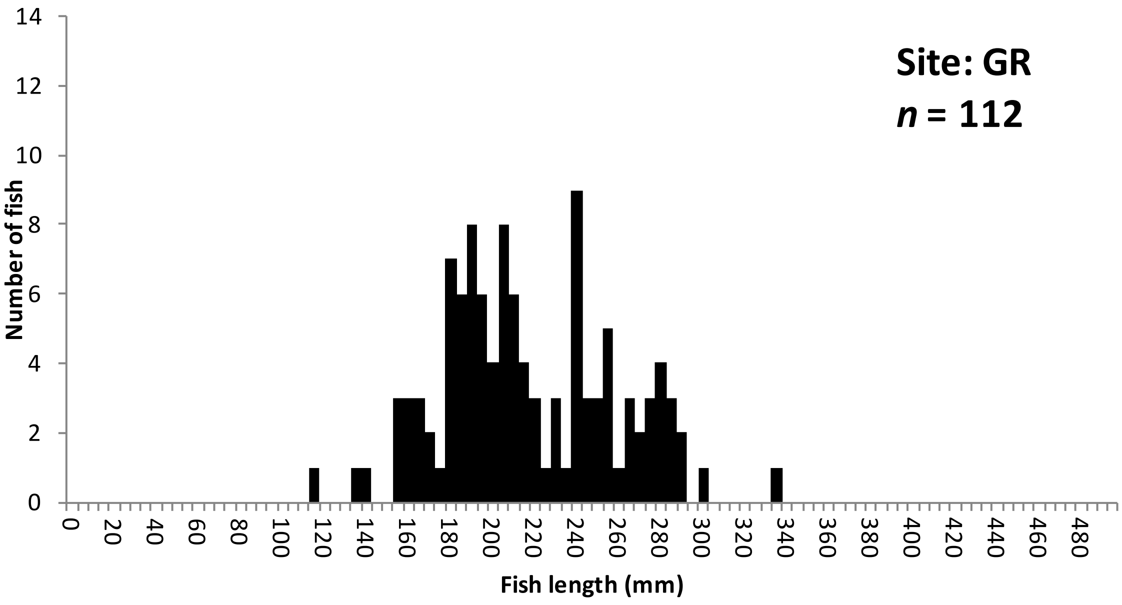


Figure 34. Length frequency histogram of brown trout caught on Grimwith Reservoir.

APPENDIX 2: LENGTH FREQUENCY HISTOGRAMS 2015

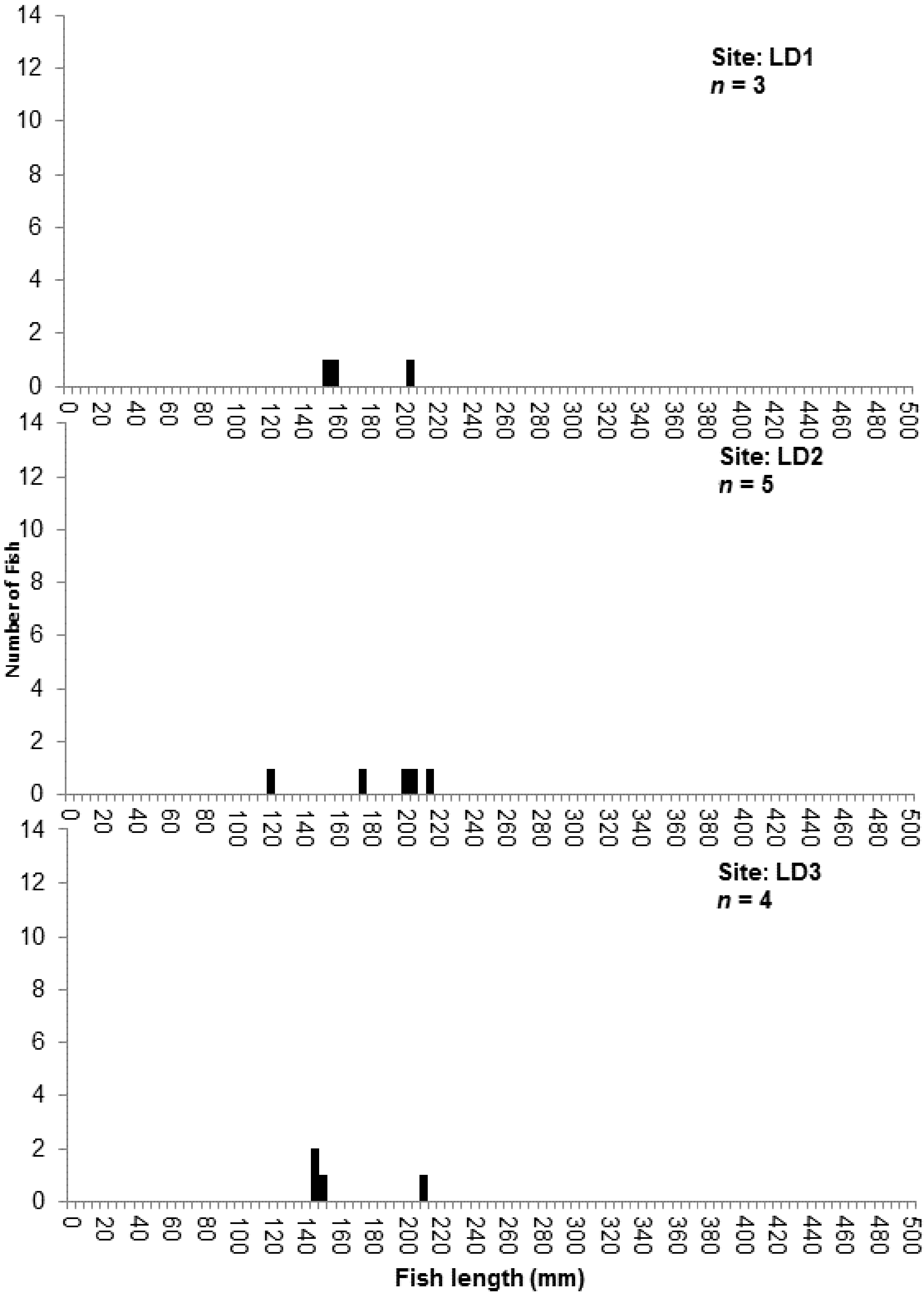


Figure 35. Length frequency histograms of brown trout caught at the River Little Don sites LD1, LD2 and LD3.

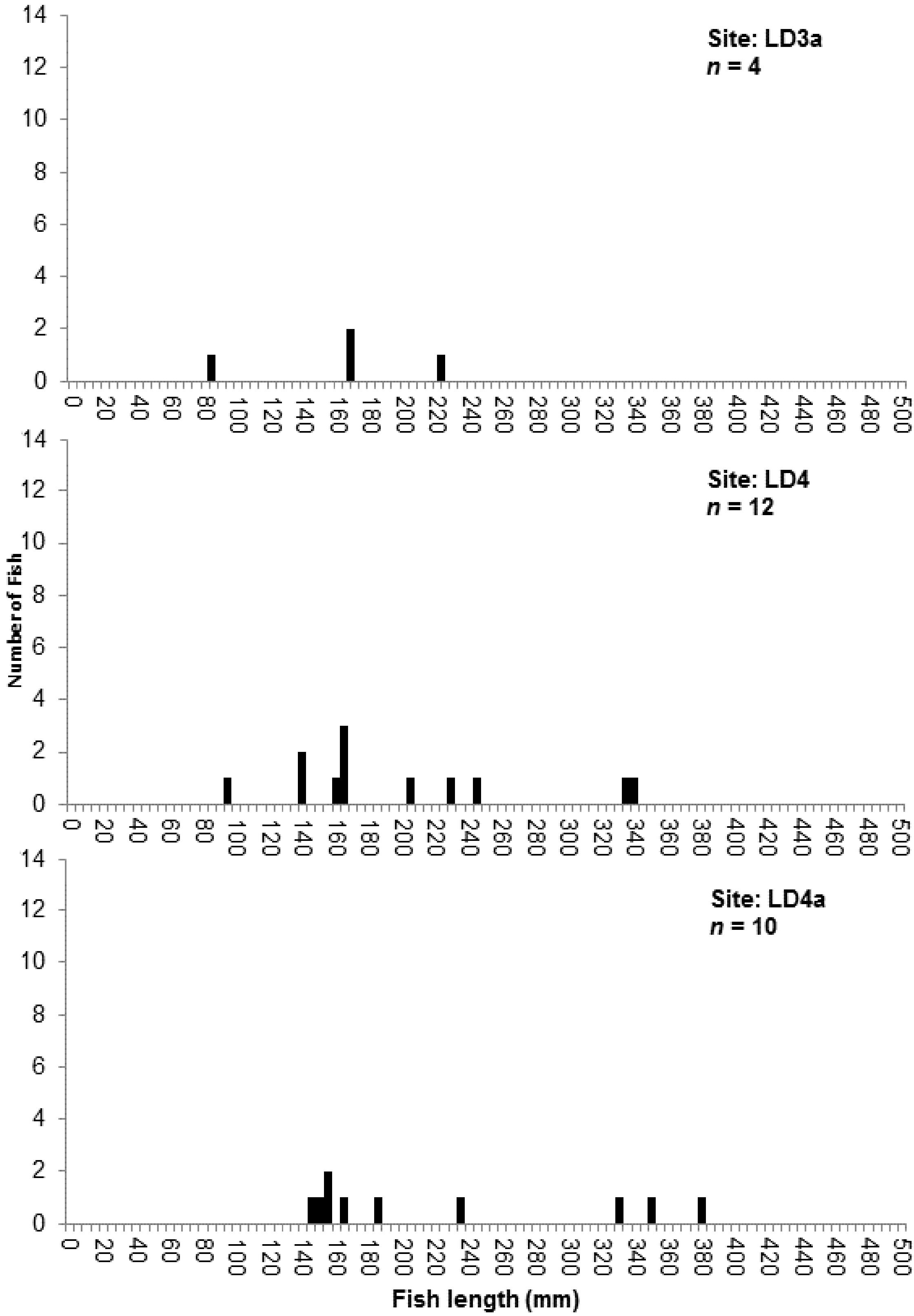


Figure 36. Length frequency histograms of brown trout caught at the River Little Don sites LD3a, LD4 and LD4a.

