Environment Agency

Evidence

Assessment of the impact of hydropower on weir pool features

Report – SC120077/R1

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Miranda Kavanagh

Director of Evidence

Executive summary

Run-of-river hydropower schemes are often installed on existing weir structures. We present the results of a study to evaluate how such installations can affect the weir pool habitats found immediately downstream of weirs.

We found that there was limited impact from on-weir hydropower installations on weir pool habitats. Patterns of velocity and water depth are likely to change but the overall amount of available habitat remains similar at high, medium and low flows. The affect of changing flows on downstream shallow riffles at the weir pool exit was also shown to be limited.

A literature review conducted for this study revealed no specific studies on weir pools as ecosystems. As a result we undertook a modelling study to predict how the characteristics of these locations may change. We also derived a framework for evaluating the potential value of weir pools to help assess the impact of proposed hydropower developments on weir pool habitats.

We used 2-dimensional hydraulic models because they can show change in the pattern of velocity and flow depth which are likely to be modified by a hydropower scheme and they require data that is relatively simple to gather. We considered how the flow and depth changes might affect aquatic plants and animals by considering known species preferences and expert judgement. Gravel deposits in shallow water around weir pool margins, and in particular tail riffles, can be important for spawning fish and invertebrates, particularly if these gravels are free of fine sediment. Larger fish may also congregate in pools where there is highly oxygenated water. However, the importance of such features is dependent on the frequency and distribution of similar habitats in a catchment or reach.

A qualitative process for assessing the ecological and hydromorphological quality of a weir pool is proposed using readily available information to consider responses to the following questions:

- Is the weir pool within a site designated for its established national or international ecological importance?
- Are fish species present that are known to be at low frequencies or densities throughout the rest of the catchment?
- Are the morphological features present of good quality?
- Are the morphological features rare?

Anecdotally, but without the support of published research, it seems that weir pools are valued by anglers, that these locations are considered attractive to fish and that more fish can be caught here compared to surrounding areas. Angling amenity could add to the value of a weir pool. The more positive answers to these questions the greater the likelihood that the weir pool is ecologically important.

We tested the modelling and quality assessment techniques at 3 lowland river locations in England where hydropower schemes have been developed or proposed. These were Romney Weir near Eton, Berkshire, and Goring Weir at Goring, Oxfordshire both on the River Thames, and Pershore Weir at Pershore, Worcestershire, on the River Avon.

The weir pool below Romney Weir is likely to be ecologically important. There was little change in the overall distribution of depths and velocities after the introduction of a hydropower turbine but some spatial variation in velocity. The ecological impacts were

interpreted as likely to be small for a scheme placed close to either river bank but the potential for displacement of a non-native species (Nuttall's Waterweed) was highlighted at this site.

At Pershore Weir the weir is likely to be important because of the presence of fish with a preference for high flows. An on-weir hydropower scheme scenario was predicted to give rise to a potential increase in faster flows preferred by some (rheophilic) fish species. A lack of data meant that no interpretation of impacts on freshwater macroinvertebrates was possible.

The weir pool below Goring Weir is less ecologically important than at the other 2 sites. The modelling suggests that velocities in the weir pool are highly dependent on the amount of water released by the sluice gates in the centre of the weir and little information was available on how this structure operated. There is potential for substantial gain in the extent of depth and velocity conditions appropriate for gravel-spawning fish species in the post-hydropower situation when compared to the pre-hydropower situation with the sluice gates closed.

Weir pool habitats might be valuable because they provide rare or good quality habitat that is being used by plants and animals with limited access to alternative habitats. However, rarity does not automatically imply that such habitats are not resilient to environmental disturbance so that evaluation can be complex. The quality of the assessment will partly depend on the availability of site data about ecological and hydromorphological properties and data sources and methods are recommended here.

Where weir pools are considered important habitats we suggest a staged process for assessing potential impacts. If hydraulic modelling is considered necessary this will require detailed data on water depth for example from bathymetry surveys and the interpretation of ecological impacts is likely to require site-specific, geo-referenced ecological and sediment data to make the most effective use of the predictive model outputs.

This study shows that there may sometimes be environmental gains to be made from a change in the operation of existing structures, regardless of hydropower development. While changes in spatial distribution of flows are likely to occur, the ecological response to low head, on-weir hydropower-induced changes in the scenarios modelled was small.

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1 Introduction

The EU Renewables Directive sets a UK target of 15% of energy production (gross final consumption) from renewable sources by 2020 and since the introduction of feed-in tariffs in 2010 (guaranteed and high fixed price for electricity for up to 20 years) the Environment Agency has received more permit applications for hydropower schemes.

Low head hydropower schemes are generally constructed on existing weir structures built for a range of purposes such as powering mills, diverting water, navigation and flood defence. Flow over weirs usually generates a pool downstream of the weir, formed by the energetic flow over the weir at high flows scouring the bed. A riffle or gravel bar (area of raised bed material) is often observed downstream of the pool due to sediment deposition following the rapid rise and then fall in river energy over the weir. We define a weir pool as the area downstream of a weir, usually characterised by complex flow patterns before the river returns to a more typical hydromorphological pattern; in other words it is inclusive of both the deep pool immediately downstream of the weir face, and the tail riffle or bar.

Weir pools can be highly valued in modified low gradient lowland rivers where there is little diversity of hydraulic habitat and may also be popular areas for angling. The addition of a hydropower turbine may change flow rates and patterns and subsequently the weir pool ecosystem. However, no systematic review of the impact of hydropower schemes on weir pools has been undertaken and there is currently no standard way to assess the quality or importance of weir pools prior to hydropower installation or predict the impact of a given hydropower scheme on a weir pool as part of the scheme design or consent determination process.

Existing guidance for hydropower development in England (Environment Agency 2013) recognises the potential importance of weir pools but does not provide detail of potential impacts on weir pool flows, habitats, associated plants and animals, or options to mitigate impacts.

The results from this project are provided in two reports: the main report (SC120077/R1) and the appendix (SC120077/R2).This report (the main report) describes a project with objectives to:

- identify which available techniques can be used to identify important weir pool features;
- evaluate how hydropower installations on weirs might affect weir pool habitats, plants and animals by using case studies of typical installations;
- demonstrate how methods can be used to determine potential impacts (both positive and negative) of a hydropower design on weir pools.

The report does not directly predict changes in ecological status or consider costs or benefits and is not intended to replace existing guidance. We do not consider impacts associated with differing turbine types and the project is focused on England as other regulatory bodies have responsibility elsewhere in the UK. We outline legislative drivers for the protection of weir pool flora, fauna and the amenity they provide, and highlight knowledge on weir pool dynamics (section 2). We propose an approach to assess weir pool importance (section 3) and review hydropower impacts to assess expected changes in weir pools (section 4). We present a review and rationale for using hydraulic modelling to predict changes in weir pools after hydropower installation (section 5) and test the importance tool and modelling on case studies (section 6), ending with discussion and conclusions (section 7). The appendix presents specific supplementary information for sections of the main report.

2 Weir pool features

2.1 Legislative protection

Protection for weir pools is provided by overarching legislation, and species and habitat-specific legislation (details of the legislative framework are provided in section 2 of the appendix report).

For the Environment Act (1995), the Water Framework Directive (2000) and the Water Resources Act (1991), the Environment Agency is tasked with preventing deterioration of the hydromorphology, flora and fauna of waterbodies. The Water Framework Directive contains the most prescriptive legislation, and makes specific reference to a large number of elements. Modification of the flow patterns in a weir pool could alter many of the biological and hydromorphological elements, potentially changing the status of the waterbody.

Under the Environment Act 1995, the Environment Agency has a duty to promote the use of inland waters for recreational use. Angling is a popular sport in the UK with around 1 million participants and the Environment Agency has duties to protect and promote angling. The Wildlife and Countryside Act (1981) and Natural Environment and Rural Communities Act (2006) (through Biodiversity Action Plans, BAPs) provide protection for a number of species. Public bodies such as the Environment Agency and local authorities must have regard to those lists when carrying out their duties (i.e. permitting of a hydropower scheme must consider any potential impacts on relevant species). Some fish species in the UK BAP list are relatively common (e.g. brown trout *Salmo trutta*), and may have to be considered in most applications for hydropower development. The aquatic animal and plant (invertebrates and macrophytes) BAP species are less common and so will likely need to be considered less frequently.

Under the Wildlife and Countryside Act and the Habitats Directive (1992), Natural England has ultimate responsibility for Sites of Special Scientific Interest (SSSIs) and Special Areas of Conservation (SAC) sites. As a Section 28G authority, the Environment Agency has a duty to take reasonable steps to further the enhancement and conservation of SSSIs. The Wildlife and Countryside Act and Habitats Directive are relevant when processing hydropower applications for sites in SSSIs or SACs. Weirs themselves are generally considered to be bad for river functioning, acting as potential barriers to sediment transport and the free migration of fish (connectivity). Many such structures are targeted for removal for environmental enhancement and to reduce long-term maintenance costs. While weir removal may be an optimal solution this may not occur for a range of reasons, for example where water level management is a critical component of flood management. The relevance of the legislation in this project is to reflect when the weir pool habitat may have value worth maintaining. This may be particularly important in more modified rivers with a lack of habitat variation.

2.2 Understanding of weir pool processes

A literature review conducted for this study revealed no specific studies on weir pools as ecosystems. Therefore, this review draws on studies undertaken at existing weirs and on weirs constructed as part of river restoration projects. The purpose of the review is to understand whether and why they have distinct hydraulic and ecological characteristics. There are a number of ecological theories (e.g. intermediate disturbance hypothesis (Connell 1978), river continuum concept (Vannote et al. 1980) and the flood pulse concept (Junk et al. 1989)), which could potentially be used to help explain weir pool dynamics and value; however no formal links have been made in published literature and so these are not explored further.

2.2.1 Existing structures

Weir pools contain different habitats compared to those upstream of a weir structure with differences in water depth, current speed, substratum composition and the transition between free flowing and interstitial zone (Mueller et al. 2011). Following this, abundance, diversity, community structure and functional ecological traits of all major taxonomic groups indicate serial discontinuity, based on study reaches from 150 to 400 m in length (Mueller et al. 2011). In some cases, within-stream discrimination induced by weirs exceeds the variation between geographically distant rivers of different geological origin and drainage systems, with community effects and the underlying drivers generally being detectable at the family and order level of most aquatic plants, animals and fish (Mueller et al. 2011).

Investigations have found that total (fish) species richness and biomass can be higher downstream of a weir than remote from the weir, suggesting a direct influence of the weir on the downstream community (Cowx et al. 1995, Poulet 2007). Poulet (2007) found a difference between native (mostly rheophilic) and introduced (mostly limnophilic - preferring still or slow waters) species, with limnophilic species thriving upstream of weirs, and rheophilic species (preferring fast flows) dominating in 'natural' sections, although both limnophilic and rheophilic species were captured in weir pools. This suggests that there can be sufficient habitat within the weir pools to allow limnophilic species to find refuge without excluding most of the rheophilic species.

Changes in community structure have been observed following weir removal in Norway. Mortality of Atlantic salmon (*Salmo salar*) eggs was reduced and the densities of juveniles showed a marked increase following weir removal in a reach which encompassed areas which were previously upstream and downstream of the weir (Fjeldstad et al. 2012). Conversely pike and cyprinids were found in samples from the reach before weir removal, but not after removal (Fjeldstad et al. 2012).

The riffle/bar formed downstream of weir pools has been found to be important in a number of studies. It is suggested that higher water velocity exposes a clean gravel substrate which appears to be used as a feeding and spawning site by rheophilic species (Cowx et al. 1995). The authors also observe that in many lowland reaches, gravel below weirs may be the only substrate available for spawning for lithophilous spawners (that require gravel) and its absence may lead to a reduction or elimination of such species from the community.

Invertebrate assemblages in the reaches downstream of storage dams have been shown to be significantly different from those in upstream reaches with substrate being the key determinant (Miyake and Akiyama 2012).

An abundance of greenside darters (*Etheostoma blennioides*) was found in riffle habitats that consist of cobbles and loose boulders with large mats of *Cladophora* spp. (filamentous green algae) immediately downstream of a weir. This was probably due to high water velocities from weir discharge, freshets and ice scour, which help maintain unconsolidated riffle areas (Bunt et al. 1998).

The tail riffles of weir pools are the only spawning habitat for barbel (*Barbus barbus*) on large stretches of the River Thames and weir pools are often the only spawning and nursery grounds for barbel within impounded sections (Martyn 2007).

The pool itself has been highlighted as valuable habitat by a number of authors. Martyn (2007) points out the difficulty of monitoring barbel due to their preference for turbulent, snaggy and often deeper water, especially in weir pools, while Peirson and Sumner

(2013) state that weir pools are favoured overwintering areas for dace. Adult perch (*Perca fluviatilis*) are known to favour moderate to deep water, especially in the vicinity of bankside cover, large woody debris and man-made structures such as locks, weirs and walls (Peirson and Sumner 2013).

Within a hydropower context, the Environment Agency commissioned Jacobs to undertake a desktop ecological baseline study at three weirs on the Thames (Romney, Goring and Osney) as a precursor to hydropower application and development. In each case Jacobs used existing catchment ecological data, survey data and other freely available data. However, as the available ecological data was generally not specific to the weir pool, recommendations for further sampling were made in each case.

2.2.2 River restoration weirs

The placement of physical structures into lotic environments to create pools, to vary channel morphology, and to provide cover and habitat for fish and other aquatic organisms has a long history (White 1996), particularly in the USA. The purpose of placing objects in the river to produce the effects of a weir is two-fold (adapted from Roni et al. 2005):

- it helps to create deep holding plunge pools providing cool upwelling oxygenated water, cover and feeding areas for fish;
- upwelling from the pool enhances flows through the tail water gravel.

This section is not intended as a review of river restoration techniques, but it is included as many of the studies provide evidence of the value that hydraulic habitat complexes created by anthropogenic in-channel interventions can provide. We do not recommend the construction of restoration weirs, but are using the evidence gathered to inform the weir pool debate since studies on weir habitats are limited.

A detailed review of habitat rehabilitation techniques provides evidence of improvements in habitat complexity and quality following the installation of instream structures, although this is dependent on pre-rehabilitation conditions (Roni et al. 2005). Many studies have reported increases in pool frequency, depth, woody debris, habitat heterogeneity, complexity, spawning gravel and sediment retention following placement of instream structures (e.g. Roni and Quinn 2001, Brooks et al. 2004). Depth and flow heterogeneity increased in rehabilitated stream reaches compared to control reaches in 13 English streams (Pretty et al. 2003). Klassen and Northcote (1988) used tandem V-shaped weirs to improve spawning habitat for Pacific salmon and found an improvement in intra-gravel dissolved oxygen and gravel permeability compared to a reference site. It should be noted, however, that the effects of the introduction of woody debris, boulders and gravel can often be swamped by larger-scale geomorphological and physicochemical effects (Feld et al. 2011). It is less clear whether observed increases in hydraulic habitat quality and complexity translate into ecological improvements.

Several studies have demonstrated the positive effects of instream structure placement on juvenile Atlantic salmon. For example, O'Grady (1995) reported higher levels of age 1+ Atlantic salmon and brown trout parr in sections of Irish streams in which boulder structures such as weirs, stone mats and boulder clusters have been installed. In a study examining juvenile Atlantic salmon and brown trout in 13 Irish streams, Gargan et al. (2002) found significantly higher numbers of both Atlantic salmon and brown trout parr in rehabilitated reaches, but no difference in numbers of older trout or trout or salmon fry.

The review by Roni et al. (2005) highlights the lack of conclusive proof of response of adult salmonids to the placement of instream structures. In part, this lack of rigorous evaluation of adult salmon and trout response to instream enhancement stems from the long time frame (>10 years) needed to detect adult response to habitat alterations. Burke et al. (2008) did find using radio-tagging that adult Coho salmon (*Oncorhynchus kisutch*) migrated quickly and directly to one or two areas saturated with large woody debris and gravel (areas known to be high quality spawning habitat) and remain there. It is also likely that success will depend on the right amount of habitat provision for all life stages throughout a catchment.

A UK study on the effectiveness of artificial riffles and flow deflectors found no significant difference in fish abundance, species richness, diversity or equitability between rehabilitated and control reaches and concluded that, in general, rehabilitation increased depth and variation, and fish species richness and diversity appeared to respond positively to increased flow velocity (Pretty et al. 2003). However, there were few significant relationships between fish fauna and physical variables, indicating that increasing physical habitat heterogeneity does not necessarily lead to higher diversity (Pretty et al. 2003).