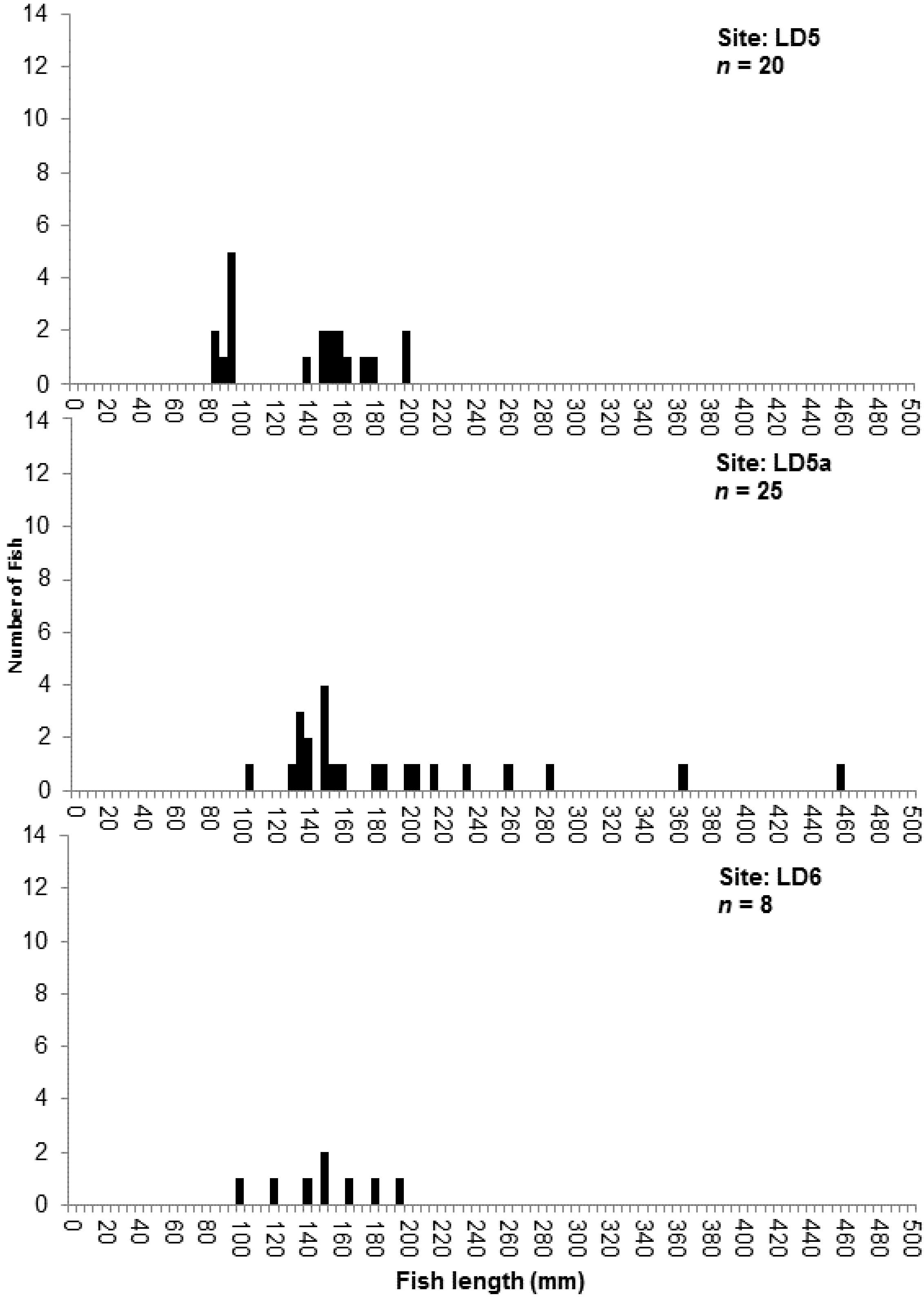


Figure 37. Length frequency histograms of brown trout caught at the River Little Don sites LD5, LD5a and LD6.

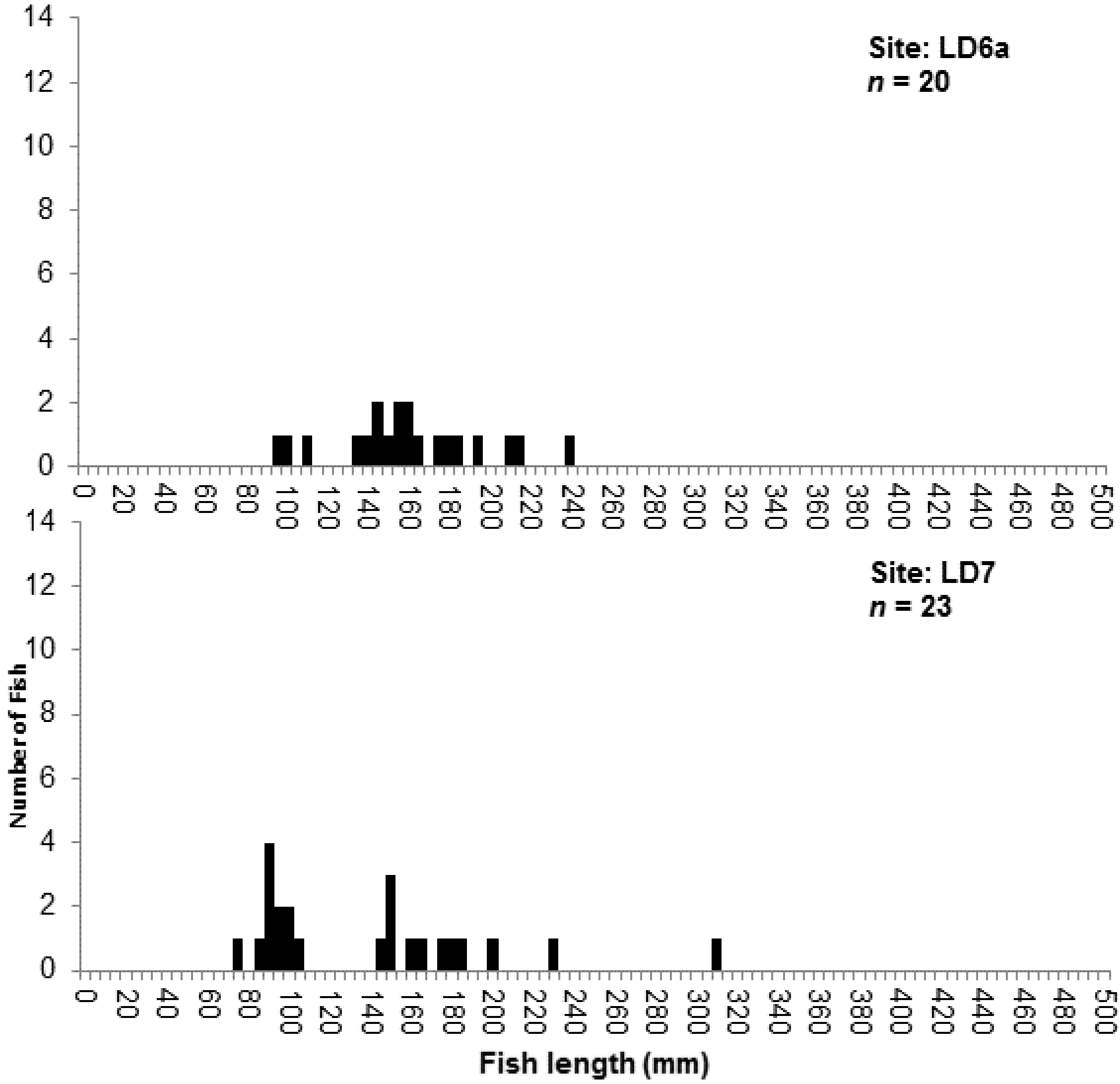


Figure 38. Length frequency histograms of brown trout caught at the River Little Don sites LD6a and LD7.

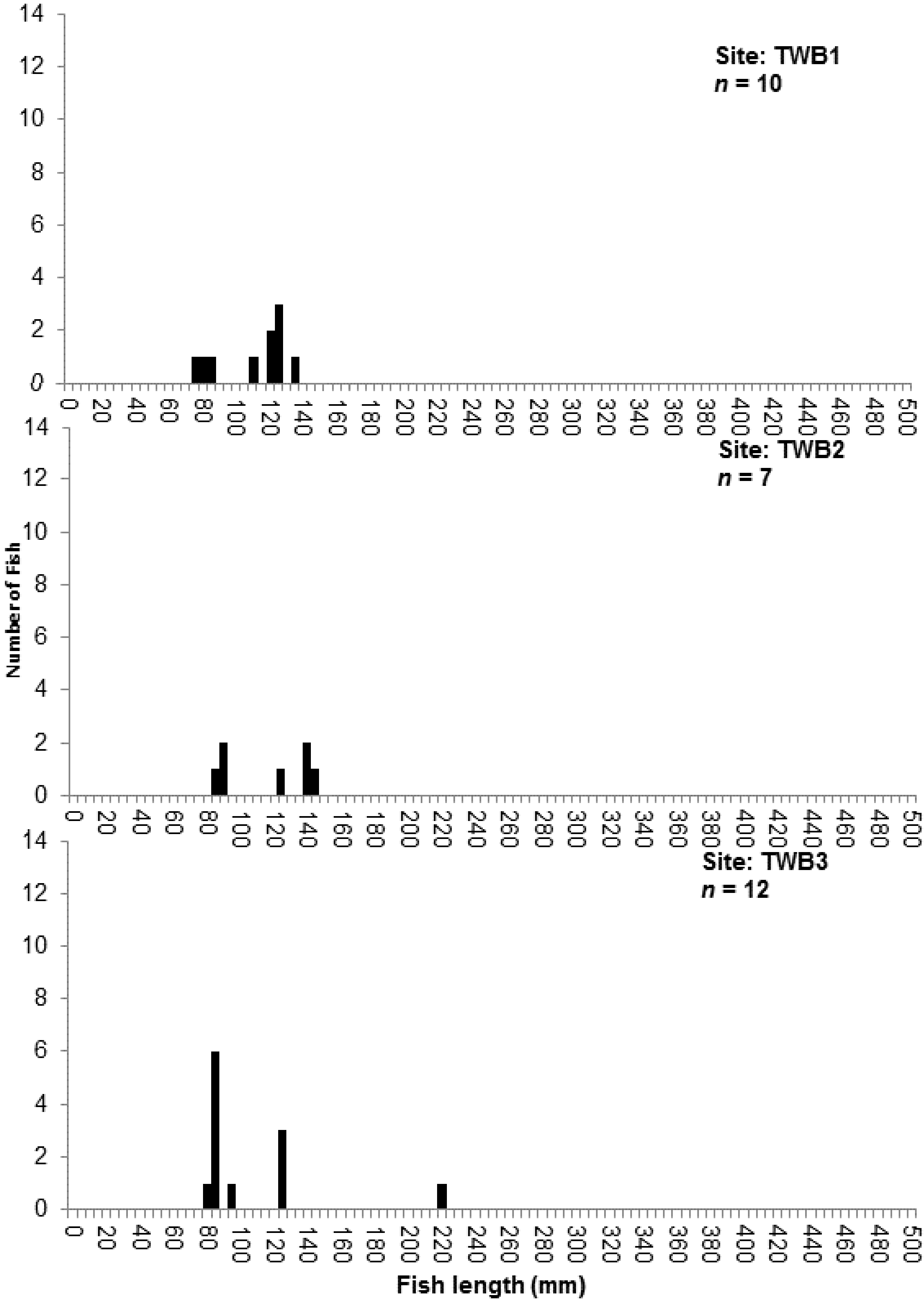


Figure 39. Length frequency histograms of brown trout caught at Thickwoods Brook sites TWB1, TWB2 and TWB3.

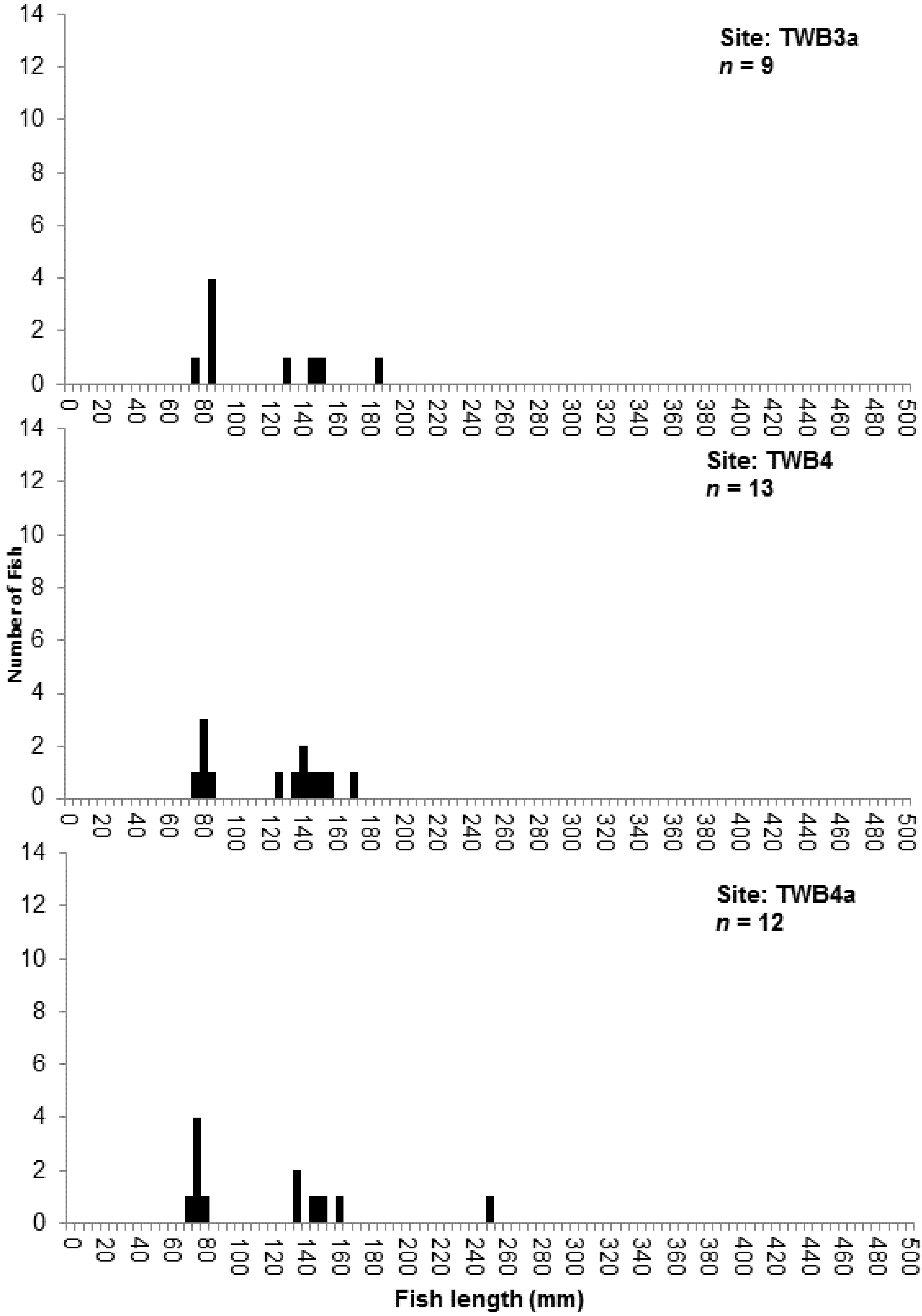


Figure 40. Length frequency histograms of brown trout caught at Thickwoods Brook sites TWB3a, TWB4 and TWB4a.

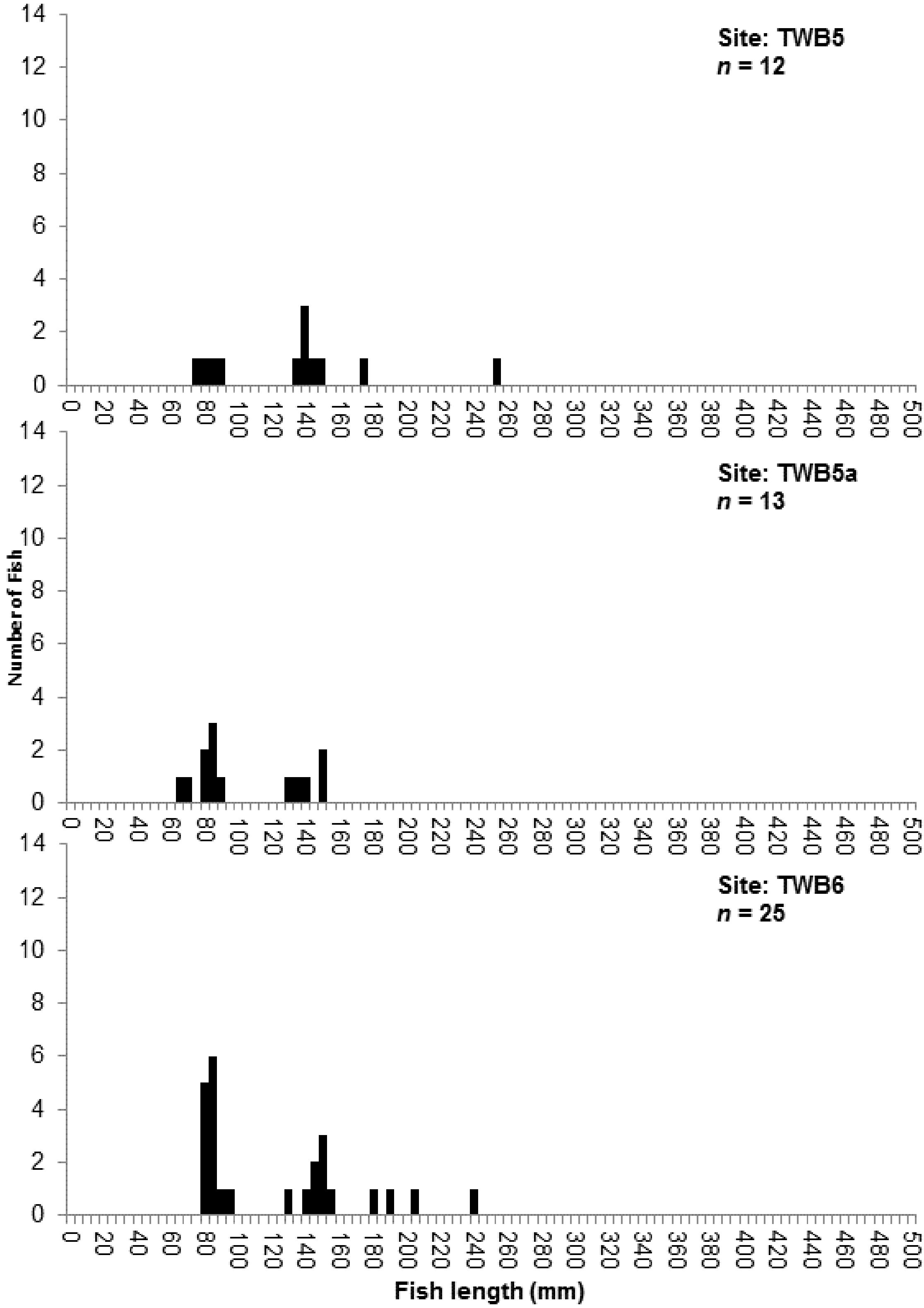


Figure 41. Length frequency histograms of brown trout caught at Thickwoods Brook sites TWB5, TWB5a and TWB6.