Kinzli and Myrick (2010) reported that bend way weirs (a rock sill located in the channel at a bend at 20 to 30 degrees into the flow with a crest level low enough to allow navigation) have been used to prevent river channel migration while enhancing aquatic habitat. Their study suggested that bend way weir installation could lead to the reduction of downstream displacement of Rio Grande silvery minnow (*Hybognathus amarus*) eggs, the creation of Rio Grande silvery minnow feeding and refugia habitat, and the creation of drought or low flow habitat through scour hole formation. However, they also noted that the weirs could serve as potential habitat for predators.

Literature on the changes in macroinvertebrate communities following the addition of instream structures is by no means conclusive (Roni et al. 2005), with some studies finding changes in community structure (feeding groups – Wallace et al. 1995) and diversity (Harper et al. 1998), while other studies detected no differences (e.g. Brooks et al. 2002).

The literature is more mature with regards to evidence of changes to aquatic plant diversity in response to instream structure placement (O'Grady 1995). Roni et al. (2005) postulate that these studies suggest some improvement in aquatic plant composition and growth from instream rehabilitation is likely to be from changes to depth and velocity.

In summary, the literature on channel restoration weirs suggests that variation in flows and channel depth can, in some locations, provide habitat benefits where such variation is currently limited.

2.3 Angling and habitat value of weir pools

Weir pools can provide diversity of habitat and good catches of fish, particularly in slow flowing lowland rivers. Anecdotally they are considered to be interesting and challenging places to fish, although evidence to support this assertion is limited an dlargely annecdotal.

A comparison of the fishing in 300 m reaches upstream and downstream of a weir on the River Don, the 'great weir fishing experiment', was published in the May 2011 edition of *Trout and Salmon* magazine. Thirty-two fish were caught in the reach downstream of the weir while only one was caught upstream of the weir; this disparity was attributed to the variety of habitat available downstream of the weir (deep bend pool, glide, riffle pocket water) compared to the canalised nature of the river upstream of the weir. It was noted, however, that only 2 of the 32 fish captured downstream of the weir were captured at the foot of the weir in the deep water. The authors of the article noted that the weir had a fish pass, and so any fish caught in the weir pool are unlikely to have been merely trapped at the base of the weir and unable to progress upstream.

When searching the word or words ‘weir pool’ in a search engine, a significant number of the search results are from angling websites with articles about how to fish weir pools, In summary, anglers appear to find weir pools interesting and productive places to fish although this may reflect ease of access rather than indicating that fish are particularly to be found in weir pools.

Aside from recreational angling weir pools can provide other benefits to fish in some circumstances. In a report assessing the effects of dredging, Martyn (2004) stated that the Mid–Upper Thames is generally lacking in suitable clean gravel (lithophilic) spawning habitat with the exception of weir pools and tributaries. Even the more suitable areas are usually sub-optimal for some lithophilic species such as barbel. Fish are forced to use some of these areas in the absence of alternative locations (Martyn 2004).

Bell and Martyn (2002) highlighted the importance of Romney Weir pool (Thames) in producing improved catches following relocation of gravels and the provision of fish shelters. Concrete fish shelters have been introduced to weir stream and weir pool locations on the Lower Thames, giving protection from predators, strong flows and angling pressure (Bell and Martyn 2002). It is thought that such features may provide lithophiles (fish which prefer coarse sediment) with a suitable juvenile habitat in an otherwise barren area, in close proximity to spawning grounds, thus further aiding chances of survival at critical phases. It appears that the context of the weir pool is of vital significance when assessing its importance for providing spawning habitat as all of the weirs highlighted in the anecdotal evidence above are in slow flowing, low gradient rivers.

2.4 Interpretation and conclusions

The lack of clarity surrounding the weir pools is neatly summarised by the three submissions to the Environment Agency’s guidance consultation (see Table 2.2). The first submission is sceptical about the assumed value of weir pools, and highlights the need for a scoping tool, the second is convinced of the ecological importance of weir pools, and the final submission highlights the importance of weir pools to anglers.

There is little published literature on weir pools. It is clear that weir pools contain different hydraulic habitat compared to the impounded reach upstream of the weir. Hydraulic habitats and ecological communities are distinct between reaches upstream and downstream of weirs, highlighting the importance of sampling multiple ecological features (Mueller et al. 2011). There is little information (published research or anecdotal) as to the importance of weir pools for macroinvertebrates and aquatic plants. However, the deep pool provides good habitat for adults of various fish species and greater fish species richness is found downstream of weirs, with both faster and slower flow loving species found in the downstream reach (Poulet 2007). The value of the tail riffle/bar has been noted (Cowx et al. 1995) and the nature of the riffle habitats downstream of weirs can result in local abundance of the rare greenside darter fish (Bunt et al. 1998). Anecdotal evidence from recreational anglers suggests a belief that larger fish are found in deep weir pools and the Angling Trust highlights the potential use of the downstream tail riffle/bar as spawning habitat.

In the anecdotal and angling evidence, the location of the weir pool appears to be pivotal to its perceived importance as the weir pools that attract the most attention are those located in low gradient streams.

3 Identifying the importance of weir pools

3.1 Evaluating weir pool significance

In this section we consider the utility of existing methodologies in classifying weir pool value. Classification tools developed to support implementation of the Water Framework Directive in the UK for fish (FCS2), invertebrates (RICT) and aquatic plants (macrophytes) (River LEAFPACS) all involve initial sampling of the ecological feature of interest and comparison with a reference site. An ecological quality ratio (EQR) expresses the quality of the sampled population against populations observed in reference sites. However, the geostatistical models of ecological community versus environmental variables are taken from near-natural reference sites (e.g. Wyatt 2005 for fisheries). In general, weir pools are likely to contain habitat very different from the majority of the river. Therefore, comparing weir pool communities with reference communities is unlikely to be helpful as although weir pool type habitat can occur naturally it is often relatively scarce compared to typical river habitat. Before and after surveys may indicate changes in wider communities upstream and downstream of any hydropower installation but would not inform change in weir pool habitat and are not considered further in this study. In addition, these methods require field visits with associated cost implications (although these are not considered here).

Other options to assess the quality of hydromorphological and biological features in weirs are listed in Table 3.1.

Table 3.1 Summary of other techniques to assess features of weir pools

Tool	Synopsis	Relevance to weir pools	Issues
RHS – River Habitat Survey	Evolving ecological impact assessment method developed before the Water Framework Directive. Results provide habitat modification score which does not equate to the Water Framework Directive status classes, but record the level of modifications based on inventories of features.	Scale of operation means that cross-section data can relate to weir pool condition and overall 200 m reach score can provide useful comparative data on weir pools and conditions upstream and downstream.	Remains a subjective survey method (linked to a semi-quantitative analysis). Requires trained auditors. Flow stage dependent results. Dependent on the assumption that habitat diversity leads to biodiversity.
ADCP – Acoustic Doppler Current Profiler	Unpublished ADCP studies have been undertaken at a number of weir pool sites by the Environment Agency and Sheffield University. By sampling repeatedly at a range of flows a detailed picture of weir pool hydraulics can be obtained.	This method captures the complex flow patterns at weir pools. Able to inform on characteristics of plunging flow. Able to give information on the vertical velocity profile within the water column.	This currently lacks any linkage to habitat and tackles weir pools from a hydromorphology perspective. ADCP devices cannot sample at shallow depths (0.25 to ~0.5 m depending on system) – thus there is potential to preclude some important habitat from the analysis. To sample a range of flows requires repeat visits.
RAPHSA – Rapid Assessment of Physical Habitat Sensitivity to	A suite of methods for producing weighted usable area (a measure of habitat) versus discharge curves without undertaking a full suite	The tiered approach could be useful to filter whether a weir pool contains habitat of interest. If the pool is	A reliance on a database of PHABSIM studies – of which none have been conducted at weir pools (M. Warren, personal

Abstraction (Acreman et al. 2008) DRAPHT – Direct Rapid Assessment of Physical Habitat Toolkit	of data collection, hydraulic and habitat analysis. Built on a database of relationships between weighted usable area and catchment characteristics. The characteristics used can vary from those gathered during a brief desk-based study ($DRAPHT_{CC}$), a detailed site walkover with channel geomorphological unit (CGU) mapping and hydraulic survey ($DRAPHT_{CM}$).	contentious or thought to be of value, the more detailed techniques can be applied incrementally.	communication).
Remote sensing – Carbonneau et al. (2005) also called APEM Fluvial Information System	Aerial photographs can be used to determine river depth and sediment grain size. Spatial mapping easily produced.	May be able to map the existing habitat in the weir pool. Could be cheap if existing photographs are available.	Needs clear water to undertake the analysis. If there are no existing pictures, photography can be expensive.
MesoHABSIM - Mesohabitat Simulation Model (e.g. Parasiewicz 2007)	Relies on repeated mapping of the hydraulic habitat (pools, riffles etc.) of the whole river reach under three or four different flows. Then uses habitat suitability indices to determine the flow–habitat relationships for each species.	Repeated visits to the weir pool will allow the development of flow–habitat relationships at the weir pool for the species of interest. This would allow the user to develop an understanding of the important elements within a weir pool and the flows needed to sustain them. Vezza et al. (2012) found that MesoHABSIM worked well in streams characterised by a high degree of flow complexity.	Repeated site visits to a weir can be costly and the need to sample a range of flows increases the organisational costs. Also relies on habitat suitability indices.

Direct measurements of weir pool habitats have been undertaken for fish habitats, for example at Castleford Mill Weir (Fishtek Consulting, 2009). Data from field surveys using transects to collect water velocity, depth and substrate were used to determine an index of spawning quality for chub and dace within the weir pool. Similar approaches have been used at Pershore (Fishtek Consulting 2012a) and Kingfisher Cottage Weir (Fishtek Consulting 2010) on the River Avon. This quite detailed methodology requires a site visit from operators able to work in high energy river environments and undertake boat surveys (in the case of large weir pools). The scoring method is simple, treating depth, velocity and substrate as having equal weight; however, in reality if the substrate is unusable for spawning, the hydraulic conditions would be largely irrelevant.

No other such weir pool impact assessments were found and none of the studies considered macroinvertebrates and aquatic plants. Many of the approaches outlined above (Table 3.1) are labour intensive, requiring site visits (sometimes multiple site visits) and ecological and hydraulic sampling using specialist skills and equipment. The RHS requires no specialist equipment and could be undertaken by one person on a walkover but does not provide very detailed information.

It would be useful to identify weir pool value before undertaking laborious field techniques and remote sensing can be cheap to apply if good quality aerial photographs are available. However, sediment sizing relies on clear water conditions which may not be available in deeper rivers.

ADCP velocity surveys sample the detailed hydraulics of the weir pool. But repeat surveys may be needed to show change. A similar repeat visit requirement applies to the MesoHABSIM approach.

3.2 Weir pool importance scoping process

There is little published literature that specifically identifies the importance of the complex of habitats commonly found immediately downstream of weirs in general, or those at which hydropower schemes have been constructed. The scale of importance is fundamental to contextualising any subsequent answer to the question of whether hydropower schemes give rise to any significant hydrological, hydromorphological or ecological impacts on the complex of habitats downstream of weirs.

A series of questions are proposed to support a rapid, qualitative assessment of potential site importance based on readily available information. The development of a quantitative tool was not considered feasible given the insufficient evidence to codify the indicators, and the undertaking of any comparative assessment of site importance, other than at three case study sites was considered outside the scope of the project. Fundamentally, the questions were designed for the purposes of providing a steer on the importance of the weir pool in the very early stages of a hydropower project, with minimal data requirements.

While an entirely objective process would be the most useful, the complexity and inter-relation of riverine processes means that it was not possible to develop a process that could be rapidly applied without some sort of subjective assessment or by applying professional judgement. Thus the process is not prescriptive in specifying further work; its purpose is to guide the user to ask sensible questions in a logical order. It also takes into account the fact that while the questions are phrased in a binary way, the answers to many of the questions will not be binary. This again requires judgement to assess the importance of the weir pool complex.

As this scoping process is designed for use in the early stage of a proposed scheme, the data requirements are minimal:

- Hydromorphological data is gathered through a brief site walkover and examination of aerial photographs. Understanding the hydromorphology of the catchment is fundamental to determining importance of a weir reach because hydromorphological processes directly impact on river organisms. In particular, some of the most important, composite features of the complex of habitats immediately downstream of a weir are gravel bar deposits, which support important life stages of fish, as well as less common invertebrates.
- Routine fish survey data is obtained from the Environment Agency, for the nearest upstream and downstream survey location related to the weir site in question.
- Any available site-specific data should be gathered.

3.2.1 Scoping process

The scoping process involves asking the following five questions:

- Is the weir pool in an SSSI/SAC?
- Are the morphological features present of good quality?

- Are the morphological features rare?
- Are fish species known to be present at low frequencies/densities in the catchment likely to be exploiting the complex of habitats associated with the weir pool?
- Does the weir pool complex provide significant angling amenity?

Question: Is the weir pool in an SSSI/SAC?

This is an easy and fundamental criteria to define and will indicate legislative protection of species or habitat. However, designation (or lack of) in no way absolutely defines environmental importance, with temporal variation caused by natural environmental processes, scientific understanding and the process for site designation being extremely difficult to align (section 2.1).

The Water Framework Directive is arguably the most important legislation as it affords generic protection to a wide range of abiotic/biotic aquatic features and processes. It does not provide a system of site classification that can be used to objectively define importance of a weir pool complex but a waterbody failing to achieve appropriate ecological status/potential is important and needs to be improved and a waterbody already achieving appropriate ecological status/potential must not be allowed to deteriorate.

Question: Are the morphological features present of good quality?

Morphological quality should be determined by comparison with other natural and non-natural gravel features (if present) in the system to help determine whether the weir pool complex provides good quality habitat. This should initially be assessed during a hydromorphic audit as aerial imagery is unlikely to give the detail necessary to answer this question. It can also be hard to identify bars, riffles and other shallow areas from aerial photography where the flow conditions are unknown (they are harder to see at higher flows).

Question: Are the morphological features rare?

Feature rarity is a complex but very important concept to consider when describing importance of a particular habitat/ecological feature. In steeper gradient rivers the frequency of depositional gravel bar features in the surrounding reach may be high so the importance of one particular weir pool complex might be low, with similar hydraulic habitat conditions existing elsewhere in the surrounding reach. In rivers with a shallower slope this type of morphology will be less frequent, which may raise the importance of an individual weir pool complex where it does occur.

If a number of weir features exist in a catchment and they are geographically concentrated, a single weir and its associated habitats could be considered rare (or important) in the context of the catchment as a whole. This is entirely dependent on the scale of the study area however, as if the same sequence of weir features is considered in isolation, a single weir between the outlying weirs is unlikely to be considered rare (and therefore its associated hydraulic habitat important). This is illustrated in Figure 3.1: the highlighted weir could be classed as rare when considered at scale 1, but not rare when considered at scale 2.

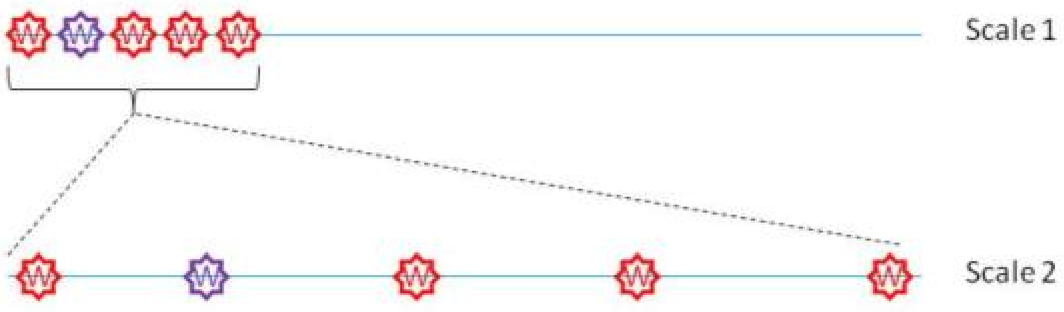


Figure 3.1 Feature rarity in relation to scale of study area

An important additional consideration in establishing rarity of habitat from a fisheries perspective is whether the feature being considered is actually accessible to fish. For example, if the complex of habitat types immediately below the weir is not accessible to fish species due to the presence downstream of substantial barriers to upstream migration, the weir reach might not be considered as important as if it was completely accessible and available for ecological exploitation (see Table 3.2)

We recommend the use of the Environment Agency's River Obstruction Database, supplemented by local knowledge, to assess accessibility for fish. This data source contains readily available and comprehensive information on in-channel structures that could represent a barrier to longitudinal migration of fish; albeit the data on barrier height are uncertain and some structures may be missing. In considering feature rarity, the database can help put the weir site in context within the catchment. Information such as distance between weirs downstream (including tributaries), presence of fish passes, head over barrier and number of barriers downstream will produce a high-level picture of habitat connectivity which could be used to inform a view on habitat accessibility, and what length of river (down to the next nearest weir feature) might be ecologically reliant on the habitat immediately downstream of the weir pool complex in question. When considered alongside the results of a hydromorphic audit, supplemented with information from aerial imagery, a picture of feature rarity can be developed. Some consideration should also be given to potential future improvements that might remove downstream obstacles to fish passage.

A summary of questions to pose to describe rarity are provided in Table 3.2. The sequence of questions asked is not rigid and the answers given should be considered in the context of each other.

Table 3.2 Questions that could be posed to describe rarity/importance

Question	Conclusion if answer is no	Conclusion if answer is yes
Do in-channel features exist downstream of the weir in question that are impassable to fish and likely to remain so?	The habitats immediately downstream of the weir in question are accessible by upstream, longitudinal migration, more likely to be ecologically exploitable and therefore potentially important	The habitats immediately downstream of the weir in question are inaccessible by upstream, longitudinal migration, less likely to be ecologically exploitable and the features therefore could be considered less important
Is the nearest impassable barrier downstream spatially remote from the weir in question?	The habitats immediately downstream of the weir in question potentially cover a small area and therefore could be considered less important	The habitats immediately downstream of the weir in question form part of a larger habitat complex and therefore are more important

Where they do exist, are impassable barriers downstream common?	The habitats immediately downstream of the weir in question are likely to be more accessible and therefore more important	The habitats immediately downstream of the weir in question are likely to be less accessible and therefore less important
Are the hydromorphological features found immediately downstream of the weir pool found elsewhere in the catchment?	The habitats immediately downstream of the weir in question are likely to be rare in the context of the catchment and therefore important	The habitats immediately downstream of the weir in question are unlikely to be rare in the context of the catchment and therefore could be considered less important
Are the hydromorphological features found immediately downstream of the weir pool found elsewhere in the reach downstream of the weir?	The habitats immediately downstream of the weir in question are likely to be rare in the context of the reach and therefore important	The habitats immediately downstream of the weir in question are unlikely to be rare in the context of the reach and therefore could be considered less important
Are the equivalent hydromorphological features well spaced when considered at catchment scale?	Habitats similar to those found immediately downstream of the weir in question are likely to be more ecologically accessible and therefore the features in the weir pool in question could be considered less important	Habitats similar to those found immediately downstream of the weir in question are likely to be less ecologically accessible and therefore the features in the weir pool in question could be considered more important

Question: Are fish species known to be present at low frequencies/densities in the catchment likely to be exploiting the complex of habitats associated with the weir pool?

Along with information about the type, quality and spatial distribution of fluvial and morphological features in the catchment we recommend assessment of fisheries monitoring data upstream and downstream of the weir to confirm whether the fish population of the audit reach reflects the habitat types identified during the audit. An understanding of the fluvial and morphological character of the complex of habitats downstream of the weir can then be used to predict what fish species known to be exploiting comparable habitats in the adjacent reaches may be present in the reach downstream of the weir. This may inform the assessment of rarity.

For example, where a large, deep water/pool feature is present downstream of a weir that might be exploited by eurytopic (generalist fish such as roach and bleak) or even limnophilic species and where such features are not widely distributed within the catchment, the presence of such species at survey sites downstream but at low frequencies/densities might suggest that the pool feature at the weir in question is exploited during certain life stages by such species, is rare and is therefore potentially important.

Similarly, where a combination of substrate type, existing weir form and resulting hydraulics lead to a predominance of bar features downstream of a weir and such features are ubiquitous in the catchment, an abundance of rheophilic, fast-flow spawning species upstream might suggest that the exploitation of the bar features downstream of the weir in question is of lesser importance.

While there is a lack of data for aquatic plants and macroinvertebrates, it is plausible to assume that they could be negatively impacted upon by reduced flows and therefore should be considered in an assessment of weir pool importance. However, few aquatic plant species of legislative importance are likely to be present in weir pool habitat complexes (see appendix section 2.2), and therefore their omission from a process that intends to utilise existing data to provide an initial steer on weir pool importance can be justified. In addition, invertebrate species are less likely to migrate upstream and the lack of routine survey data for the complex of habitats within the influence and downstream of a weir suggests their omission could also be explained. Nevertheless, where such site-specific data does exist it should be considered.

Question: Does the weir pool complex provide significant angling amenity?

Weir pool complexes are likely to be more important if they provide a service to the local community or attract angling tourists from further afield. Freely available online resources (angling club websites, Environment Agency angling guides) supplemented by discussion with locals can help identify angling amenity.

The greater the number of ‘yes’ answers to the above questions the more likely it is the weir pool is important.

4 Expected changes to weir pool features following hydropower installation

This section describes the potential impacts of hydropower installations on weir pool flows and features which are dependent on the site and the type of hydropower scheme.

Hydropower installations are of two main types. In general, high head schemes are located on upland, steep rivers. A small low head impounding structure is usually introduced into the channel to divert a portion of the flow into a pipeline. The water accelerates down the pipeline and is used to drive turbines in a powerhouse. Subsequently, water is returned to the river downstream without storage. We do not consider high head schemes further because there will be no existing weir pool if a new structure is introduced. It is likely that the weir used to direct flow into the take-off is shallow with a small weir pool, and high head schemes tend to be on steep rivers which have a natural plunge-pool type hydraulic habitat so weir pool habitat in such circumstances is likely to be limited.

Low head run-of-river (RoR) hydropower schemes are generally developed on existing structures. Typically these structures have a head difference of <5 m. There are a large number of hydropower turbines on the market, but, for the purpose of this project, it is not the type of turbine which is important, rather the amount of water used compared to the natural flow regime of the river. RoR hydropower schemes generally operate during the middle of the flow range, thus maintaining high flows and protecting low flows (SNIFFER 2011). There are two main types of RoR hydropower, 'mill leat' and 'on-weir' (Table 4.1 and Figure 4.1).

The mill leat type hydropower scheme will take flow away from the weir pool, while the on-weir hydropower scheme will have a nominal depleted reach but could force a redistribution of flow patterns in the weir pool. Each of these situations will be discussed in turn.

Table 4.1 Summary of low head hydropower types

Type	Description	Impact on flow
Mill leat	Flow is diverted via an existing mill leat, through a turbine, and re-routed back into the river via the mill leat.	This can lead to a substantial depleted reach between the off-take and return to the main channel. There will be a reduction both in overall flow and variability in the depleted reach (including the weir pool).
On-weir	The turbine is located at or very close to the weir.	A negligible depleted reach, but has the potential to change the flow patterns in the weir pool.

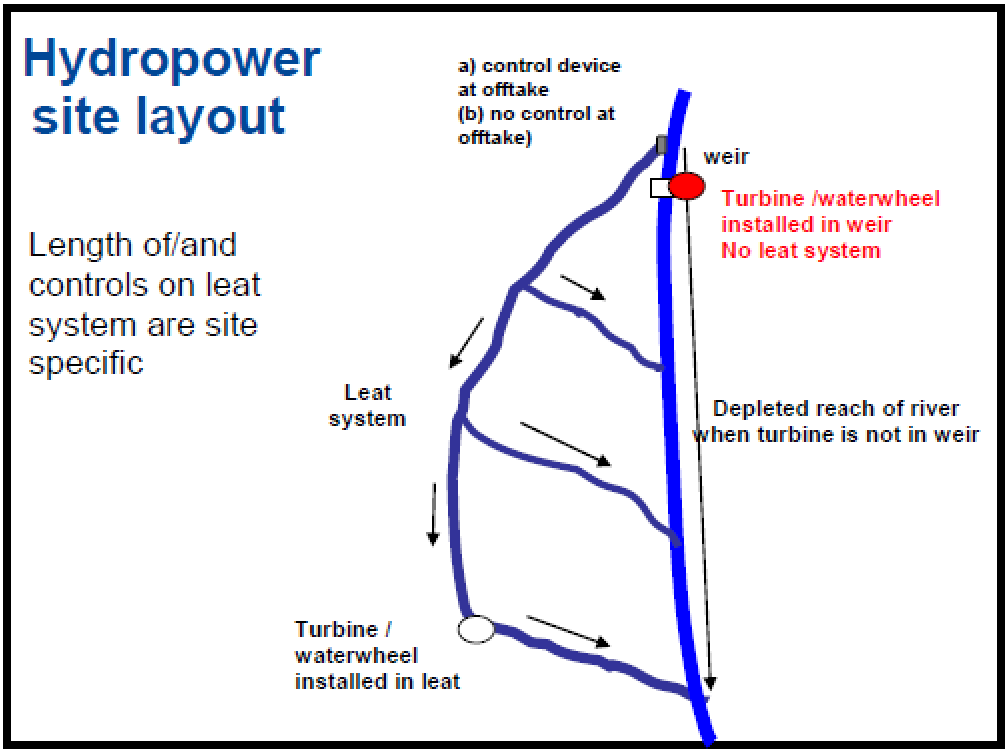


Figure 4.1 Typical low head hydropower layouts. From Environment Agency (2012)

4.1 Low head – mill leat type

The hydraulic habitat complex within a depleted reach will be changed by a reduction in overall flow and flow variability. Hydrological variability is important for shaping the biophysical attributes and functioning of river ecosystems (e.g. Poff et al. 1997, Richter et al. 2003), and the physical habitat of river ecosystems (e.g. Bunn and Arthington 2002). Hydrological variability also contributes to the diversity of instream ecosystems and many species have evolved life history strategies in direct response to natural flow regimes (Bunn and Arthington 2002). Any human changes to the natural flow regime may result in change to the river function. The most obvious impact of depleted reaches is the loss of wetted area. However, no studies were found that specifically relate to impacts of depleted reach schemes on weir pool habitats where some of the flow may have been diverted away from the weir and downstream pool.

4.1.1 Response to altered flows

A recent study, WFD21 (SNIFFER 2012), which included a literature study and expert workshop to collate the current knowledge of the response of various species to changes in flows, highlighted conflicting opinions and prompted further data collection (M. Warren, personal communication) (2014). The findings were presented as a conceptual model, a description of published evidence and summary tables. The tables have been edited and are presented below for salmonids, coarse fish, macroinvertebrates and aquatic plants (Tables 4.2–4.4). Tables 4.2 and 4.3 present a summary of the impacts proposed in WFD21 for salmonids and coarse fish respectively and could be considered relevant to impacts associated with depleted reach hydropower schemes, although not all of the flow changes considered in that study are included. Information is presented on extreme and extended low flow and the loss of small floods as these are potentially analogous to depleted reach hydropower schemes.

Depleted reach hydropower schemes vary as the proportion of take above a ‘hands-off flow’ can vary, as can the proportion of flow going down the depleted reach. However, the non-specific nature of the summary tables means that the potential impact of a range of depleted reach hydropower schemes can be inferred.

Impacts particularly relevant to salmonids arising from flow changes are principally negative and include loss of gravel flushing, loss of depth and increased competition in deeper water; impacts particularly relevant to coarse fish species are given as potentially negative and positive. It should be noted, however, that in the context of depleted reach hydropower schemes, the potential positive impacts are unlikely to be realised in any situation or scale context other than on small rivers where installed turbines can accommodate a high proportion of flood flows and conditions in the depleted reach remain relatively constant. It is also worth noting that positive impacts realised as a result of reduced flow variability in the depleted reach could quickly be negated by the speed of flow and level change resulting from turbine start-up/shut-down.

Table 4.2 Salmonid flow response summary (adapted from SNIFFER 2012)

Life stage	**Extreme and extended low Q**	**Loss of small floods (≤1 year), including freshets**
Egg incubation **(October–March)**	Desiccation Loss of gravel flushing **N↓**	Loss of gravel flushing **N↓**
Fry swim up **(March–April)**	Area/habitat loss Predation increased Competition increased Displacement to deeper water **N↓**	
0+ **May–November**	Area/habitat loss Predation increased Competition displacement to deeper water **N↓ G↓**	
0+ and >0+ (winter)	Loss of depth shelter **N↓**	
>0+ (including adult residents)	Area/habitat loss Food loss predation increased Displacement to deeper water **N↓ G↓**	
Smolting (not applicable to brown trout or grayling) **(April–June)**		Lack of cues **N↓**
Adult passage **(All year, mainly May–October)**	Obstructed passage **N↓**	Lack of stimuli and directional cues **N↓**
Spawning **(October–December)**	Access restricted **N↓**	Lack of stimuli **N↓**
Kelt **(November–April)**	(Likely barriers, and greater energy demand) **N↓**	Slow or delayed downstream passage

Notes
G↑ Growth increase
G↓ Growth decrease
N↑ Number increase (mortality decrease)
N↓ Number decrease (mortality increase)

Q discharge in m^3/s

(Brackets round responses) – less important, or likely but unsubstantiated

Table 4.3 Coarse fish flow response summary (adapted from SNIFFER 2012)

Life stage	Lithophilic coarse fish		Phytophilic coarse fish	
	Extreme low and extended Q	**Loss of small floods including freshets (≤1 year)**	**Extreme low and extended Q**	**Loss of small floods including freshets (≤1 year)**
Egg incubation (March–June)	Desiccation Poor infiltration of oxygen, siltation N↓		Reduced availability of spawning habitat results in high egg densities and elevated predation risk N↓	Reduced risk of eggs deposited in depleted reach becoming desiccated as a result of rapidly receding levels N↑
Free embryos and larvae (March–June)	Lack of access to marginal nursery habitats G↓ N↓	Reduced risk of displacement and flushing of phyto/zooplankton blooms G↑ N↑	Lack of access to marginal nursery habitats G↓ N↓	Reduced risk of displacement and flushing of phyto/zooplankton blooms G↑ N↑
0+ (April–September)	Lack of access to marginal nursery habitats G↓ N↓	Reduced risk of displacement and flushing of phyto/ zooplankton blooms G↑ N↑	Lack of access to marginal nursery habitats G↓ N↓	Reduced risk of displacement and flushing of phyto/zooplankton blooms G↑ N↑
0+ (winter)	Loss of marginal refuge habitat and floodplain connectivity N↓	Reduced risk of displacement N↑	Loss of marginal refuge habitat and floodplain connectivity N↓	Reduced risk of displacement N↑
>0+ (including adult residents)	Congregation of shoals (increased competition and predation pressure) N↓ G↓		Congregation of shoals (increased competition and predation pressure) N↓ G↓	
Adult spawning migration (February–June)	Obstructed passage of weirs N↓	Potential negative impact on longitudinal migration and physiological cues	*(Obstructed passage of weirs) N↓	Reduced access to floodplain/off-river habitats
Spawning (March–June)	Reduced habitat quality through siltation and poor infiltration of clean well-oxygenated water Access restricted N↓		Reduced availability of spawning substrate through lack of access to marginal macrophytes and floodplain N↓	Reduced risk of eggs deposited in depleted reach becoming desiccated as a result of rapidly receding levels N↑

Notes

G↑ Growth increase
G↓ Growth decrease
N↑ Number increase (mortality decrease)
N↓ Number decrease (mortality increase)

Q discharge in m^3/s

(Brackets round responses) – less important, or likely but unsubstantiated
* of lower importance than lithophilic guild

An important feature in weir pools is the tail riffle/bar, which can be used as spawning habitat by many fish species. Gravels used for spawning need to be free of fine sediment, which is achieved by being flushed through with highly oxygenated fast flowing water. Abstraction associated with a mill leat hydropower scheme which leads to the reduction in medium and high flow events could alter these flushing flows.

The accumulation of fine sediment within salmonid spawning gravels (called redds) is generally considered to be one of the main factors contributing to a reduction in embryo survival (Sear et al. 2008). Fine sediment can either accumulate in the gravels from the bottom up (termed accumulation) or form a crust over the redd (termed sedimentation). Accumulation is most likely to impact on incubating embryos while sedimentation is likely to impact upon alevins at the time of emergence. Particles associated with accumulation are likely to be finer than those associated with sedimentation (Sear et al. 2008).