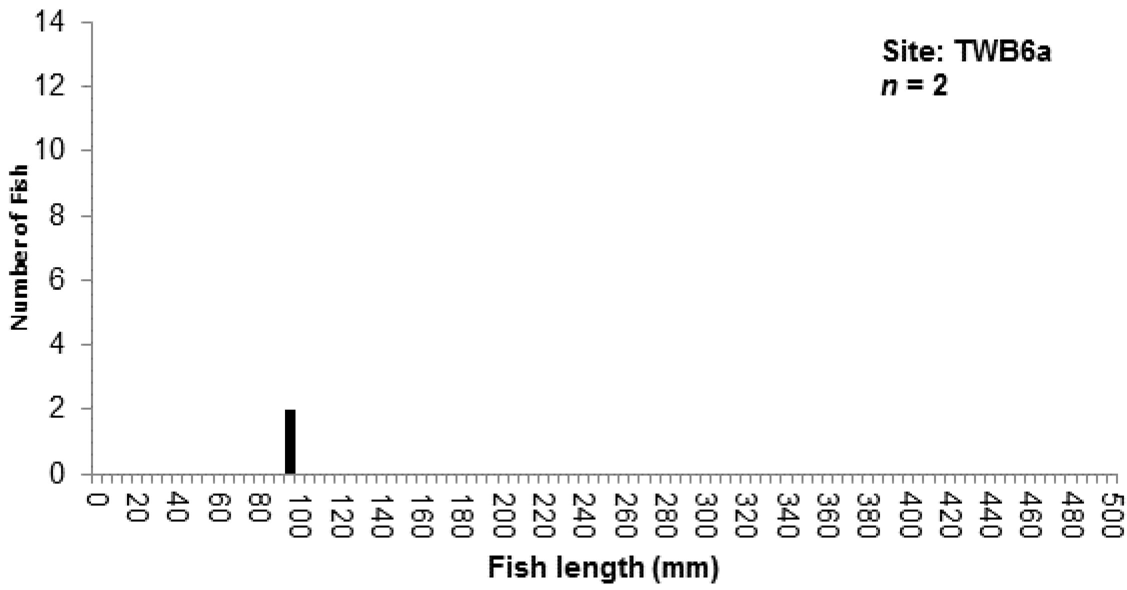


Figure 42. Length frequency histogram of brown trout caught at Thickwoods Brook site TWB6a.

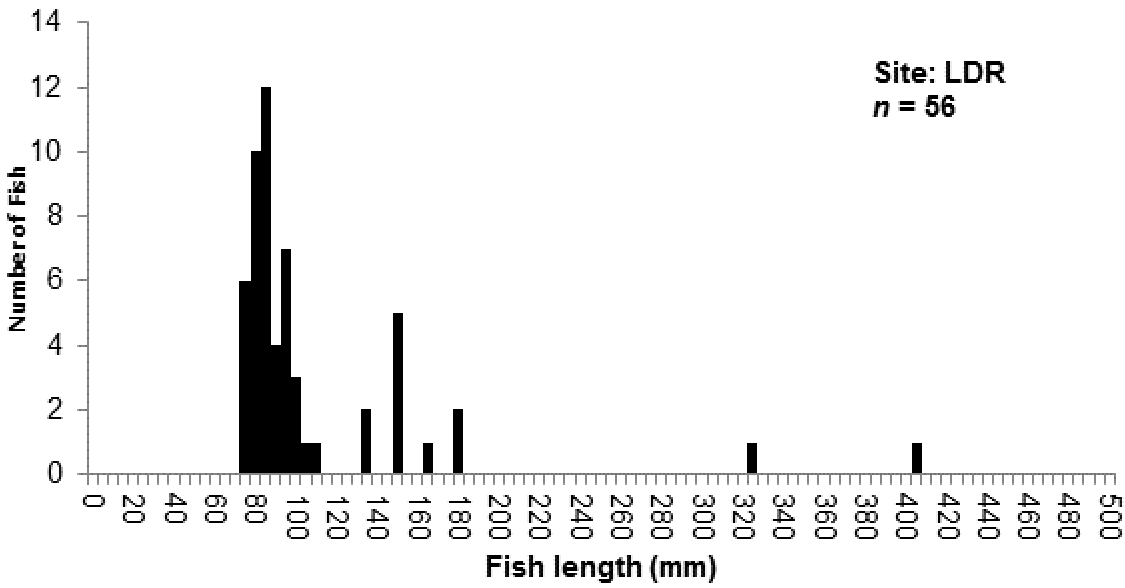


Figure 43. Length frequency histogram of brown trout caught in the River Little Don downstream of the weir, site LDR.

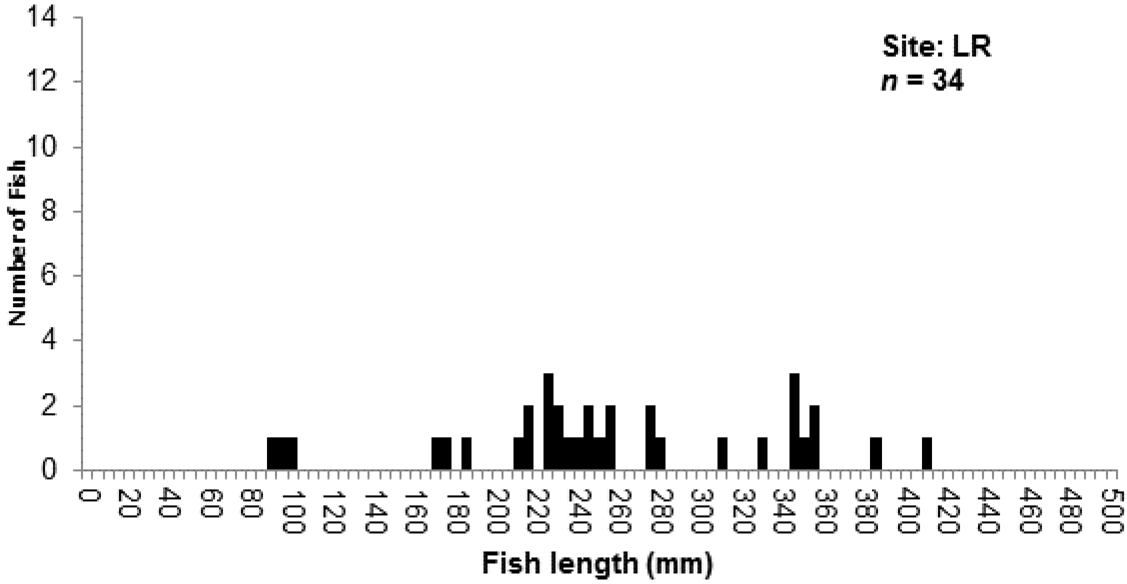


Figure 44. Length frequency histogram of brown trout caught in Langsett Reservoir.

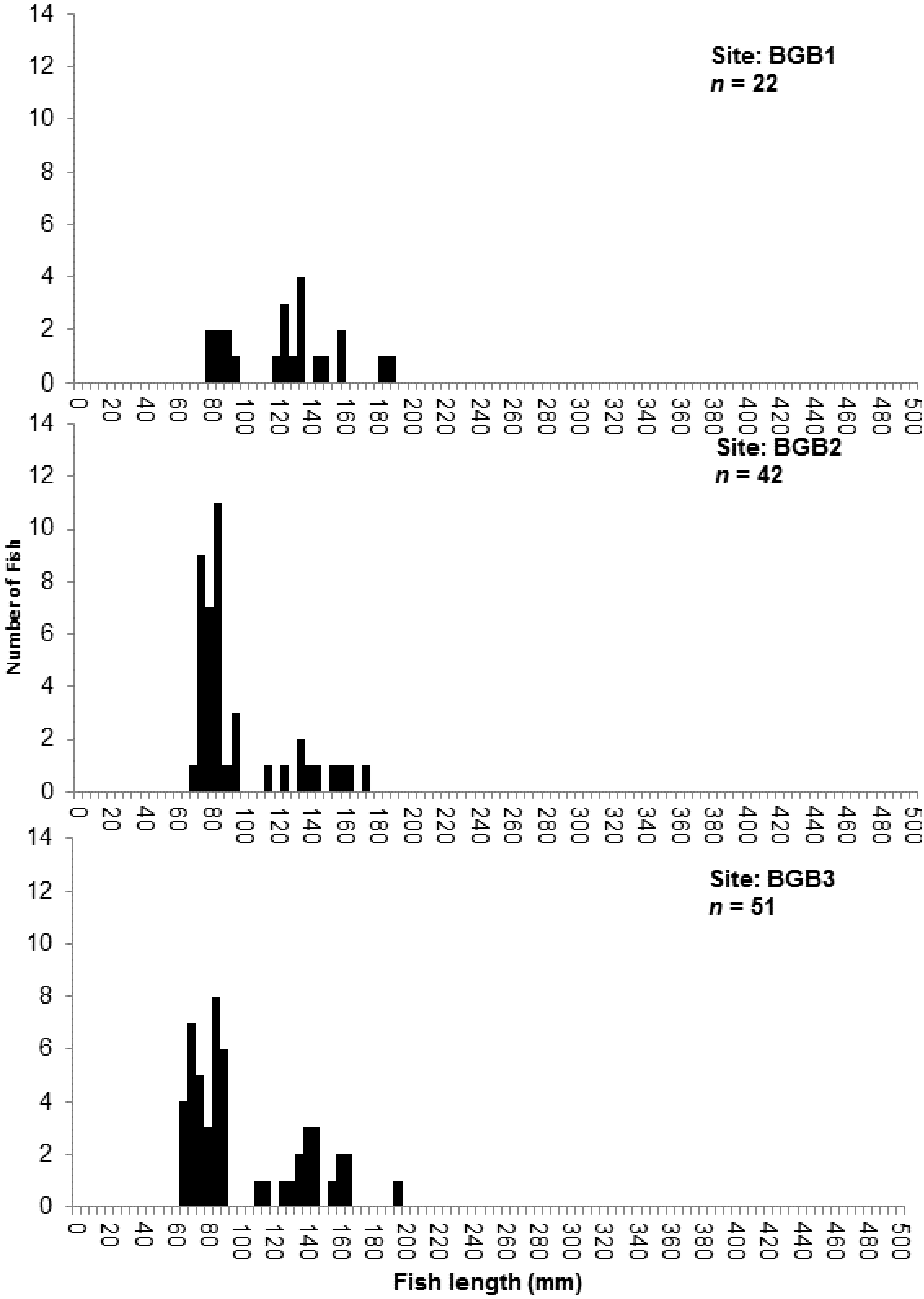


Figure 45. Length frequency histograms of brown trout caught at Blea Gill Beck.