Excess sedimentation can also cause gill irritation, impede movement, alter foraging behaviour, affect blood physiology and sometimes induce mortality (SNIFFER 2011). Reduced flows in depleted reaches may render gravel spawning areas too shallow, leading to redd dewatering or freezing of eggs or alevins (Gibbins et al. 2008). The increased stability of baseflows and reduced flow variability has been observed to reduce the number of sub-adult humpback chub *Gila cypha* (Converse et al. 1998).

Flow reductions can affect the hydromorphology and water quality of the river, with artificially reduced discharge having slower velocities, increased water temperatures and shallower habitats (Anderson et al. 2006). A reduction in flow could result in shallow areas and marginal areas drying out (as per Kubecka et al. 1997), potentially reducing the amount of spawning and/or nursery habitat.

When low flows were simulated in an artificial stream (using weir offtakes and penstocks) two New Zealand fish species were observed to actively emigrate from riffles in direct response to reduced flows (Davey et al. 2006). Reductions in flow in the abstracted reach of mill leat hydropower schemes may force juvenile salmonids (which favour shallow riffle areas) into deeper areas where they may face predation from larger salmonids (North, 1979). A number of authors have reported reduced fish populations in response to reduced flows (e.g. Elliott et al. 1997, SNIFFER, 2011).

Invertebrates and aquatic plants could suffer habitat loss due to prolonged low flows and the lack of sediment flushing provided by flow variability (Table 4.4). Increased stability of baseflow and reduction in flow variability has been associated with an increased standing crop and reduced species diversity of macroinvertebrates (e.g. Armitage 1977, Lillehammer and Saltveit 1979). A reduction in Average Score per Taxa was observed in a depleted reach in a stream in Snowdonia where up to 50% of the annual flow is abstracted for power generation, but there was no significant difference in diversity (Copeman, 2007). Some taxa (invertebrates) respond to the stress of reduced flow by drifting downstream (James et al. 2009).

The number of macroinvertebrate taxa in riffle and pool-rock assemblages has been found to be significantly lower at regulated sites (reduced and stable flows) on the Hawkesbury–Nepean River, Australia, when compared with unregulated sites, but the number of stream-edge macroinvertebrate taxa was unaffected by regulation (Growns and Growns 2001). This is surprising given that any reductions in flow are likely to affect the marginal areas more than other areas of the watercourse.

However, Dewson et al. (2007) comment on the site-specific nature of the impacts of water abstraction, finding that that the impacts of abstraction on invertebrate communities differed between streams that vary in water quality, probably because of the relative sensitivities of invertebrate communities to changes in the physical habitat of these streams.

The potential impact of lowered baseflows on aquatic plant (macrophyte) communities were summarised in SNIFFER (2012) as:

- constant reduced flow could lead to stable exposed substratum, associated with perennial rather than annual species (e.g. Holmes and Whitton 1977);
- an increase in terrestrial plant species in the margins (e.g. Westwood et al. 2006);
- an increase in filamentous algae in high energy river types which can smother submerged macrophytes.

In a study of sedimentation in north-east Spain invertebrate assemblages were relatively taxon poor and had low densities in locations with high fine sediment content compared to those with low fine sediment (Buendia et al. 2013). Increased deposition of fine sediment can also smother submerged plants which cannot alter their rooting depth (SNIFFER 2012).

Table 4.4 Macroinvertebrate and macrophyte flow response summary table (adapted from SNIFFER 2012)

	Macroinvertebrates		**Macrophytes**	
	Extreme low and extended Q	**Loss of small floods including freshets (≤1 year)**	**Extreme low and extended Q**	**Loss of small floods (≤1 year)**
March to May	Area/habitat loss Predation increased Competition increased Density in deeper fast flowing refuges **N↓ R↓**	Loss of gravel flushing **N↓ R↓**	Area/habitat loss Conditions suitable for algae growth **N↓ R↓**	
June to August				
August to September				
October to February	Area/habitat loss Predation increased Competition increased Density in deeper fast flowing refuges **N↓ R↓**	Loss of gravel flushing **N↓ R↓**	Loss of clearing of dead macrophytes and fine sediment **N↓ R↓**	Loss of clearing of dead macrophytes and fine sediment **N↓ R↓**

Notes

R↓ Taxon richness decrease

N↓ Number decrease (mortality increase)

Q discharge in m^3/s

4.2 Low head – on weir

No studies could be located that investigated the potential ecological and hydromorphological impacts of adding an on-weir hydropower turbine to an existing weir. Recreational anglers have highlighted concerns that such installations could have a deleterious effect on weir pool habitat but have no additional evidence of these effects.

Determining the hydromorphological and ecological impact of an on-weir hydropower turbine is difficult. The hydromorphology and subsequent ecology of a weir pool is obviously dependent on the site-specific hydrology and geomorphology which combine to create ecological habitat. The amount of flow, position on the weir (both in terms of proximity to banks and proximity to desirable habitat) and angle of orientation of the turbine and tailrace will be unique to each hydropower scheme. Where a depleted reach is absent, only the flow patterns will change in the weir pool and as such any changes to the hydromorphology of the weir pool may be subtle, with changes in velocity more prevalent than changes in depth. Changes in flow over the weir may affect fish passage but this impact is not considered further in this project.

If, for example, a tail riffle/bar contains a good gravel spawning habitat, a small change in current velocity through the gravel may not lead to deterioration in incubation success. The literature suggests that fish can use sub-optimal habitat for spawning; for example, Barlaup et al. (2008) found that nests of Atlantic salmon were found to be aggregated in the area with the highest water current, but successful nests were also found in areas where the water current was much reduced. The literature was not clear, however, on the occurrence (or otherwise) of population-level impacts as a result of opportunistic utilisation of sub-optimal habitats.

4.3 Interpretation and conclusions

Studies of hydropower schemes with depleted reaches (including weir pools) can show a decrease in wetted area and a change in fish population (a reduction in biomass). The evidence is less clear with regard to macroinvertebrates and macrophytes.

The conceptual model summary from the SNIFFER (2012) WFD21 study was used as the basis for a more hypothetical exploration of the potential impacts of abstraction on fish, macrophytes and macroinvertebrates. Salmonid and coarse fish species are negatively impacted by both a reduction in overall flow and a reduction in flow variability. SNIFFER (2012) presents tentative evidence that coarse fish may benefit from a less variable flow regime although such benefits are unlikely to be realised in many hydropower schemes. Macroinvertebrate and macrophyte populations are negatively impacted by any reduction in baseflow and the reduction in variability in the depleted reach.

No studies were found that specifically address the impact of on-weir hydropower schemes on weir pools. A hypothetical discussion highlights that the depth of the weir pool is unlikely to change, but the flow pattern in the weir pool could change depending on site-specific circumstances. This could lead to changes in the flow velocities in the tail riffle/bar, which may or may not impact upon lithophilic spawning fishes depending on site-specific circumstances. As a result it is necessary to identify techniques with a predictive element to explore these impacts.

5 Predictive tools

This section evaluates the approaches that could be used to predict the impact of hydropower schemes on weir pool complexes.

5.1 Hydromorphological assessment tools

In-channel, riparian and infrastructure features can be assessed through well-developed morphological condition survey methods to provide reasonable certainty in the assessment of pressures and impacts (UK-TAG 2008). Relevant hydromorphological assessment tools are summarised in Table 5.1.

Table 5.1 Summary of hydromorphological assessment tools

Tool	Synopsis	Relevance to weir pools	Issues
MIMAS – Morphological Impact Assessment System	Developed specifically for the Water Framework Directive. Expert judgement based risk assessment tool for rivers. Assumes a direct relationship between ecological status and degree of morphological alteration from pristine. Uses set limits of ecological degradation dependent on type and extent of morphological alteration and river type. Predicts standard river response to morphological pressure based on river type.	Scale of operation means that overall waterbody pressure score is influenced by engineering at weirs but does not provide a useful measure of local impact on weir pool hydromorphology.	Best at waterbody scale. User must accept expert judgement values regarding hydromorphic impact and engineering. Relies on typology developed in north-west USA and modified for Scottish rivers. Uses a reference condition as a baseline (as RICT, FCS2).
RAT – River Assessment Tool	Developed to facilitate consistent and thorough evaluation of the potential impacts of proposed projects on river habitat. Assigns a classification for a waterbody based on the departure from reference condition for the channel type. The technique assigns a morphological classification directly related to that of Water Framework Directive – high, good, moderate, poor and bad.	Scale of operation means that overall waterbody classification is influenced by presence of weirs but does not provide a useful measure of local impact on weir pool hydromorphology.	Most useful at waterbody scale. Uses a reference condition as a baseline (as RICT, FCS2).

5.2 Flow apportionment tools/guidance

5.2.1 WALES methodology

WALES (Water Abstraction Licensing using Ecological Scoring) is an evidence-based method for assessing the sensitivity of river ecology to changes in flow. It was developed to determine an acceptable abstraction regime for upland, high head hydropower schemes in Wales. Flow variability in the depleted reach is protected by splitting the flow. The sensitivity of a given river (an environmental score) is determined by using its physical attributes and measures of the fish, invertebrates and macrophyte communities. Depending on the total environmental score, a maximum instantaneous abstraction rate above the hands-off flow (as a percentage of available flow) is specified. This is unlikely to be appropriate for low head schemes especially on low gradient rivers, which is where weir pools are likely to have high importance.

5.2.2 SNIFFER WFD48

The SNIFFER WFD48 (2006) project proposed a revision to water resource regulatory standards covering abstraction and impoundments for rivers and lakes throughout the UK based upon ecological status.

Analysis of changes in the physical character of river waterbodies (based on wetted river width) reinforced the significance of Q95 (the flow which is exceeded 95% of the time) as a threshold at which the sensitivity to flow can change (SNIFFER 2006). Practical standards were derived using expert judgement, with a risk-based approach acknowledging that some river waterbodies may fail to achieve the desired ecological status, but these would be identified by appropriate monitoring. In this way, standards are defined to achieve different levels of Water Framework Directive ecological status. The strictest standards were those for steep upland rivers and chalk streams while the least stringent tend to be for lowland clay substrate rivers. This juxtaposes the finding of the literature review where weir pools are considered more important (anecdotally at least) in lowland rivers rather than upland rivers. Weir pools are unlikely to be typical features characteristic of lowland rivers in more natural situations. This approach may help in setting flow limits for hydropower schemes which involve the creation of a depleted reach but less useful for on-weir, RoR sites which need to take account of site-specific complexity.

5.3 Habitat assessment tools

The relevance of habitat assessment tools for weir pools are summarised in Table 5.2.

Table 5.2 Summary of habitat assessment tools

Tool	Synopsis	Relevance to weir pools	Issues
HEFT – Hydro-Ecological Flow Thresholds (Atkins). No reference – information from SNIFFER (2013)	A minimum of three flow surveys need to be conducted at each of a number of riffle transects throughout the study reach. Regressions of depth and velocity against flow are then produced for these data and used to establish guideline flows, based on the velocity and depth requirements of the species and life stages of interest.	A weir pool is likely to only contain one riffle. This technique could establish ecological flow thresholds for that riffle (if the velocity and depth requirements of the species/life stage of interest are known).	Focuses on the shallowest transects within a reach and so is unlikely to work on weir pools where there is considerable diversity of flow. Lack of assessment of the temporal flow requirements of aquatic organisms.
FHAT – Functional Habitat Assessment Tool (APEM 2012)	Uses a combination of habitat walkover to identify channel geomorphological units (CGUs) and hydraulic data (ADCP surveys) collected at representative cross-sections throughout the study area. The percentage of usable habitat for each species/life stage of interest is calculated for each ADCP transect and multiplied up to the reach scale using the CGU data. Modelling is used to calculate the depth and velocity at different flows.	Designed to be applied at the reach scale – could feasibly be used to map a weir pool. Due to the flow complexity in a weir pool, the modelling approach would need to be carefully considered (if the velocity and depth requirements of the species/life stage of interest are known).	ADCP approach is not going to sample shallow (<0.3 m) water very well. This may well influence the results for juvenile salmonid habitat. Doubtful whether a transect ADCP sampling approach would be able to capture the flow complexity within a weir pool.

5.4 Modelling

5.4.1 Hydraulic modelling

Hydraulic models are computer programs that simulate the flow of water through river systems. Models cover varying spatial scales and levels of complexity and the choice of model is dependent on the feature to be modelled. A significant advantage of using models is that altering the model geometry and inflows allows predictions to be made. By running before and after scenarios for a range of flows, hydraulic models can provide a quantitative estimation of the spatial and temporal impact of a hydropower scheme on the hydraulics of a weir pool. This section summarises the three main approaches available in order of increasing complexity and presents an argument for selecting two-dimensional (2D) models to predict impacts at three case study sites in section 5.

One-dimensional modelling

In one-dimensional (1D) models river topography is represented using a series of cross-sections, with geometry interpolated between the sections (Figure 5.1).

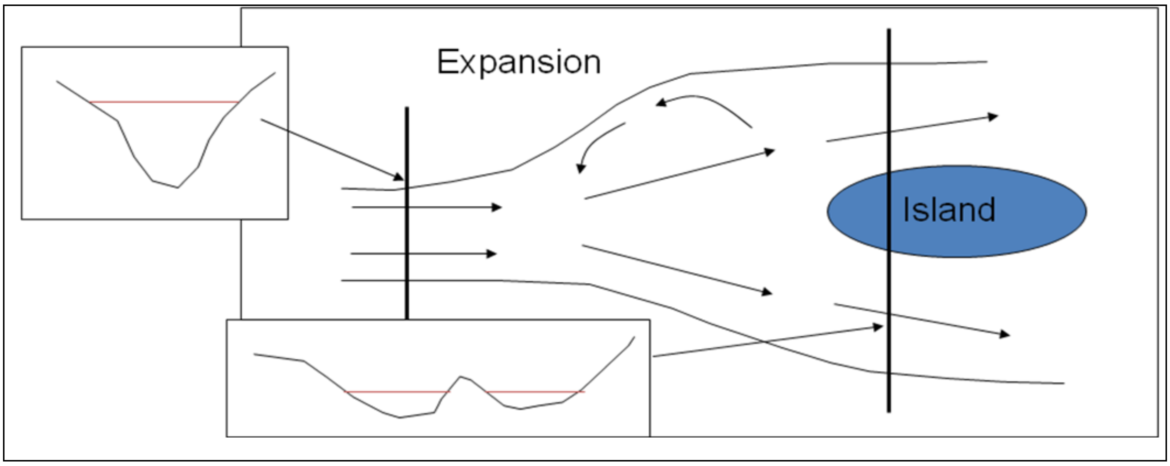


Figure 5.1 Schematic of 1D cross-section interpolation

For each cross-section model outputs include water level (horizontal across the section), cross-section average velocity and discharge (Figure 5.2).

Figure 5.2 Schematic of 1D cross-section results

1D modelling is frequently used for flood risk mapping (e.g ISIS, HEC-RAS and MIKE-11. 1D models are relatively simple to run and have less onerous survey requirements than higher resolution models. They can cover greater distances than reach scale, but the cross-sectional nature of the model geometry means that much in-channel complexity will not be included in the model. The cross-section averaged velocity values will be appropriate for some river types and locations; however, for situations such as weir pools, where there is considerable lateral heterogeneity of flow velocities, a cross-section average approach to velocity is a gross simplification. A dense close cross-section spacing would be required to capture the longitudinal variation within the weir pool, which rather defeats the purpose of using 1D models.

Two-dimensional modelling

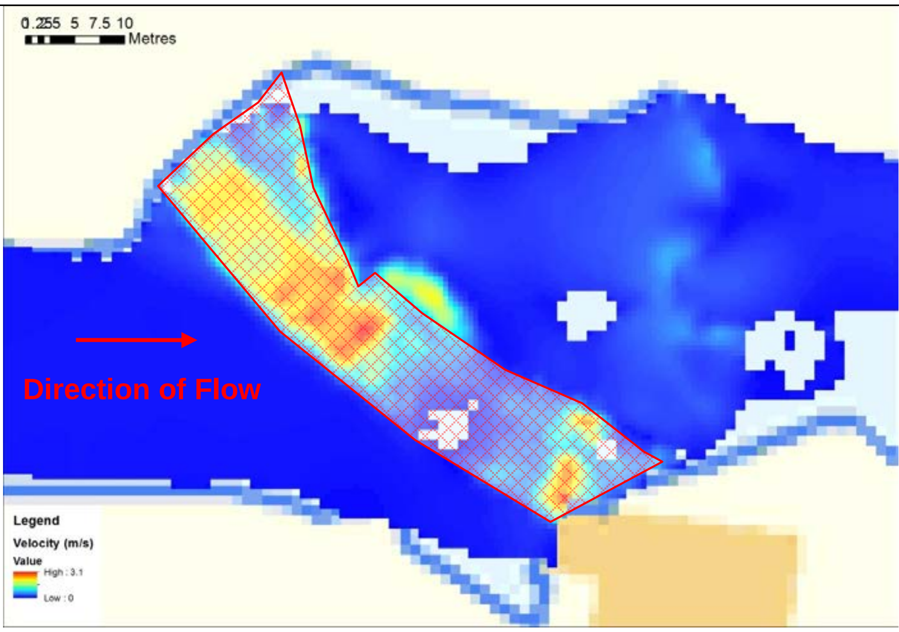
2D models split the river into a series of cells, with the water level and velocity in each cell dependent on the conditions in adjacent cells. The equations which govern transfer of water between cells are called the shallow water equations. These provide predictions of depth and depth averaged velocity for each computational cell in the model. The size of a cell is user defined, and can either take the form of a mesh formed by irregular shapes or a mesh with fixed regular square cells (depending on the type of model used). The smaller the cell size, the greater the input data requirements and processing time required to run the model.

2D modelling is widely used for flood risk mapping (especially on floodplains), where its strength lies in accurately determining overland flow routes and patterns. The advantage of 2D over 1D models is that a 2D model produces a spatially varying map of flow velocities (Figure 5.3). Basic model output is water depth and velocity at each cell in the model; however advanced outputs can include variables such as Froude number and shear stress which could help assess sedimentation/accumulation impacts (e.g. TUFLOW, River2D and MIKE-21).

The extent of the model mesh needs to cover the study area and sufficient distance downstream to ensure the downstream boundary of the model has no impact on the model results (the downstream boundary in this case is a user-specified rate at which water can leave the modelled domain). If the boundary is too close to the area of interest, the model results can be heavily influenced by this user-chosen parameter.

The model requires topographic information about the river bed, but as a topographic survey sufficient to create a sufficiently detailed digital elevation model (DEM) can be expensive, instream 2D models have generally been constrained to the reach scale. This is acceptable for a weir pool study as that is the scale of interest. If the study site is suitable it is possible to use very detailed Acoustic Doppler Current Profiler (ADCP) surveys to provide topographic data. However, if the site is not accessible by ADCP or contains a lot of shallow water, a traditional spot level survey would be required. The resolution of the model is only proportional to the resolution of the survey (i.e. the model cannot contain more detail than the survey) and so if a very detailed model is required the survey (using traditional methods) costs may be high. The depth-averaged velocities produced by a 2D model can provide a picture of the planform flow structure but will not be able to show vertical movements of water (i.e. any upwelling and down welling of water within the deep weir pool).

The nature of the shallow water equations means that many 2D models will be unable to run successfully when there are very steep slopes or plunging flow (i.e. over the crest of a vertical weir). This may preclude some weir structures from being modelled using 2D shallow water flow equations. 2D models are more complicated to set up and run than 1D models, and require expert users and more time.



Notes: hatched area = sloping face of the weir. Area of high velocity downstream is the sloping face of the weir.

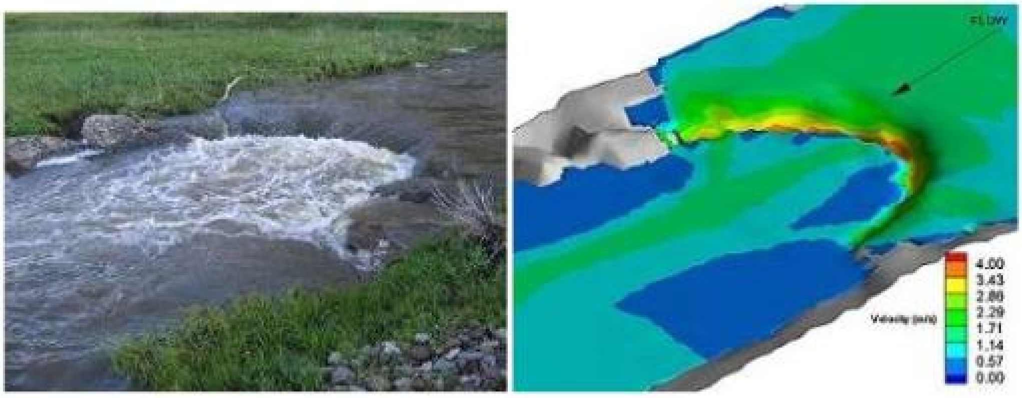
Figure 5.3 Example output from an instream 2D hydraulic model (JBA, model of Salts Mill Weir)

Most proprietary 2D hydraulic models have a fixed bed (i.e. the flows in the model have no influence on the topography of the river), and the same mesh is used for the whole simulation. However, some 2D models (such as RiverFLO-2D) have a mobile bed (i.e. the river geometry responds to the flows), which can change the mesh of the model in response to predicted erosion and deposition patterns. For such models to be of use, a detailed understanding (including grain sizes) of the bed sediment in the reach would be needed, and the model would need to be run using flows which are likely to be geomorphologically significant (i.e. flows which combined with the specific bathymetry of a given reach produce velocities capable of entraining and moving the river bed).

Three-dimensional modelling

As with 2D models the bed of a 3D model is composed of a mesh of computational cells. The equations solved in 3D models produce a depth of water for each cell and velocities throughout the water column at user-specified intervals.

The topographic survey data requirements are similar to those for 2D modelling; however, unlike 2D modelling, flow characteristics such as jets and plunging flow can be modelled using 3D models, an increased understanding of which can help to understand scour pool development. Holmquist-Johnson (2009) used 3D modelling to assess the complex flow patterns and performance of rock weirs (Figure 5.4). Using a hydraulic modelling approach allowed the author to run over 30 model geometries over a range of flows to assess the performance of the rock weir structures, providing guidance to practitioners on the appropriate geometries to generate desirable flow parameters. 3D modelling has also been used to assess the hydraulic impact of hydro-peaking in a Norwegian regulated stream (Pedersen 2012).



From:
http://www.usbr.gov/pmts/sediment/kb/SpanStructs/Hydraulic%20Differences%20Between%201D%20and%203D%20Modeling.htm

Figure 5.4 Example 3D outputs from Holmquist-Johnson (2009)

Recently, ARUP (2013) undertook computational fluid dynamics (CFD) modelling of Romney Weir on the River Thames to assess the impact of a hydropower scheme on the hydraulics of the associated weir pool. The modelling was conducted using the open source CFD code OpenFOAM. The model had approximately 7 million computational cells, with a cell size of approximately 0.1 to 0.2 m around the weir structure and 0.2 to 0.4 m in the remainder of the watercourse. At this resolution, the simulation time was significant, taking around 1 week to predict flow properties for 4 minutes of real time. Arup (2013) found very little difference in flow patterns and velocities at low flows (Q95), but a greater change in flow patterns at moderate flows (Q50). 3D modelling is an advanced technique, rarely used in England for flood modelling or river restoration studies, and requires the input of expert users and has higher costs than 1D or 2D models.

5.4.2 Habitat modelling

Hydraulic modelling enables an assessment of the change in hydraulics downstream of a hydropower scheme, and habitat models can help reinterpret the hydraulic output into maps of habitat suitability. Some of these techniques are described below.

PHABSIM

A commonly used physical habitat model is the Physical HABitat SIMulation (PHABSIM) model developed by the US Geological Survey. This model is based on a cross-sectional sampling approach whereby high precision measurements of physical habitat (substrate and cover) and flow (depth and velocity) parameters at a micro-scale are taken under several flow scenarios and, along with simulated hydraulic data (analogous to a 1D model) for unobserved flow conditions, are compared with habitat suitability for the fish species and life stage of interest (SNIFFER 2013).

The conversion of simulated hydraulic data (e.g. depth and velocity) to a measure of habitat suitability is done using habitat suitability indices, presented as curves. These curves have the hydraulic parameter of interest on the *x*-axis and a measure of habitat suitability on the *y*-axis (generally better for salmonid fish rather than coarse fish). Using multiple curves for each hydraulic parameter of interest builds up a habitat suitability score for a given location.

PHABSIM contains several assumptions, the most important of which is that habitat suitability indices can be used to represent the preferred conditions of the species/life stage of interest. It has been observed that the PHABSIM is heavily reliant on the use of appropriate habitat suitability indices (Moir et al. 2005). PHABSIM requires a large amount of data, which can lead to considerable expense. PHABSIM has been widely used, especially in the USA. For example, Gore and Hamilton (1996) undertook PHABSIM modelling of Brushy Branch (Georgia, USA) and found that the simulation demonstrated that benthic macroinvertebrate habitat can be dramatically increased at low flows after placement of structures (weirs) that improve hydraulic conditions to sustain maximum diversity of the benthic community.

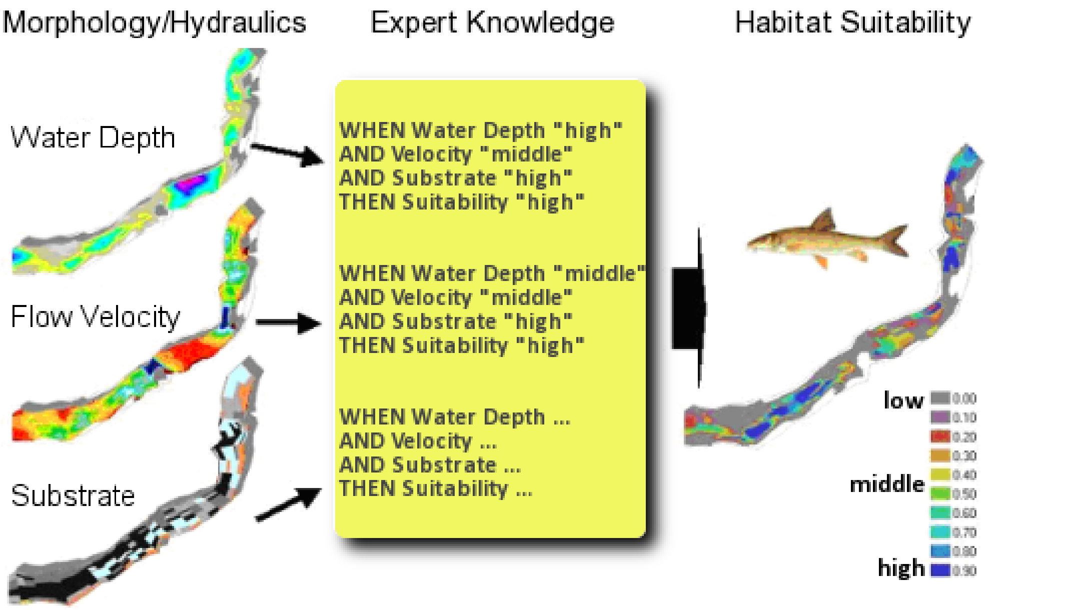
RAPHSA – CHAT

As part of the RAPHSA set of tools Acreman et al. (2008) developed the Catchment-scale Habitat Assessment Tool (CHAT), which uses 1D modelling (an interface has been written for the ISIS modelling software). It uses the depth and velocity predictions from the model to produce PHABSIM style predictions. Acreman et al. (2008) report that the tool was applied on the whole River Itchen catchment as part of the Itchen Sustainability Study. However, as discussed in section 3.1 the applicability of RAPHSA in weir pools is limited because the model was calibrated against a number of PHABSIM studies, none of which involved weir pools.

Two-dimensional habitat modelling

2D hydraulic modelling has been used as the basis for habitat modelling around the world in a range of studies including minimum flow studies (e.g. Lane et al. 2006), hydro-peaking (e.g. Wieprecht et al. 2010) and river restoration studies (e.g. Gard 2013). The CASiMiR tool (see Figure 5.5) uses a fuzzy logic habitat modelling engine which takes the predictions of the water depth and velocity from the 2D model combined with substrate information on site to produce a map of habitat suitability (Schneider et al. 2001). JBA's habitat modelling software JHab has a similar fuzzy logic habitat modelling engine.

The fuzzy logic model approach has a number of advantages over the traditional PHABSIM habitat suitability curve approach, as it does not treat the depth, velocity and substrate independently and the fuzzy rules (i.e. rules about what depths and velocities certain species require) are intuitive and understandable by river managers. The key improvement on PHABSIM is due to the way that any uncertainty in the fuzzy rules is inherently accounted for in the fuzzy logic engine, and the rules do not need to be built via laborious site work but can be specified using expert knowledge. This could be a potential cost saving over the PHABSIM type approach. However, this form of modelling needs a 2D hydraulic model, and there are increased costs associated with that method over the PHABSIM approach.



From: http://www.casimir-software.de/ENG/aufbau_eng.html

Figure 5.5 Schematic of the CASiMiR approach to habitat modelling

5.5 Physical modelling

Building scale models of hydraulic structures is commonplace for structures which result in complex fluid flow patterns that cannot be modelled by mathematical means. However, physical modelling is very expensive and would certainly be beyond the economic viability of many schemes. To some extent physical modelling has been used to investigate weir pool dynamics, but for scour protection studies rather than river restoration or habitat studies. For example, Pagliara et al. (2011) studied the sediment dynamics in weir pools for a range of experimental geometry set-ups.

5.6 Interpretation and conclusions

A range of tools could be used to determine hydropower scheme impacts on weir pools; however, these methods are not always appropriate. Both of the hydromorphological assessment tools considered (MIMAS and RAT) are more appropriate for waterbody scale studies than site-specific assessments. Methods to impose informed flow limits (WALES and WFD48) are designed for steeper rivers.

The HEFT habitat assessment tool focuses only on the shallowest water in the reach and does not take into account the temporal requirements of aquatic organisms. APEM's FHAT approach is a blend of ADCP survey, hydraulic habitat mapping and hydraulic modelling; however, the choice of hydraulic model would need to be carefully considered to capture weir pool complexity.

Hydraulic modelling approaches present the best options and a range of modelling outputs are possible, depending on budget and the desired level of detail. There is the potential to use ADCP techniques to undertake the topographic survey which, given a suitable site, could reduce survey costs significantly compared to traditional survey techniques.

5.7 Rationale for two-dimensional models of case studies

We selected 2D hydraulic modelling to investigate the impact of hydropower schemes at three case study sites. It is a reasonable compromise, as it captures spatial and temporal variability, without the large data and computing requirements of 3D modelling. Table 5.3 summarises how the 2D modelling meets the objectives and requirements for this project and subsequent sections describe our approach and the limitations.

Table 5.3 Summary of rationale for use of 2D modelling

Requirement	How met by 2D modelling?
A predictive approach – capable of detecting before and after impacts	By changing the schematisation (layout) of the model, a number of situations can be modelled.
	Short run times and reasonable data requirements of 2D models mean a range of scenarios can be tested.
At a scale relevant to the species of interest	2D modelling produces depth-averaged velocities (i.e. one velocity per model cell). Depth-averaged velocities are pertinent to fish and macrophytes, whereas near-bed velocities may be more appropriate for sediment transport and macroinvertebrates. However, expert judgement can be used to interpret depth-averaged velocities in those instances.
A approach which could feasibly be used by developers on other sites where necessary	2D modelling skills are commonplace within the wider water industry. Where needed, such modelling could be carried out cost-effectively.
	2D modelling software is ubiquitous and some software is available as freeware.

5.7.1 Summary of approach

The key information required for the hydraulic modelling is an understanding of the river flows, bathymetry and the location and dimensions of the proposed hydropower scheme (Figure 5.6). We describe general limitations that apply to each case study (section 5.7.2) and site-specific limitations (appendix sections 3.5.5, 4.5.5 and 5.5.5).

Where possible available data were used to calibrate the hydraulic models, to ensure they work well at the chosen site (appendix sections 3.5.3, 4.5.3 and 5.5.3). A sensitivity test was also conducted for each site where changes in modelled depths and velocities as a result of changes to parameters were compared to the changes as a result of hydropower installation. In this context the key parameters are user-specified values representing the roughness of the bed of the river and the downstream boundary of the model. In all three case studies, larger changes in modelled depths and velocities were observed as a result of hydropower installation than observed following changes to key model parameters. This indicates that any changes to weir pool hydraulics predicted by the models can be thought of as independent from model parameterisation.