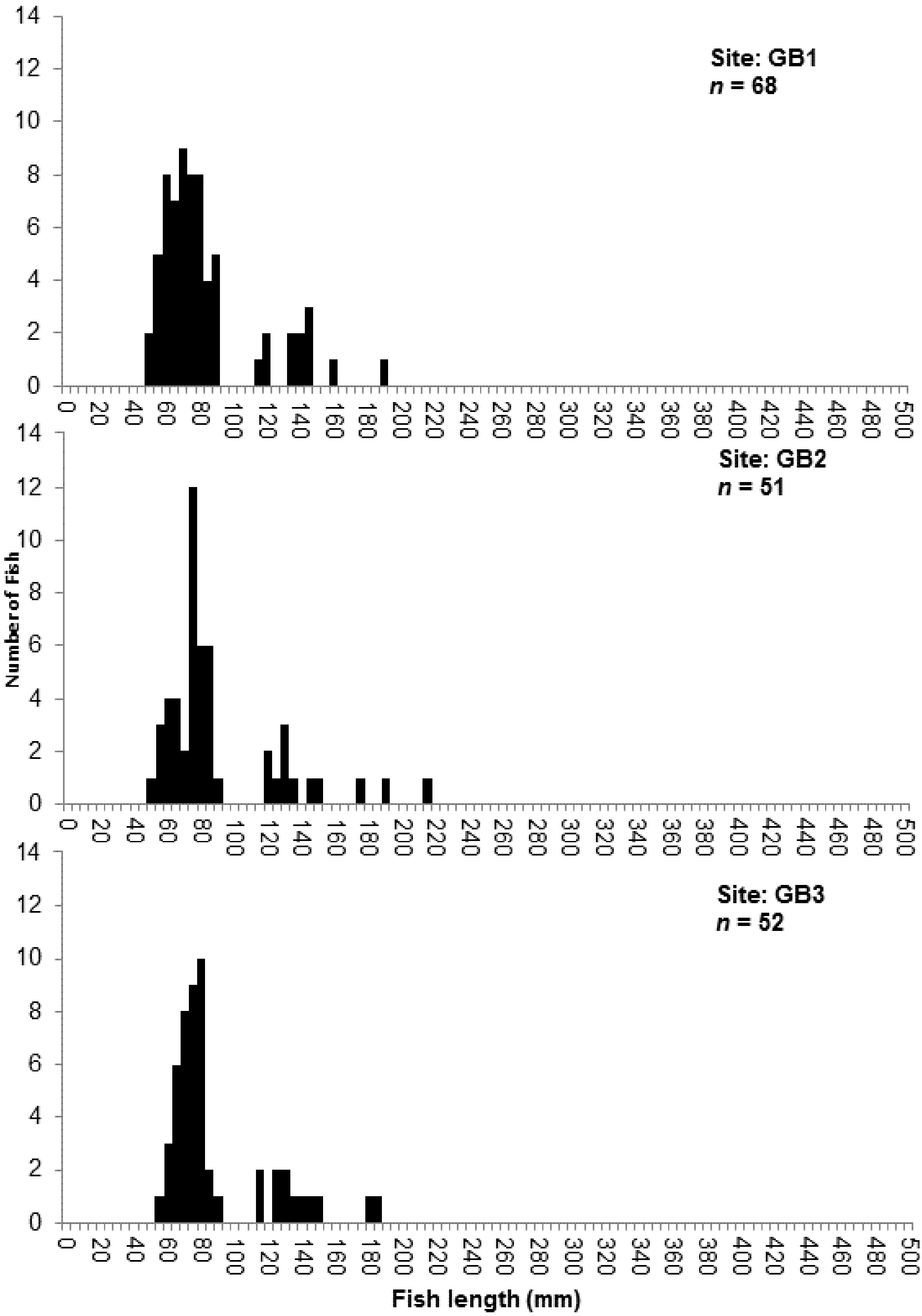


Figure 46. Length frequency histograms of brown trout caught at Grimwith Beck.

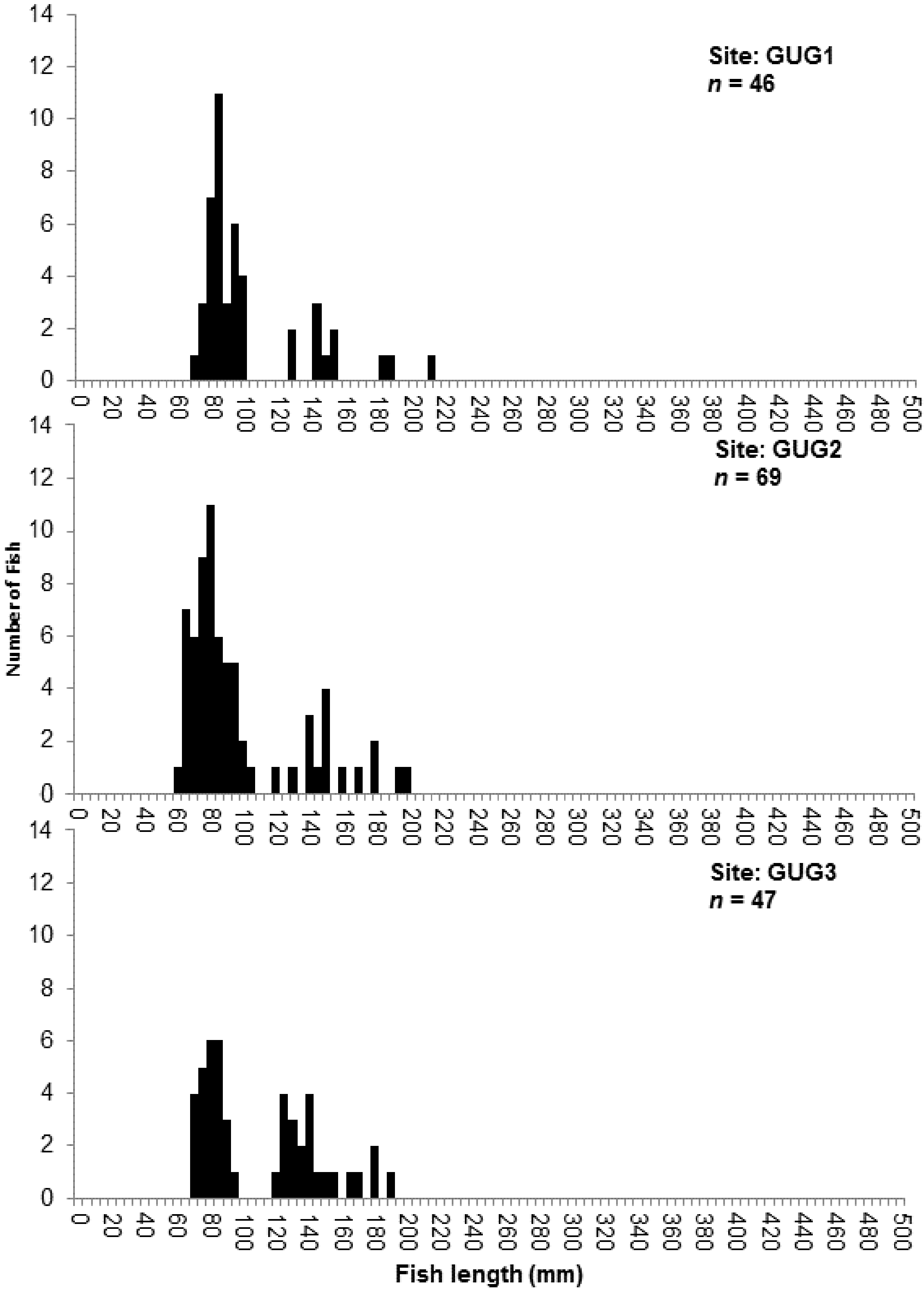


Figure 47. Length frequency histograms of brown trout caught at Gate Up Gill.

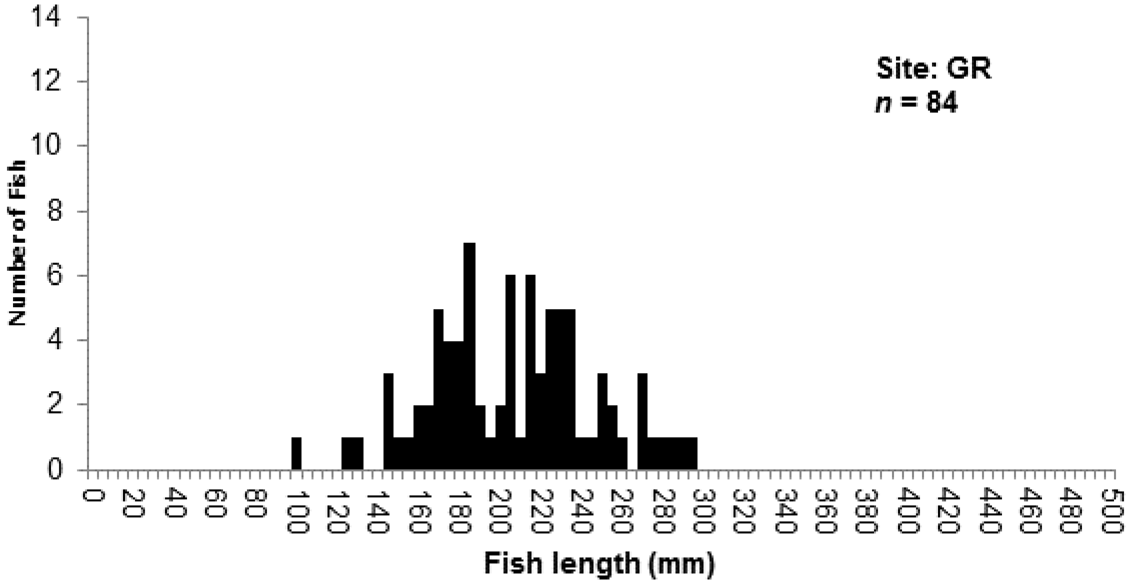


Figure 48. Length frequency histogram of brown trout caught in Grimwith Reservoir.

APPENDIX 3. HABSCORE OUTPUTS 2014 AND 2015

Table 29. HABSCORE outputs for 0+ brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2014. Shaded area represents the observed population was significantly lower (HUI upper C.L. column; red) than expected under pristine conditions.

Reservoir / River name	Site identifier	Observed number	Observed density	HQS (density)	HQS lower CL	HQS upper CL	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir										
The River Little Don	LD1	0	0	20.12	5.49	73.70	0.03	0.00	0.21	-3.51
	LD2	0	0	17.61	4.63	64.23	0.03	0.00	0.20	-3.51
	LD3	0	0	13.48	3.66	49.65	0.03	0.00	0.20	-3.51
	LD4	0	0	15.92	4.34	58.40	0.02	0.00	0.14	-3.91
	LD5	0	0	12.34	3.39	44.95	0.03	0.00	0.2	-3.51
	LD6	5	2.17	18.38	5.02	67.24	0.12	0.02	0.77	-2.12
Thickwoods Brook	TWB1	18	27.48	31.82	8.58	117.99	0.06	0.13	0.67	-2.81
	TWB2	10	16.67	24.48	6.65	90.08	0.60	0.10	4.45	-0.51
	TWB3	24	24.48	26.33	7.05	98.28	0.93	0.14	6.14	-0.07
	TWB4	10	20.62	57.95	15.62	214.98	0.36	0.05	2.34	-1.02
	TWB5	16	18.29	29.35	7.86	109.26	0.62	0.09	4.11	-0.48
	TWB6	13	11.09	20.25	5.53	74.18	0.55	0.08	3.56	-0.60
Grimwith Reservoir										
Blea Gill Beck	BGB1	15	9.83	14.01	3.80	51.62	0.70	0.11	4.53	-0.36
	BGB2	28	17.89	13.77	3.75	50.53	1.30	0.20	8.48	0.26
	BGB3	33	22.30	13.44	3.67	49.19	1.66	0.25	10.80	0.51
Gate Up Gill	GUG1	9	5.90	14.89	4.04	54.91	0.40	0.06	2.60	-0.92
	GUG2	17	10.56	9.15	2.47	33.89	1.15	0.18	7.60	0.14
	GUG3	45	25.31	9.45	2.55	35.07	2.68	0.41	17.59	0.99
Grimwith Beck	GB1	27	21.21	9.55	2.64	34.56	2.22	0.34	14.34	0.80
	GB2	35	29.54	10.92	3.03	39.35	2.70	0.42	17.42	0.99
	GB3	35	22.67	9.50	2.62	34.41	2.39	0.37	15.41	0.87

Table 30. HABSCORE outputs for 0+ brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2015. Shaded area represents the observed population was significantly lower (HUI upper C.L. column; red) than expected under pristine conditions.

Reservoir / River name	Site identifier	Observed number	Observed density	HQS (density)	HQS lower CL	HQS upper CL	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir										
The River Little Don	LD1	0	0	12.41	3.25	47.43	0.04	0.01	0.27	-3.22
	LD2	0	0	4.29	1.18	15.62	0.10	0.02	0.65	-2.30
	LD3	0	0	12.60	3.29	48.25	0.04	0.01	0.24	-3.22
	LD4	1	0.54	6.99	1.89	25.82	0.08	0.01	0.51	-2.53
	LD5	8	2.56	7.32	2.00	26.80	0.35	0.05	2.28	-1.05
	LD6	1	0.47	14.08	3.78	52.44	0.03	0.01	0.22	-3.51
	LD7	11	2.96	4.97	1.35	18.38	0.60	0.09	3.90	-0.51
Thickwoods Brook	TWB1	3	5.24	27.58	7.43	102.35	0.19	0.03	1.25	-1.66
	TWB2	3	3.99	19.00	5.13	70.36	0.21	0.03	1.38	-1.56
	TWB3	8	9.07	17.55	4.70	65.52	0.52	0.08	3.41	-0.65
	TWB4	5	7.25	22.99	6.11	86.49	0.32	0.05	2.09	-1.14
	TWB5	4	5.91	44.10	11.36	171.12	0.13	0.02	0.91	-2.04
	TWB6	13	11.58	9.48	2.61	34.52	1.22	0.19	7.91	0.20
Grimwith Reservoir										
Blea Gill Beck	BGB1	7	3.42	4.17	1.11	15.69	0.82	0.12	5.46	-0.20
	BGB2	32	15.57	4.12	1.12	15.10	3.78	0.58	24.64	1.33
	BGB3	33	16.75	5.75	1.55	21.35	2.91	0.44	19.13	1.07
Gate Up Gill	GUG1	30	15.46	5.08	1.40	18.49	3.04	0.47	19.70	1.11
	GUG2	53	31.55	4.22	1.31	17.61	7.47	1.15	48.46	2.01
	GUG3	25	14.46	5.36	1.41	19.16	2.70	0.41	17.78	0.99
Grimwith Beck	GB1	57	54.76	9.75	2.85	37.03	5.61	0.87	36.12	1.72
	GB2	39	33.77	7.11	2.18	28.42	4.75	0.74	30.48	1.56
	GB3	41	30.19	12.79	3.20	42.04	2.36	0.37	15.24	0.86

Table 31. HABSCORE outputs for >0+<20 cm brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2014. Shaded area represents the observed population was significantly higher (blue) or lower (red) than expected under pristine conditions.

Reservoir / River name	Site identifier	Observed number	Observed density	HQS (density)	HQS lower CL	HQS upper CL	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir										
The River Little Don	LD1	1	0.65	6.97	1.68	23.88	0.09	0.02	0.55	-2.41
	LD2	1	0.54	11.06	2.67	45.82	0.05	0.01	0.29	-3.00
	LD3	1	0.41	4.75	1.14	19.78	0.09	0.01	0.51	-2.41
	LD4	2	0.70	7.21	1.73	34.00	0.10	0.02	0.57	-2.30
	LD5	3	1.14	5.65	1.37	23.38	0.20	0.03	1.18	-1.61
	LD6	12	5.21	8.44	2.04	34.96	0.62	0.10	3.63	-0.48
Thickwoods Brook	TWB1	4	6.11	16.24	3.84	69.70	0.38	0.06	2.24	-0.97
	TWB2	1	1.67	17.60	4.21	73.55	0.09	0.02	0.56	-2.41
	TWB3	1	1.02	12.12	2.90	50.72	0.08	0.01	0.50	-2.53
	TWB4	2	4.12	35.48	6.46	148.99	0.12	0.02	0.69	-2.12
	TWB5	2	2.29	20.86	4.93	88.23	0.11	0.02	0.65	-2.21
	TWB6	4	3.41	24.89	5.93	104.47	0.14	0.02	0.81	-1.97
Grimwith Reservoir										
Blea Gill Beck	BGB1	4	2.61	6.59	1.55	27.94	0.40	0.07	2.36	-0.92
	BGB2	5	3.19	3.36	0.40	14.18	0.35	0.16	5.76	-1.05
	BGB3	4	2.70	2.96	0.69	12.77	0.91	0.15	5.51	-0.09
Gate Up Gill	GUG1	16	10.49	7.94	1.91	33.05	1.32	0.23	7.76	0.28
	GUG2	20	12.42	3.15	0.73	13.55	3.96	0.65	23.82	1.38
	GUG3	27	15.19	4.48	1.08	18.56	3.39	0.58	19.84	1.22
Grimwith Beck	GB1	9	7.07	5.14	1.23	21.54	1.38	0.23	8.14	0.32
	GB2	16	13.50	4.36	1.04	18.18	3.10	0.53	18.23	1.13
	GB3	22	14.25	3.19	0.75	13.63	4.46	0.74	26.75	1.50

Table 32. HABSCORE outputs for >0+<20 cm brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2015. Shaded area represents the observed population was significantly lower (HUI upper C.L. column; red) than expected under pristine conditions.

Reservoir / River name	Site identifier	Observed number	Observed density	HQS (density)	HQS lower CL	HQS upper CL	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir										
The River Little Don	LD1	2	1.00	7.81	1.82	33.46	0.13	0.02	0.77	-2.04
	LD2	2	0.86	6.87	1.68	28.10	0.13	0.02	0.72	-2.04
	LD3	3	1.33	6.55	1.52	28.17	0.20	0.03	1.22	-1.61
	LD4	6	3.26	6.95	1.67	28.94	0.47	0.08	2.75	-0.76
	LD5	10	3.20	6.95	1.67	28.92	0.46	0.08	2.70	-0.78
	LD6	7	3.32	7.89	1.87	33.24	0.42	0.07	2.49	-0.87
	LD7	10	2.69	3.15	0.75	13.15	0.85	0.15	5.03	-0.16
Thickwoods Brook	TWB1	7	12.22	22.53	5.37	94.52	0.54	0.09	3.20	-0.62
	TWB2	4	5.32	12.47	2.95	52.67	0.43	0.07	2.54	-0.84
	TWB3	3	3.40	11.92	2.84	50.03	0.29	0.05	1.69	-1.24
	TWB4	3	4.35	18.55	4.35	79.08	0.23	0.04	1.40	-1.47
	TWB5	7	10.34	20.74	4.74	90.79	0.50	0.08	3.05	-0.69
	TWB6	10	8.91	10.31	2.51	42.35	0.86	0.15	5.02	-0.15
Grimwith Reservoir										
Blea Gill Beck	BGB1	15	7.33	3.72	0.86	16.03	1.97	0.33	11.92	0.68
	BGB2	10	4.87	2.49	0.59	10.59	1.95	0.33	11.64	0.67
	BGB3	18	9.14	5.21	1.21	22.39	1.75	0.29	10.55	0.56
Gate Up Gill	GUG1	10	5.15	3.75	0.87	16.14	1.37	0.23	8.29	0.31
	GUG2	14	8.33	3.45	0.79	14.19	2.41	0.41	14.38	0.88
	GUG3	22	12.72	4.14	0.96	17.26	3.07	0.51	18.35	1.12
Grimwith Beck	GB1	12	11.53	4.87	1.18	21.61	2.37	0.40	14.21	0.86
	GB2	11	9.52	4.32	1.07	19.06	2.20	0.37	13.12	0.79
	GB3	12	8.84	5.83	1.25	22.38	1.52	0.25	9.02	0.42

Table 33. HABSCORE outputs for >0+>20 cm brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2014. Shaded area represents the observed population was significantly higher (blue) or lower (red) than expected under pristine conditions.