The hydraulic model can be used to simulate the hydraulic conditions resulting from a range of scenarios and for a range of flows (i.e. across the whole flow range). Rather than only modelling a ‘before’ and ‘after’ hydropower installation scenario, we modelled one further scenario at each case study site, namely a depleted reach scheme, placement of a scheme on different banks and a comparison of the impacts of a hydropower scheme and a flood event on the hydraulics of the weir pool.

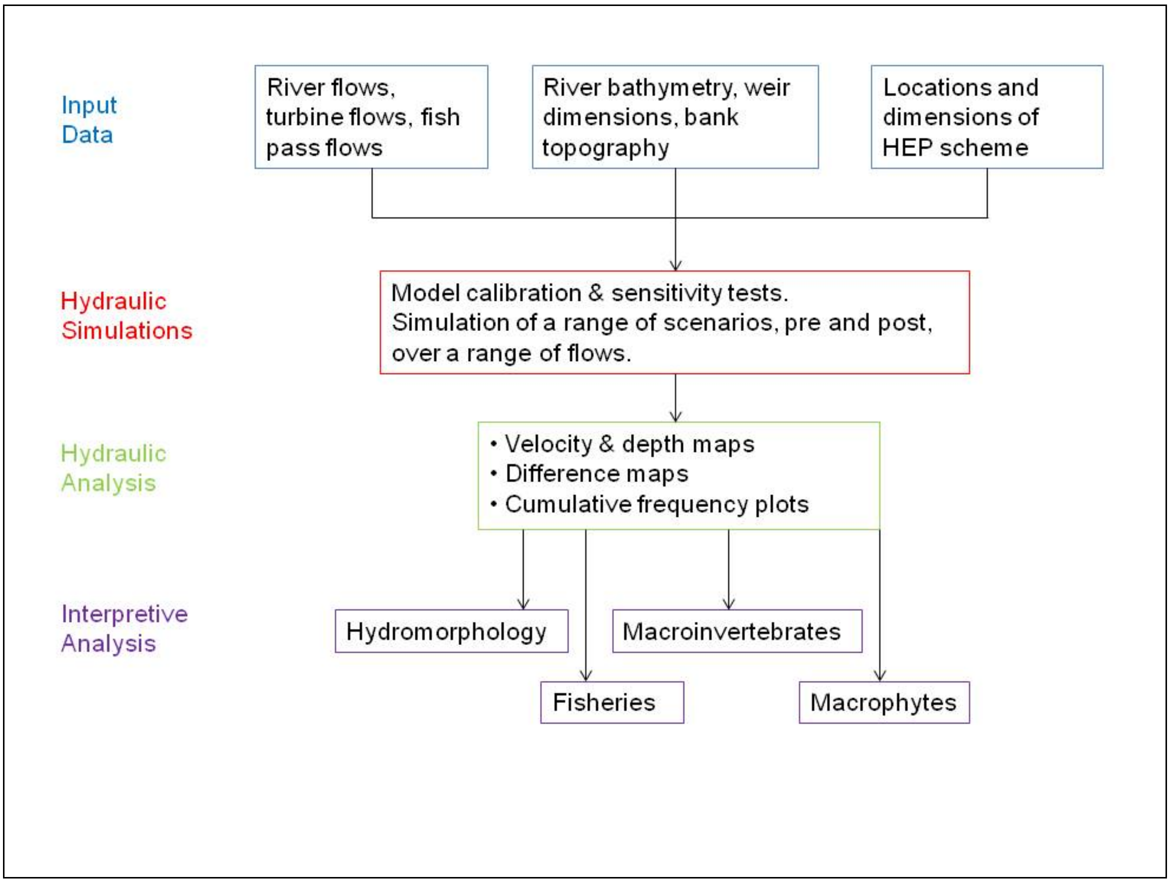


Figure 5.6 Modelling process chart

For each study site we produced difference maps calculated by subtracting the pre-installation results from the post-installation results. The example in Figure 5.7 shows the Q60 velocity difference map at Romney Weir. We also produced graphs showing the frequency of occurrence of a given depth and velocity of flow. Analogous to a flow duration curve (e.g. for a velocity plot), the 80th percentile is the velocity which is exceeded at 80% of modelled cells. Thus we can show overall how much the hydraulic environment is changed.

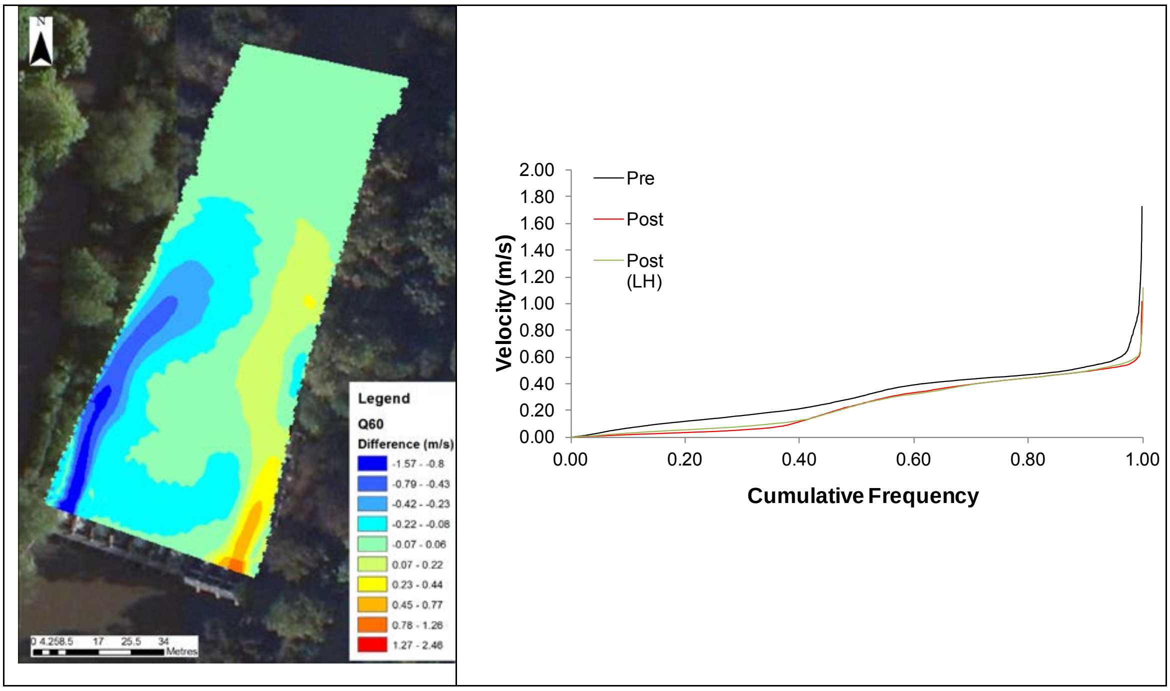


Figure 5.7 Example data analysis techniques

Values from published literature and expert judgement were used to determine the implications of a change in hydraulic patterns on species and habitat features of interest. We assessed potential hydromorphological change within the weir pool complex as a result of proposed hydropower schemes by comparing pre- and post-scheme outputs from the hydraulic modelling and focused on change in velocity as a useful predictor for erosion, transportation and deposition of sediment in rivers. Peak and average velocities were analysed within the study reaches for a range of flows and were compared against the Hjulstrom Curve (Figure 5.8), which is used as a tool to predict sediment erosion, transport and deposition using sediment size data. Changes in hydromorphology were then made using this information when compared to existing processes within the channel (i.e. with no hydropower scheme in place).

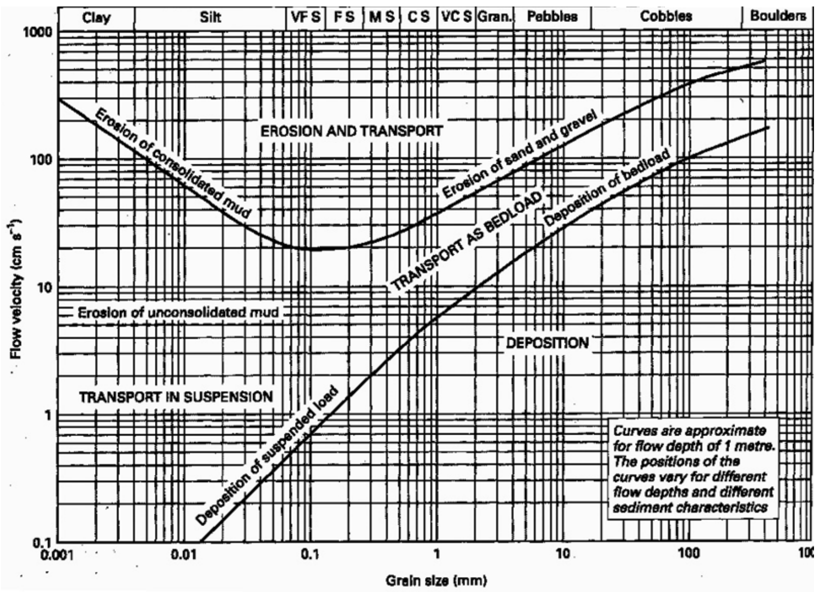


Figure 5.8 Hjulstrom Curve

Available macroinvertebrate data were analysed alongside modelled velocity changes and information on potential physical habitat change to predict any impacts from hydropower schemes. Specifically, published information on macroinvertebrate velocity preferences and sensitivity to fine sediment (e.g. Extence et al. 1999, 2011) was used alongside expert judgement (based on research experience from UK hydropower schemes) to estimate taxon response. This was considered alongside the conservation status of each taxon (using Chadd and Extence 2004) to predict the likely magnitude and significance of any changes.

5.7.2 Limitations of approach

Table 5.4 highlights general limitations of the modelling approach; site-specific limitations are discussed in appendix sections 3.5.5, 4.5.5 and 5.5.5.

Table 5.4 General limitations of the modelling approach

Limitation	Explanation/mitigation
Depth-averaged velocities	Depth-averaged velocities produced by 2D modelling are less useful in explaining rates of sediment transport or macroinvertebrate communities compared to the detailed picture of the near-bed velocities generated by 3D models. However, the large run times and data requirements of 3D modelling would have limited the number of scenarios modelled and limited the transferability of the method for future use. Expert judgement can be used to infer near-bed velocities from depth-averaged velocities. Furthermore, the key areas of interest in weir pools are generally shallow features, where the vertical detail of velocities produced by 3D modelling would be less important than in deep areas of the channel.
ADCP data – shallow water	ADCP data has been used as the basis for the river bed bathymetry for each case study. This data has many advantages over traditional survey methods including speed of capture and high resolution; however, as highlighted in the literature review this technique cannot survey depths of less than around 0.6 m. This leaves the marginal areas of the channel and other shallow areas as gaps in the data. These data gaps have been interpolated using expert judgement, local knowledge and other data as appropriate.
Turbulence from turbines	It is beyond the capabilities of 2D modelling to represent the turbulence created by the turbines explicitly, and there is no published literature on either the turbulence or velocities of the outflow from the turbine. Therefore it seems reasonable to assume that the velocity of the water leaving the tailrace will be a function of the discharge, the flow area and downstream water levels, all of which are known. In the absence of turbine tailrace velocity literature, discussion with an established turbine supplier (Spaans Babcock) confirmed that this approach is entirely reasonable, with velocities at the terminal end of the tailrace being a function of discharge, tailrace geometry and downstream water level (David Brockington, personal communication)(2014). Best efforts have, however, been made to ensure that the exit velocities from the turbines are representative of what would be expected by ensuring that the modelled tailrace dimensions are the same dimensions as those used in the scheme, which coupled with the correct flow should lead to a reasonable velocity at the turbine

Limitation	Explanation/mitigation
	exit in the model.
Fish pass velocity	2D modelling is unable to explicitly model the velocities in a technical fish pass (e.g. a bottom baffle pass such as a Larinier). Again, the dimensions of any outfall channel will be modelled as accurately as possible to ensure that velocities at the bottom of the fish pass in the model are reasonable. Velocities in the case study model were compared against velocities determined using Environment Agency guidance on fish pass design for structures of a similar type and size and were found to be reasonable.
Resolution of model grid	Model resolution is insufficient to capture the influence of small-scale bed detail such as boulders, and their associated habitat features (e.g. resting/feeding areas for adult fish).
Model grid not dynamic	The 2D model used does not have a dynamic bed (i.e. the topography of the river will not change in response to changes in flow direction or magnitude). For each of the case study sites, only pre-installation bathymetry was available, therefore the post-installation model runs are the post-installation flow splits on the pre-installation topography. It is likely that the most extensive re-working of the geomorphology of a weir pool would happen during flood or high flows, and so the change in flow distribution due to hydropower may not directly lead to large-scale changes in the geomorphology of the weir pool. Changes in geomorphology are not modelled directly, but whether the modelled change in flow resulting from hydropower installation is capable of geomorphological change is considered in the hydromorphology assessment for each case study. In particular, the potential for silt accretion is considered (with a focus on any gravel features in the weir pool complex).
Depth and velocity only	The hydraulic modelling approach only considers changes to the hydraulics of the weir pool, as it does not take account of any potential changes to water quality parameters. It must be noted that the hydraulic conditions may not be the only factor limiting ecological populations in any given weir pool. This highlights the importance of local knowledge when designing studies on a given weir pool.
Vertical drops	2D modelling is unlikely to be able to model a weir which has a vertical or very steep face, as the equations are not able to solve such flow types. All of the three case study sites modelled have sloping weir crests, and so this 2D approach can be used. A similar limitation applies to sluice gates and other complex instream structures, which are unlikely to be explicitly modelled in a 2D model. When encountered in this study, the flows which be discharged by the structure were calculated and introduced to the model at the exit of the sluice gates. It is again assumed that the velocity of the water leaving the sluice gates will be a function of the discharge, the flow area and downstream water levels, all of which are known.

6 Case studies

This section describes three case studies exploring the potential impacts of hydropower schemes on weir pool hydromorphology, fisheries, macrophytes and macroinvertebrates. A rationale behind site selection is provided in Table 6.1. Summaries of the scoping process application, modelling results and ecological interpretation are presented in sections 6.1 to 6.3, and more detail is available in appendix sections 3, 4 and 5.

Table 6.1 Rationale for choice of case study sites

Romney Weir, River Thames	Good topographic/bathymetric data and available scheme-specific studies including sampling and 3D CFD modelling which could be compared with 2D approach. Results from this site may also be transferable to other weirs on the Thames.
Pershore Weir, River Avon	Bathymetric data available prior to hydropower installation, and some local studies. Avon Catchment provides comparison with Thames sites although the Avon is very similar in character to the Thames.
Goring Weir, River Thames	Two high quality bathymetry surveys (June 2013 and February 2014). Survey in 2014 was preceded by a substantial flood event enabling a comparison of hydropower and flood impacts on the weir pool.

6.1 Romney

Table 6.2 Romney case study background information

Site description	Romney Weir is located on the River Thames near Eton. The complex consists of 10 radial gates, each around 4.5 m wide (bays 2 to 11), with an 11th smaller gate adjacent to the left hand bank. A fish pass is located adjacent to the right hand bank. The weir is 55 m wide.

Key features	A large weir pool is located downstream of the weir with a shallow depositional shoal approximately 80 m downstream of the weir. The gravel shoal is considered particularly important as it could provide spawning habitat for rheophilic fish in an otherwise slow flowing reach.
Ecological context	Romney Weir sits within the River Thames (Cookham to Egham) heavily modified waterbody (ref GB106039023231) currently classed as achieving moderate ecological potential and failing Water Framework Directive objectives. The fish, macrophyte and macroinvertebrate quality elements are currently classed respectively as moderate, high and no information. Invertebrate communities are dominated by species common to large, lowland rivers. Three species of significant conservation value were found. Invertebrate communities in and around the gravel shoal were indicative of moderately sedimented and sedimented conditions (Jacobs 2012). 16 macrophyte species were recorded at Romney Weir. Fish surveys at sites close to the weir reveal a variety of rheophilic and eurytopic fish species.
Description of scheme	Two Archimedes screw turbines were installed adjacent to the right bank in 2013. Before the scheme was installed the majority of the flow was released by gates adjacent to the left hand bank. The turbine and fish pass use 54% of the total flow at Q95, 88% at Q60 and 53% at Q30.

6.1.1 Evaluating site habitat and ecological quality

The scoping process discussed in section 3.2.1 was applied using a desk study (blue text) and using site-specific reports where available (*red italic text*) to compare outcomes using different data inputs.