Reservoir / River name	Site identifier	Observed number	Observed density	HQS (density)	HQS lower CL	HQS upper CL	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir										
The River Little Don	LD1	1	0.65	0.91	0.34	2.77	0.71	0.23	2.15	-0.34
	LD2	1	0.54	1.36	0.45	4.10	0.40	0.13	1.20	-0.92
	LD3	0	0	0.87	0.29	2.64	0.47	0.16	1.43	-0.76
	LD4	1	0.35	0.93	0.31	2.79	0.34	0.13	1.14	-1.08
	LD5	3	1.14	0.66	0.22	1.98	1.74	0.58	5.28	0.55
	LD6	4	1.74	1.02	0.34	3.08	1.70	0.56	5.14	0.53
Thickwoods Brook	TWB1	1	1.53	2.32	0.76	7.14	0.66	0.21	2.02	-0.42
	TWB2	0	0	2.86	0.94	8.74	0.54	0.19	1.73	-0.62
	TWB3	1	1.02	2.01	0.65	6.17	0.51	0.17	1.56	-0.67
	TWB4	2	4.12	3.33	1.09	10.15	1.24	0.41	3.77	0.22
	TWB5	2	2.29	2.42	0.79	7.41	0.94	0.31	2.69	-0.06
	TWB6	1	0.85	3.08	1.02	9.34	0.24	0.09	0.84	-1.43
Grimwith Reservoir										
Blea Gill Beck	BGB1	1	0.65	0.87	0.28	2.64	0.75	0.25	2.30	-0.29
	BGB2	0	0	1.09	0.35	3.40	0.59	0.19	1.82	-0.53
	BGB3	0	0	0.79	0.25	2.48	0.86	0.27	2.70	-0.15
Gate Up Gill	GUG1	2	1.31	1.46	0.48	4.41	0.90	0.30	2.72	-0.11
	GUG2	2	1.24	1.08	0.34	3.42	1.15	0.36	3.62	0.14
	GUG3	0	0	1.46	0.48	4.48	0.38	0.13	1.18	-0.97
Grimwith Beck	GB1	0	0	1.13	0.37	3.47	0.70	0.23	2.14	-0.36
	GB2	0	0	0.82	0.27	2.51	1.02	0.34	3.12	0.02
	GB3	0	0	0.91	0.29	2.83	0.72	0.23	2.24	-0.33

Table 34. HABSCORE outputs for >0+>20 cm brown trout surveyed in tributaries to Langsett and Grimwith Reservoirs, 2015. Shaded area represents the observed population was significantly lower (HUI upper C.L. column; red) than expected under pristine conditions.

Reservoir / River name	Site identifier	Observed number	Observed density	HQS (density)	HQS lower CL	HQS upper CL	HUI	HUI lower CL	HUI upper CL	Ln (HUI)
Langsett Reservoir										
The River Little Don	LD1	1	0.50	1.19	0.40	3.59	0.42	0.14	1.26	0.23
	LD2	3	1.29	1.55	0.52	4.66	0.83	0.28	2.49	0.91
	LD3	1	0.44	1.02	0.34	3.09	0.43	0.14	1.32	0.28
	LD4	5	2.72	1.46	0.48	4.40	1.87	0.62	5.64	1.73
	LD5	2	0.64	1.44	0.47	4.35	0.45	0.14	1.37	0.31
	LD6	0	0	1.23	0.41	3.70	0.39	0.13	1.17	0.16
	LD7	2	0.54	0.86	0.28	2.63	0.63	0.20	1.94	0.66
Thickwoods Brook	TWB1	0	0	3.92	1.29	11.84	0.45	0.15	1.35	0.30
	TWB2	0	0	3.50	1.15	10.68	0.38	0.12	1.16	0.15
	TWB3	1	1.13	2.54	0.84	7.71	0.45	0.15	1.35	0.30
	TWB4	0	0	4.55	1.48	13.97	0.32	0.10	0.98	-0.02
	TWB5	1	1.48	3.22	1.05	9.88	0.46	0.14	1.55	0.44
	TWB6	2	1.78	3.46	1.14	10.48	0.51	0.17	1.56	0.44
Grimwith Reservoir										
Blea Gill Beck	BGB1	0	0	1.93	0.64	5.84	0.25	0.08	0.77	-1.39
	BGB2	0	0	1.78	0.58	5.44	0.27	0.09	0.84	-1.31
	BGB3	0	0	3.15	1.03	9.61	0.16	0.05	0.49	-1.83
Gate Up Gill	GUG1	1	0.52	1.43	0.48	4.32	0.36	0.12	1.08	-1.02
	GUG2	0	0	1.40	0.48	4.32	0.42	0.14	1.28	-0.86
	GUG3	0	0	1.58	0.48	4.38	0.37	0.12	1.10	-0.99
Grimwith Beck	GB1	0	0	1.77	0.63	5.72	0.54	0.18	1.64	-0.61
	GB2	1	0.87	1.18	0.39	3.52	0.73	0.24	2.21	-0.31
	GB3	0	0	1.30	0.39	3.61	0.57	0.19	1.71	-0.56

APPENDIX 4 DENSITY ESTIMATES

Table 35. Total population estimate (N), probability of capture (P), population density (D ± 95% C.L. at quantitative sites; numbers of fish per 100m^2) and EA-FCS abundance classifications of brown trout derived from fisheries surveys in Langsett Reservoir tributaries in 2014. Details of derivation of estimates are provided in the text.

River name	Site code	Total Population (N)		Probability of capture (P)		Population density (D)		Abundance classification	
		0+	≥1+	0+	≥1+	0+	≥1+	0+	≥1+
The River Little Don	LD1	0	2	0	1	0	1.30	F	E
	LD2	0	2	0	1	0	1.07	F	E
	LD3	0	1	0	1	0	0.40	F	E
	LD4	0	3±0	0	0.75±0.18	0	1.02±0.13	F	E
	LD5	0	6±0	0	0.86±0.11	0	2.49±0.12	F	D
	LD6	5	16±1	1	0.82±0.08	2.15	6.90±0.44	E	C
	LD7	14±1	19±1	0.65±0.11	0.76±0.09	6.34±0.87	7.24±0.60	D	C
Thickwoods Brook	TWB1	18±0	5	0.86±0.07	1	31.50±0.77	8.77	B	C
	TWB2	10	1	1	1	8.6	0.86	C	E
	TWB3	24±1	2	0.69±0.09	1	23.50±2.09	1.96	B	E
	TWB4	11±0	4	0.79±0.10	1	25.00±1.43	9.09	B	C
	TWB5	16±1	4±0	0.73±0.09	0.85±0.15	18.20±1.5	4.55±0.38	B	D
	TWB6	12±0	5±0	0.80±0.09	0.78±0.15	10.80±0.54	4.51±0.83	C	D

Table 36. Total population estimate (N), probability of capture (P), population density (D ± 95% C.L. at quantitative sites; numbers of fish per 100m^2) and EA-FCS abundance classifications of brown trout derived from fisheries surveys in Langsett Reservoir tributaries in 2015. Details of derivation of estimates are provided in the text.

River name	Site code	Total Population (N)		Probability of capture (P)		Population density (D)		Abundance classification	
		0+	≥1+	0+	≥1+	0+	≥1+	0+	≥1+
The River Little Don	LD1	0	3±0	0	0.75±0.17	0	1.51±0.20	F	E
	LD2	0	5±0	0	1	0	2.04±0.00	F	D
	LD3	0	4±0	0	0.80±0.15	0	1.77±0.19	F	E
	LD4	1±0	11±0	1	0.92±0.07	0.53±0.00	5.78±0.07	E	C
	LD5	8±1	12±0	0.67±0.12	0.80±0.09	2.74±0.40	4.11±0.23	E	D
	LD6	1±0	7±1	1	0.64±0.13	0.48±0.00	3.33±0.61	E	D
	LD7	11±1	13±2	0.73±0.11	0.52±0.14	3.03±0.28	3.58±1.04	E	D
Thickwoods Brook	TWB1	3±1	7±0	0.50±0.20	1	4.81±1.89	11.22±0.00	D	C
	TWB2	3±0	4±0	1	0.80±0.15	4.49±0.00	5.99±0.58	D	C
	TWB3	8±0	4±0	0.80±0.11	0.80±0.15	8.80±0.49	4.40±0.39	C	D
	TWB4	5±1	8±0	0.56±0.15	0.80±0.11	7.81±2.00	12.50±0.72	D	B
	TWB5	4±0	8±0	1	0.73±0.12	5.47±0.00	10.94±1.10	D	C
	TWB6	13±0	12±0	0.87±0.08	0.75±0.10	11.71±0.33	10.81±0.87	C	C

Table 37. Total population estimate (N), probability of capture (P), population density (D ± 95% C.L. at quantitative sites; numbers of fish per 100m^2) and EA-FCS abundance classifications of brown trout derived from fisheries surveys in Grimwith Reservoir tributaries in 2014. Details of derivation of estimates are provided in the text.

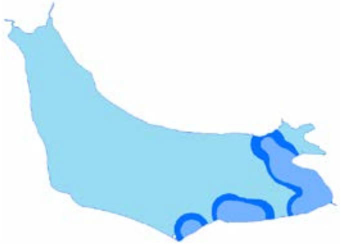
River name	Site code	Total Population (N)		Probability of capture (P)		Population density (D)		Abundance classification	
		0+	≥1+	0+	≥1+	0+	≥1+	0+	≥1+
Blea Gill Beck	BGB1	15±0	5±0	0.79±0.09	1	9.75±0.52	3.30±0.00	C	D
	BGB2	28±2	5±1	0.64±0.10	0.56±0.16	18.18±2.19	3.25±0.92	B	D
	BGB3	33±2	4±0	0.65±0.09	1	21.43±2.25	2.60±0.00	B	E
Gate Up Gill	GUG1	9±0	18±0	0.90±0.08	0.90±0.07	6.21±0.16	12.41±0.17	D	B
	GUG2	17±2	22±0	0.57±0.12	0.89±0.06	10.43±2.08	13.39±0.26	C	B
	GUG3	45±1	27±3	0.78±0.06	0.56±0.11	24.17±0.85	14.50±2.69	B	B
Grimwith Beck	GB1	27±1	9±0	0.73±0.08	0.82±0.10	22.03±1.51	7.34±0.39	B	C
	GB2	35±1	16±0	0.75±0.06	0.84±0.07	28.46±1.43	13.01±0.42	B	B
	GB3	35±1	22±1	0.78±0.06	0.79±0.08	20.69±0.82	13.00±0.60	B	B

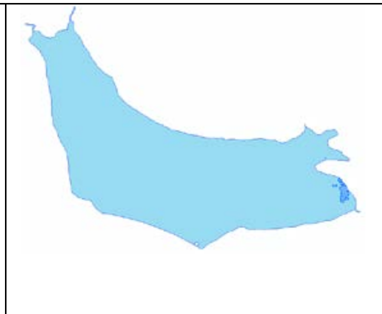
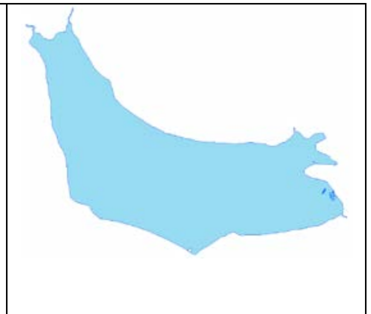
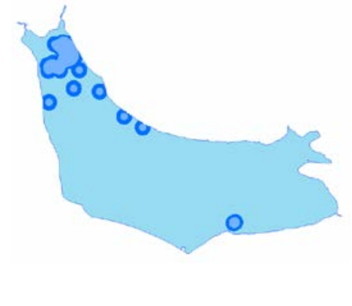
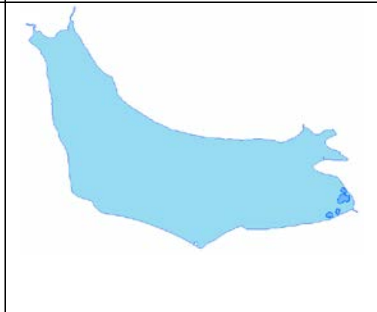
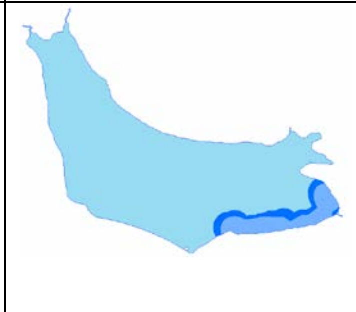
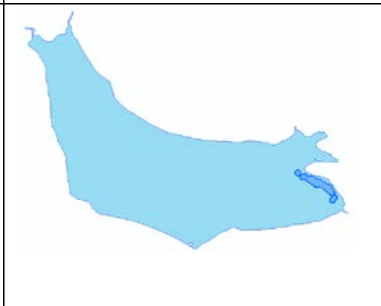
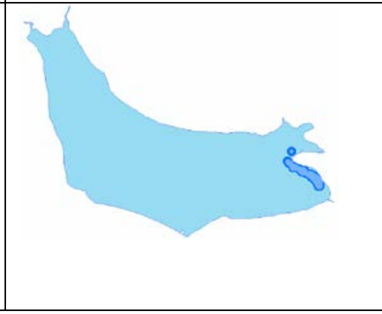
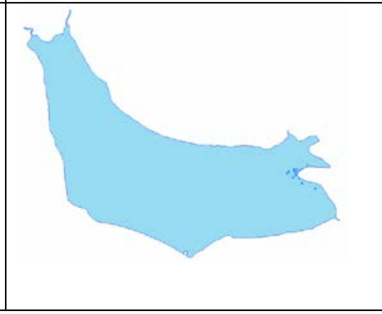
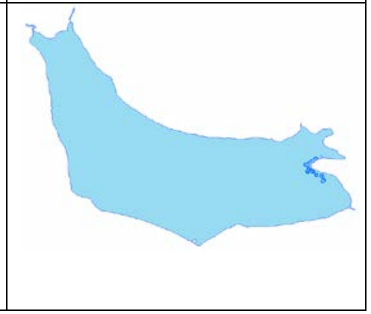
Table 38. Total population estimate (N), probability of capture (P), population density (D ± 95% C.L. at quantitative sites; numbers of fish per 100m[2]) and EA-FCS abundance classifications of brown trout derived from fisheries surveys in Grimwith Reservoir tributaries in 2015. Details of derivation of estimates are provided in the text.

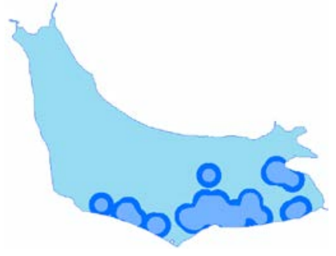
River name	Site code	Total Population (N)		Probability of capture (P)		Population density (D)		Abundance classification	
		0+	≥1+	0+	≥1+	0+	≥1+	0+	≥1+
Blea Gill Beck	BGB1	7±0	15±0	0.70±0.13	0.88±0.07	3.52±0.46	7.54±0.20	D	C
	BGB2	32±1	10±0	0.76±0.07	0.77±0.10	16.16±0.79	5.05±0.36	C	C
	BGB3	33±1	18±0	0.72±0.07	0.86±0.07	17.01±1.00	9.28±0.24	B	C
Gate Up Gill	GUG1	36±2	11±0	0.66±0.09	0.85±0.09	18.97±1.77	5.80±0.20	B	C
	GUG2	53±0	16±0	0.85±0.04	0.80±0.08	29.78±0.44	8.99±0.46	B	C
	GUG3	25±0	22±1	0.89±0.05	0.76±0.08	13.59±0.17	11.96±0.66	C	C
Grimwith Beck	GB1	57±2	12±0	0.72±0.07	0.92±0.07	55.88±3.06	11.76±0.18	A	C
	GB2	39±0	12±0	0.83±0.05	0.86±0.08	34.51±0.75	10.62±0.35	B	C
	GB3	41±2	12±0	0.67±0.08	1.00±0.00	30.37±2.54	8.89±0.00	B	C

APPENDIX 5. FISH OCCUPANCY OF GRIMWITH RESERVOIR

Table 39. Areas of Grimwith Reservoir utilised by acoustic tagged individual fish (no. 20542-20561) between October 2014 and February 2015, grey indicate insufficient data to calculate occupancy.

Fish ID	October 2014	November 2014	December 2014	January 2015	February 2015
20542					
20543					

20544					
20545					
20546					

20547					
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20549					

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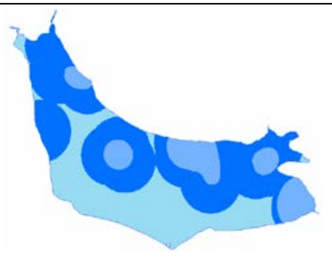
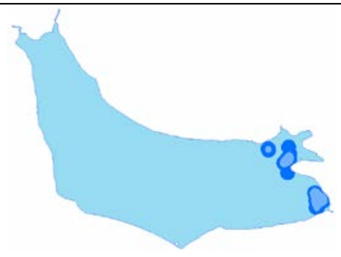
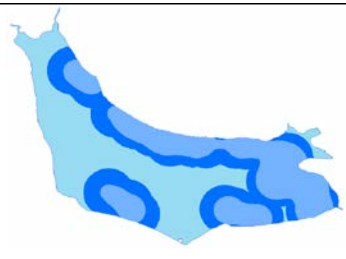
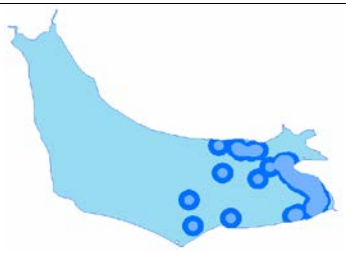
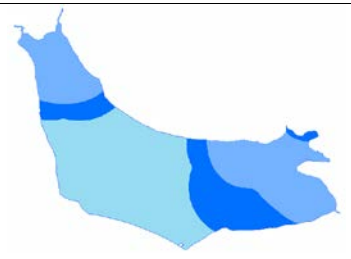
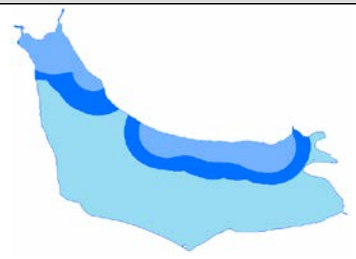
20551					
20552					

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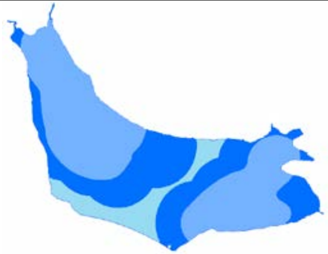
20561					

Table 40. Areas of Grimwith Reservoir utilised by acoustic tagged individual fish (no. 20542-20561) between October 2014 and February 2015, grey indicate insufficient data to calculate occupancy.

Fish ID	March 2015	April 2015	May 2015	June 2015	July 2015
20542					
20543					
20544					
20545					
20546					

20547					
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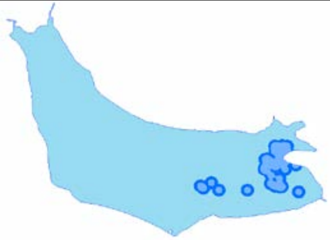
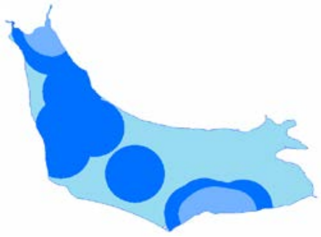
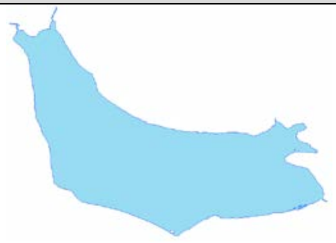
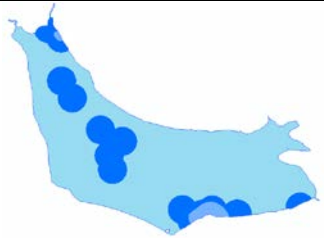
20549					
20550					
20551					

20552					
20553					
20554					
20555					

20556					
20557					
20558					
20559					
20560					
20561					

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