Table 6.3 Scoping process – Romney

In an SSSI/SAC?	No
Fish population status with reference to wider catchment	Fish species of diverse habitat requirements were found both upstream and downstream of Romney Weir. *Three macroinvertebrate species of significant conservation value are present in or near the weir pool complex.*
Rare habitat?	Google Earth imagery shows limited evidence of local active areas (e.g. exposed gravel features and higher energy flow types) upstream and downstream of the site. Old Windsor Weir downstream has a fish pass which is likely to make the potentially rare habitat between Old Windsor and Romney accessible to salmonids and large coarse fish. There are a large number of weirs on the Thames system which could provide similar habitat, although there are few morphological features comparable to the complex immediately downstream of Romney Weir within the reach downstream.
Good quality?	The quality of this gravel shoal cannot be determined from the Google Earth imagery due to the resolution. *Jacobs (2012) describe the gravel shoal immediately downstream of Romney Weir as relatively clean and therefore not prone to significant amounts of fine sediment deposition and infilling.*
Angling amenity?	The weir pool is fished by Old Windsor Angling Club.

The weir pool and gravel shoal is believed to be in good condition on review of existing reports, and could be a rare feature in a gravel system heavily constrained by in-channel structures. Different results were obtained with different resolution of input data (i.e. desk and detailed site-specific reports) particularly in the determination of weir pool ecological sensitivity and quality. Romney Weir pool is likely to be considered of importance due to the quality of the habitat, the angling amenity and the three macroinvertebrate species of conservation value (Table 6.4).

Table 6.4 Summary of scoping process – Romney

	In an SSSI/SAC?	Fish population status with reference to wider catchment	Is the weir pool type habitat rare?	Is the morphology of the weir pool complex good quality?	Angling amenity?
Desk study	No	No	Possibly	Unknown	Yes
Available reports + desk study	No	Yes	Possibly	Yes	Yes

6.1.2 Hydraulic habitat mapping

We modelled three stages of the flow: low flow (Q95) where the flow is exceeded 95% of the time, moderate flow (Q60) and moderately high flow (Q30), and three scenarios (see Tables 6.5, 6.6 and 6.7).

Table 6.5 Flow splits – Romney

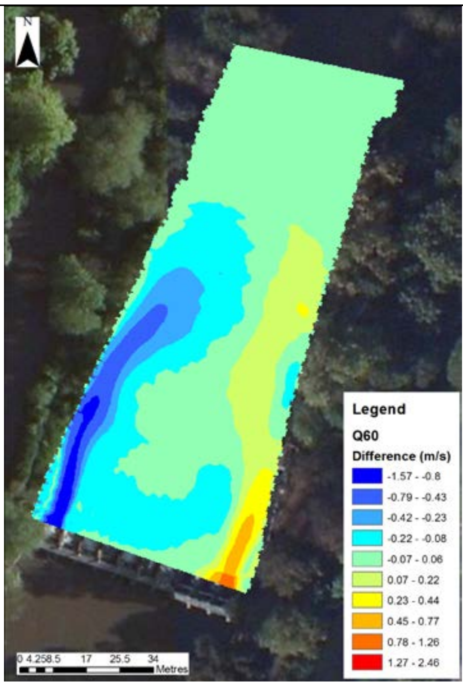
Pre-installation	At low flow (Q95) the flow is relatively evenly split between each of the gates, while for moderate and higher flows, Q60 and Q30, the majority of the flow is released by gates near the left hand bank.
Post-installation	At Q95 and Q60 the majority of the flow is released next to the right hand bank through the fish pass and turbines. At Q30 the flow is almost evenly split between the right hand bank (turbine complex) and the left hand bank (released by a sluice gate).
Post-installation – turbines on left hand bank	A mirror image of above, with the turbine and fish pass complex located on the left bank. Designed to explore the impact of installation of a scheme on either side of a weir.

Table 6.6 Summary of results – Romney

<table>
<tr><td>Low flows (Q95)</td><td>Very little difference between the three scenarios. A slight decrease in the availability of slower velocities and an increase in availability of higher velocities Changes were confined to within 20 m of the structure.

Very little change in flow characteristics over the gravel shoal.</td></tr>
<tr><td>Moderate flows (Q60)</td><td>When the whole weir pool complex is considered, the installation of the hydropower scheme on the right hand bank, leads to an increase in velocities adjacent to the right hand bank and a corresponding decrease in velocities on the left hand bank (figure right). The reverse pattern is observed when the hydropower scheme is located on the left hand bank. The frequency plot shows a general decrease in velocities in the reach.

Analysis of velocities over the gravel shoal showed a very slight decrease in the availability of higher velocities.



</td></tr>
<tr><td>Higher flows (Q30)</td><td>Similar flow pattern changes observed in both post-installation hydropower scenarios, with an increase in velocities on the right bank and a decrease adjacent to the left bank. Despite this change in flow pattern the frequency plots show very little difference in the availability of modelled velocities between the two post-installation scenarios. Analysis of velocities over the gravel shoal showed a slight decrease in the availability of higher velocities.</td></tr>
<tr><td>Comparison with 3D model results</td><td>Differences between our 2D modelling results and 3D modelling undertaken in another study are evident at Q95 where 3D modelling showed velocities ranging from 0.2 m/s close to the bed of the river to 0.8 m/s around 0.4 m above the bed, while the maximum velocity observed in the 2D modelling is around 0.2 m/s. Section 3.6.1 in the appendix outlines possible reasons for this including different roughness parameters used, the lack of digital results from the 3D modelling, potential differences in bathymetry and a lack of a direct comparison.

However, overall using 2D or 3D modelling made little difference to the hydraulics over the gravel shoal from the modelled scheme scenario.</td></tr>
</table>

Table 6.7 Implications interpretation

Hydromorphology	Under Q95 flow conditions impacts are likely to be minimal but under higher flows there could be increased deposition away from the outfall location where velocities reduce, and possible increased scour at the outfall location. There may be small changes along the edge of the gravel shoal as a result of increased velocities with smaller gravel being transported downstream. The composition of the gravel shoal is unlikely to be significantly influenced by the installation of hydropower at either location. Velocities remain within bands similar to those for pre-installation conditions for all the flow events, with only subtle changes evident. The magnitude of change is unlikely to be sufficient to dramatically change the depositional and erosive processes in the reach, with only localised variations.
Macroinvertebrates	The changes to velocity at the shoal (both reductions and increases) may drive relatively minor changes to the current invertebrate communities. The most marked hydraulic changes are predicted to be in the deep weir pool immediately downstream of the weir. Unfortunately, this particular habitat patch was not directly sampled in baseline surveys (due to safety issues) so specific predictions of invertebrate community response are not possible. Communities here are likely to be adapted to fast flows but may be impacted by any increases or decreases. However, such changes are likely to be relatively localised.
Macrophytes	Nuttall's waterweed (a non-native invasive species listed on Schedule 9 of the Wildlife and Countryside Act, 1981) may be displaced due to higher velocities, or change in flow patterns, although spatial data on this species was not available. Displacement of this species may lead to an increase in extent of the invasive species and so compromise macrophyte diversity downstream. River water crowfoot *Ranunculus flutians*, the dominant species in the channel, is associated with fast flow and rivers liable to spate (Haslam 2006). Therefore, the faster flows generated in the central part of the river channel, in both the left and right bank scenario, are unlikely to significantly impact on this species' occurrence. Under all scenarios there still remains a balance of slower flowing areas and faster flowing areas, although the distribution of these areas changes across the channel length and cross-section. The species communities within the channel may gradually adjust to these velocity changes following installation.
Fisheries	Hydropower installation does not change modelled velocities over the gravel shoal; combined with the lack of condition change predicted by the hydromorphological assessment, it is likely that the quality of this spawning habitat will not be compromised by hydropower installation. It is unlikely that the macrophyte communities will fundamentally change. Changes in distribution of Nuttall's waterweed as a result of its displacement downstream could have an effect of reducing macrophyte diversity, which may have an impact on phytophilic spawning/refugia habitat, but a fisheries population-level impact may be hard to discern.

Synthesis	The scoping process highlighted the potential importance of the Romney Weir pool complex due to the good quality of the spawning habitat in the gravel shoal, macroinvertebrate species of conservation importance and the angling amenity. The 2D modelling showed limited hydraulic change over the shoal following hydropower installation, with population-level impacts hard to predict. The overall distribution of depths and velocities remained unchanged but the spatial pattern of velocities does change following hydropower installation. This could lead to subtle changes in macrophyte and macroinvertebrate community structure. The potential for increased displacement of invasive species is highlighted.

6.2 Pershore

Table 6.8 Pershore case study background information

Site description	Pershore Weir pool is located on the River Avon at Pershore, west Worcester (SO 95228 45677). Pershore Weir, lock and sluice gate together are one of a number of structures built to improve navigation along the Avon. The study is limited to the reach downstream of the weir, as that is likely to be the area affected by a proposed hydropower scheme.

Ecological context	Pershore Weir sits within the River Avon (Evesham to confluence with River Severn) heavily modified waterbody (GB109054044403) that is currently classed as achieving moderate ecological potential and therefore failing Water Framework Directive objectives. Individual quality elements are currently classed as fish (moderate), macrophyte (no information) and macroinvertebrate (good). No site invertebrate data was found. Invertebrate records from 3.3 km upstream to 500 m downstream, with no data after 1994, show a mix of taxa with preferences for flowing/standing water and moderately fast

	flows, with no species of conservation concern present. However, this data is not representative of the invertebrate communities presently at the site. Baseline data on aquatic macrophytes for Pershore Weir is extremely limited, with only a basic river corridor and protected species survey report available (Keystone Environmental 2011). Downstream of the weir on the right bank, there is one small section of reed/sedges, dominated by common reed *Phalaris arundinacea*, with locally dominant rushes and occasional bulrush (presumably *Typha latifolia*). A range of fish species are present near Pershore Weir. At the site closest to the weir pool complex (approximately 600 m downstream of the weir), rheophilic species such as chub, dace and gudgeon *Gobio gobio*, and generalist eurytopic species such as bleak *Alburnoides bipunctatus,* perch, pike and roach *Rutilus rutilus* are present.
Description of scheme	A hydropower scheme is in development to be located on the left hand bank adjacent to the weir, with no expected changes to the weir itself. Scheme requirements: Q95, 69% of total flow; Q50, 87%; Q20, 82%. A hypothetical depleted reach scenario was modelled to indicate what happens to the weir pool if water is diverted away from the weir. This has little to do with hydropower itself as these kind of impacts would be observed for any such abstraction of flow diversion. It is unlikely that such an arrangement would gain approval.

6.2.1 Evaluating site habitat and ecological quality

The scoping process outlined in section 3.2.1 was applied using a desk study (blue text) and using any site-specific reports if available (*red italic text*) so as to explore the performance of the process with a range of data inputs.

Table 6.9 Scoping process – Pershore

In an SSSI/SAC?	No
Fish population status with reference to wider catchment	Rheophilic species only found below the weir.
Rare habitat?	The nearest main river instream barrier downstream of Pershore Weir is 8 km downstream (Nafford Weir), and there are only two other instream barriers between Nafford Weir and mean high water level. It could be concluded therefore that the complex of habitats immediately below Pershore Weir is relatively rare in the context of the catchment, with riffle features potentially contributing to sustaining the presence of the rheophilic species recorded in the Environment Agency fish surveys in the reach downstream of the weir.
Good quality?	The quality of this gravel bar cannot be determined from the Google Earth imagery due to the resolution. *A Fishtek Consulting (2012a) report suggests that some sections of*

	gravel bed within the weir pool may be suitable spawning habitat, which suggests the gravels are relatively clean and have limited fine sediment infilling. The modelled flow velocities in the report for a Q80 flow event are up to 0.8 m/s in shallower areas, which would be energetic enough to prevent significant fine sediment deposition on the bed of the channel.
Angling amenity?	Fishing controlled by Birmingham Anglers Association, and the site appears to attract some interest among anglers, with good access to the weir pool complex.

The desk study established that the weir pool ecosystem is potentially helping to sustain rheophilic fish species downstream and that weir pool habitat may be rare in this stretch of the Avon; however, no information was found on the quality of the habitat in the weir pool. Reports suggest that the gravel is free of fine sediment and so may provide vital spawning habitat. The analysis presented in Table 6.10 shows that the weir pool complex at Pershore is important given its rarity, quality and angling amenity, and likely role in sustaining rheophilic fish species downstream of the weir.

Table 6.10 Summary of scoping process – Pershore

	In an SSSI/SAC system?	**Fish population status with reference to wider catchment**	**Is the weir pool type habitat rare?**	**Is the morphology of the weir pool complex good quality?**	**Angling amenity?**
Desk study	No	Yes	Yes	Possibly	Yes
Available reports + desk study	No	Yes	Possibly	Yes	Yes

6.2.2 Hydraulic habitat mapping

Three scenarios have been modelled at exceedance flows of Q95, Q50 and Q20. The flows at Q20 were used because there was no existing information on the flows at Q30 for this scheme (Table 6.11).

Table 6.11 Flow splits – Pershore

Pre-installation	The flow over the weir is assumed to be the sum of the fish pass, turbine and weir flow specified by Renewables First (2011).
Post-installation	Inflows defined by using the values specified by Renewables First (2011).
Depleted reach	A hypothetical depleted reach hydropower scheme was explored by removing the turbine flow from the post-installation run (i.e. as if the turbine were located on a mill leat or similar so that the turbine flow bypasses the weir pool complex (Figure 4.1)). The location of the fish pass was modified to reflect best practice.*
*According to the Environment Agency guidelines (Environment Agency 2013), the maximum depleted reach abstraction in a high baseflow river (such as the Avon) is QMean, with a Q95 hands-off flow. The mean daily flow at Pershore is 15.40 m^3/s, which is only slightly lower than the maximum turbine flow of 16.40 m^3/s. Current guidance would not allow the depleted reach hydropower scheme to operate at Q95.	

With an on-weir hydropower scheme, there is a noticeable increase in depths of the range 1 to 1.5 m in the post-installation scenario for all exceedance flows (Figure 6.1). This is due to the dredging associated with scheme construction on the left hand bank. The on-weir hydropower scheme leads to little change in the availability of velocities at Q95, but a decrease in availability of the lowest flows and an increase in the availability of moderate flows observed at Q50 and Q20. The changes were concentrated at or near the turbine exit and close to the weir. Little change is observed in the highest velocities.

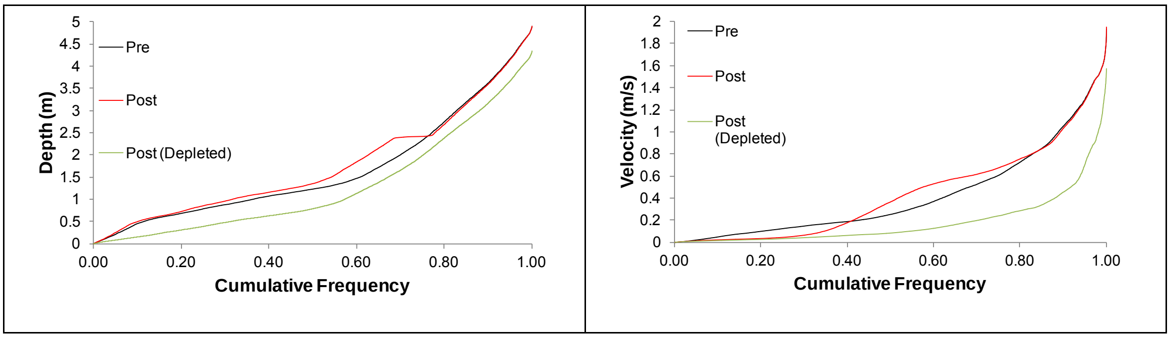


Figure 6.1 Cumulative frequency plots – Pershore (left Q20 depth, right Q20 velocity)

The hypothetical depleted reach hydropower scheme leads to more fundamental changes to the hydraulics of the weir pool complex. Figure 6.1 shows that there is a decrease in the available depths and velocities under the depleted reach hydropower scheme at Q20. These results are mirrored at Q50 and Q95 (to a slightly lesser extent). A full set of plots can be found in appendix section 4.6.

Under both Q95 and Q50 flows the bar adjacent to the left hand bank dries out and flow is forced towards the right hand bank (Figure 6.2). In the Q20 scenario, the bar remains dry, but water depths are lowered by around 0.5 m and velocities lowered by around 0.5 to 1 m/s. Results are summarised in Table 6.12.

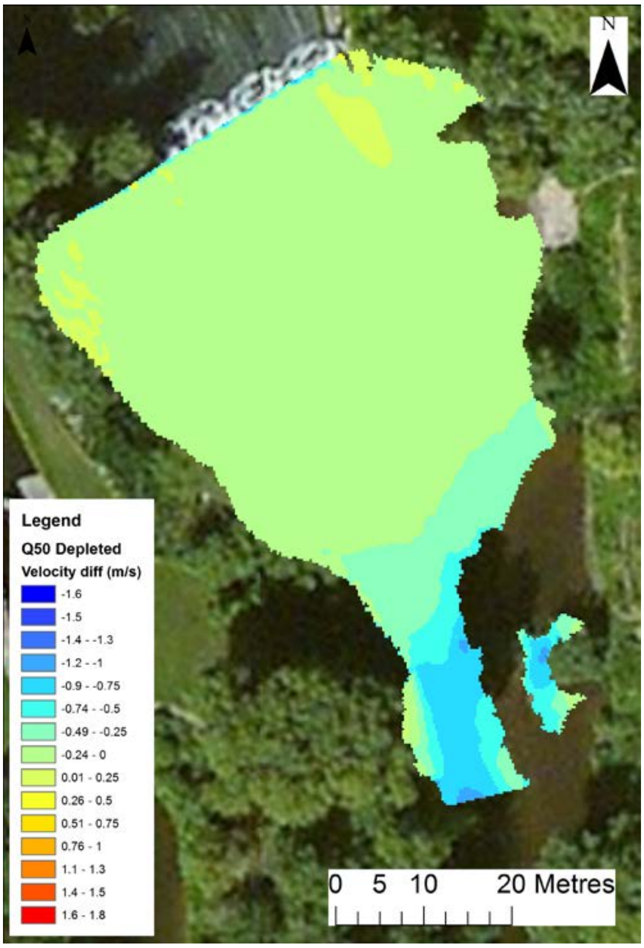


Figure 6.2 Q50 Depleted reach depth difference map (post-change – pre-change)

Table 6.12 Implications interpretation

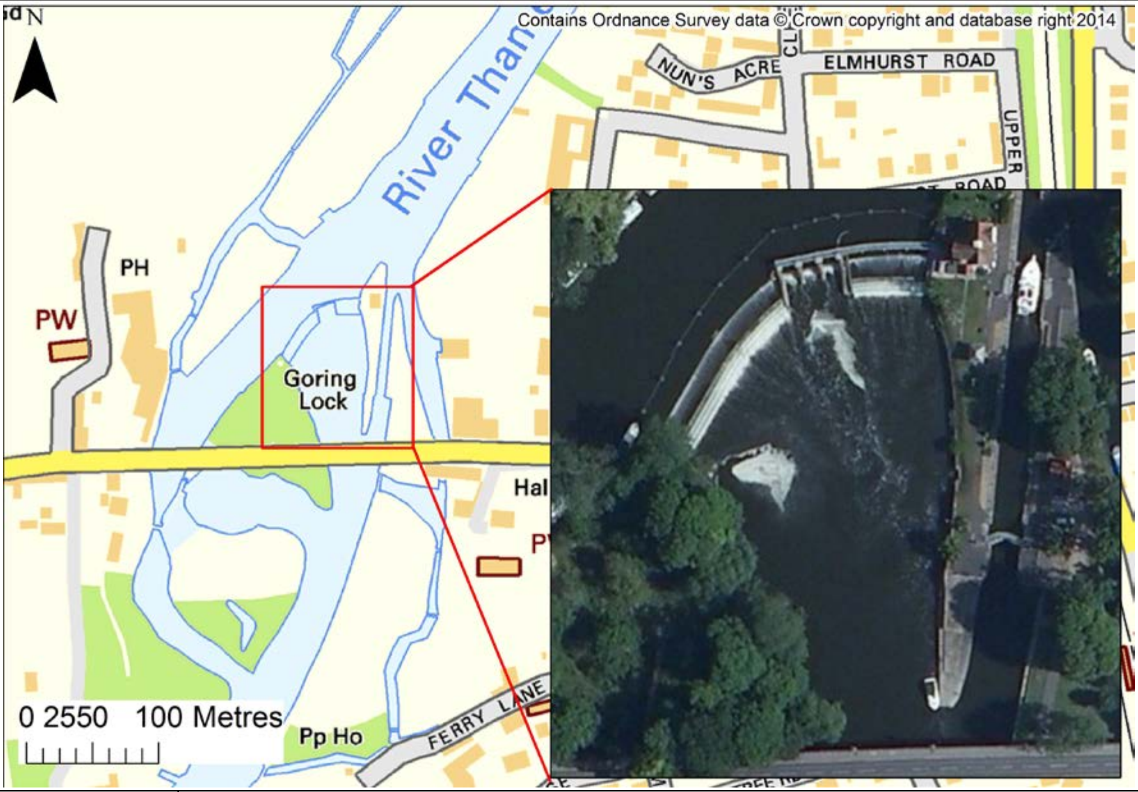
Hydromorphology	At Q95 the impacts are minimal; however, the changes within the deeper pool areas under higher flows show that there could be a greater rate of deposition of larger sand material with reductions in velocities of up to 0.3 m/s under Q50 and Q20 flow conditions so dredged areas will infill over time. In the on-weir scenario, higher flow dynamics across the gravel bar are impacted to a greater degree and could result in a change to the composition of the upstream end of the gravel bar in the medium to long term with velocities of 0.8–0.9 m/s under Q20 flow conditions. This would be through gradual coarsening and possible small-scale erosion of the upstream end of the point bar feature as a result of the increase in velocities at higher flows. It is unlikely the bar will migrate downstream as flow velocities at the downstream end of the bar remain high enough under higher flow conditions to prevent significant deposition of any material carried in suspension.
Macro-invertebrates	The lack of any site-specific macroinvertebrate data means that no assessment of impacts is possible.

Macrophytes	Very limited data on macrophyte composition and distribution restricts interpretation of the modelled impacts. The on-weir hydropower scheme leads to subtle changes in depth distribution which is unlikely to exceed the tolerances of the species present. Decreases in velocity predicted under the depleted reach hydropower scheme may lead to an increase in the extent of common reed and yellow water-lily *Nuphar lutea*, particularly towards the downstream end of the weir pool complex.
Fisheries	The lack of significant change in depth (at all flows) associated with the on-weir scheme means there is unlikely to be any immediate change in availability of deeper holding pool features. At moderate flows (Q50), the co-location of optimal water depths and velocities for lithophilic/phytolithophilc spawning coarse fish is largely confined to the large bar feature adjacent to the left bank, approximately 60 m from the weir apron. Our post-installation, on-weir scenario JHab analysis shows a small increase in the extent of rheophilic spawning habitat, while in the depleted reach scheme this bar dries out in at Q50 and Q95 flows, leading to a significant loss of habitat.
Synthesis	The scoping process suggests that the weir pool may be important, due to the potential rarity, quality of the habitat, and angling amenity provided by the weir pool complex. The key feature of interest is the gravel bar on the left bank. The construction of the hydropower scheme on the left bank leads to increased velocities at the head of this bar, which could lead to gravel movement, but also marginally improves hydraulic rheophilic spawning conditions on the bar compared to the pre-installation conditions. The depleted reach scenario leads to the drying out of this bar at Q95 and Q50, and substantial reductions in depth and velocity at Q20, resulting in a significant loss of habitat. Unfortunately, very little site-specific data were available for macroinvertebrates or macrophytes, which limited the level of interpretation possible, although the slower velocities predicted in the depleted reach scenario may lead to an increase in extent of common reed and yellow water-lily.

6.3 Goring

Table 6.13 Goring case study background information

Site description	Goring Weir is located in a heavily modified section of the Thames and is part of a larger structure with two smaller weirs. The focus of this work is on Goring Weir itself as no bathymetric data is available for the other weirs in this complex. Goring Weir consists of two broad-crested weirs with three sluice gates and a fish pass between the two weirs. Upstream water levels are controlled by lock keepers using the sluice gates and other structures nearby. There are no records of flows over the weir or through the gates, but there are extensive records of water levels upstream and downstream of the weir.



Ecological context	Goring Weir sits within the River Thames (Wallingford to Caversham) heavily modified waterbody (GB106039030331) that is currently classed as achieving moderate ecological potential and therefore failing Water Framework Directive objectives. No information on the quality of fish or macrophytes was available but macroinvertebrate quality elements are currently classed as good. Invertebrate communities within the weir pool are of moderate abundance and diversity, with no species of conservation concern. Communities do not differ notably from surrounding habitats within the system and have preferences for moderate flow conditions. David Rogers Associates (2009 report that no submerged or floating aquatic vegetation was seen in the area, except for a light covering of the algae *Cladophora* sp. covering a concrete weir under the road bridge of the Streatley channel. David Rogers Associates (2009) attribute this to the turbidity of the channel, or overshading (Eeles, 2014). The fish community in the Goring Weir pool complex is dominated by generalist eurytopic fish species (e.g. bleak, bream, perch, pike, roach and carp). Three rheophilic fish species are recorded immediately downstream (chub, dace and gudgeon).
Description of scheme	A proposed hydropower scheme consists of three Archimedes screw turbines and a new fish pass, located in the area currently occupied by the easterly of the two broad-crested weirs. The proposal also includes the provision of a fourth sluice gate adjacent to the existing gates. Details of exact scheme requirements can be found in appendix section 5.5.2.

6.3.1 Evaluating site habitat and ecological quality

The scoping process outlined in section 3.2.1 was applied using a desk study (blue text) and using any site-specific reports if available (*red italic text*) so as to explore the performance of the process with a range of data inputs.

Table 6.14 Scoping process – Goring

In an SSSI/SAC?	No
Fish population status with reference to wider catchment	A variety of fish guilds were found both upstream and downstream of Goring Weir.
Rare habitat?	The nearest weir downstream (Whitchurch) is approximately 6.5 km from Goring Weir, with Mapledurham Weir a further 4 km downstream. Each of these structures is passable via an 'Alaskan A' fish pass. The shallower riffle habitat associated with Goring Weir is partially accessible and of moderate rarity (given the lack of similar structures in the stretch 10 km downstream to Mapledurham Weir).
Good quality?	The quality of any present gravel shoal cannot be determined from the Google Earth imagery due to the resolution and flow levels when this was undertaken. *Eeles (2014) reports that the channel margins and shallow water areas tended to have a fine sediment/silt covering. The bed of the channel within the deep pools is described as being composed of larger, cleaner gravels (Eeles 2014), which is unsurprising given the turbulence associated with flow over the structures and the scour it creates. Despite this, the shallower gravel features within the weir pool complex are of poor quality due to fine sediment and silt infilling.*
Angling amenity?	No fishing access to the weir pool complex.

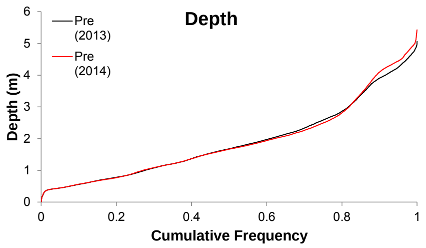
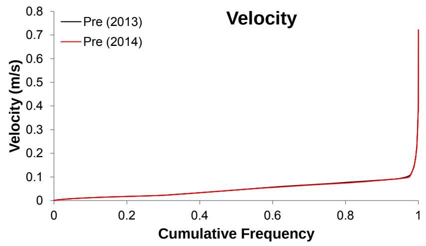
The desk-based study indicates that there were unlikely to be fish species specific to the complex of habitats immediately downstream of Goring Weir. It is likely the habitat could be considered of moderate rarity given the proximity of comparable habitats in the downstream reach. The quality of the weir pool habitat was assessed using the site-specific study (in particular Eeles 2014). The weir pool habitat at Goring is likely to be of limited importance, and the installation of a hydropower scheme could be considered unlikely to have community-level ecosystem impacts (Table 6.15).

Table 6.15 Summary of scoping process – Goring

	In an SSSI/SAC system?	Fish population status with reference to wider catchment	Is the weir pool type habitat rare?	Is the morphology of the weir pool complex good quality?	Angling amenity?
Desk study	No	No	Possibly	Possibly	No
Available reports + desk study	No	No	Possibly	No	No

The ADCP surveys in 2013 and 2014 were used to generate two model grids to represent the channel before and after the Christmas 2013 floods (5 to 10 year return period, but of extremely long duration – Environment Agency, personal communication)(2014). The aim of this was to compare changes in weir pool hydraulics as a result of hydropower installation with flood-driven change (Table 6.16). Changes in patterns of velocity distribution following the installation of a hydropower scheme were more different and were greater in magnitude than the changes to the distribution of velocities following a flood event (Table 6.17).

Table 6.16 Hydraulic habitat mapping – Goring

<table>
<tr><td rowspan="3">Test 1: Comparison between 2013 and 2014</td><td colspan="2">There is very little difference in the modelled velocities using either the 2013 or 2014 bathymetry (and minimal change in modelled depths). The key driver for weir pool velocities appears to be the distribution of the inflows (i.e. flow splits between different weirs, turbines etc.).</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>The sluice gates are one of a number of structures used to control water levels upstream of the weir; however, there is no quantification of flows through the sluice gates or records of gate operating levels. There is uncertainty as to the exact operation of the sluice gates for a given exceedance. Therefore, two pre-installation scenarios have been modelled and then compared against the post-installation results to produce an ‘envelope’ of potential change. These are: (a) gates closed – this leads to an increase in flow in the model when the hydropower scheme is added to the model, (b) gates</td><td>
</td></tr>
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<table>
<tr><td></td><td>‘open’ and passing the turbine flow (i.e. flow neutral).</td><td></td></tr>
<tr><td rowspan="3">Test 2:

Gates and hydro operation</td><td colspan="2">The gates open scenario produces a change in spatial distribution of the velocities, with peak velocities observed near the turbine exits rather than downstream of the sluice gates; however, the overall availability of velocity remains largely unchanged.

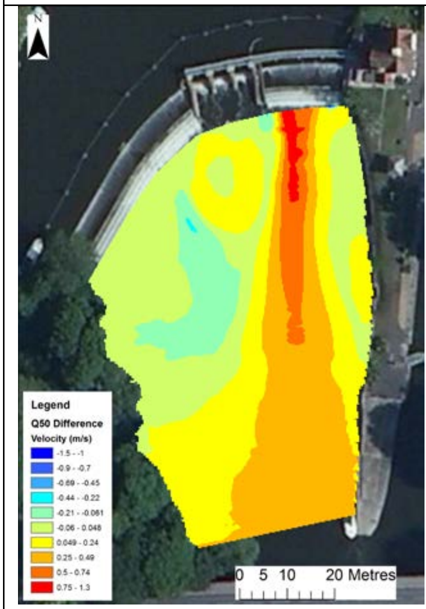
When the pre-change gates closed scenario is compared to the post-change, there is both a substantial change in spatial velocity distribution and overall velocity availability. The figure below shows that at Q50 the increased velocities originate from the turbines and propagate through the entire weir pool complex.</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td></td><td></td></tr>
</table>

Table 6.17 Implications interpretation

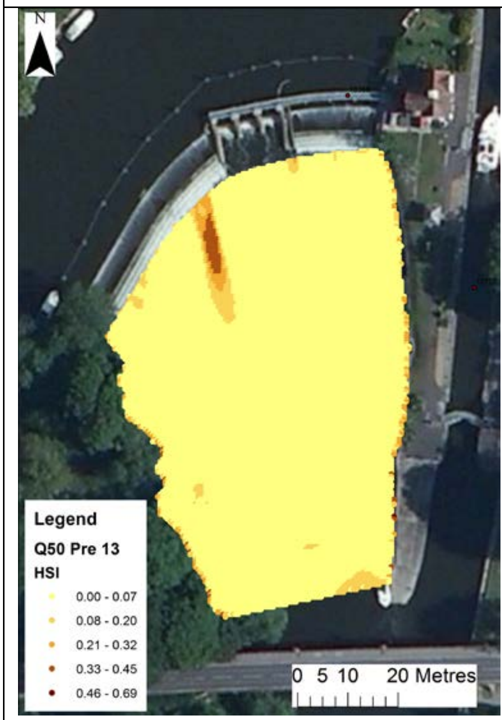
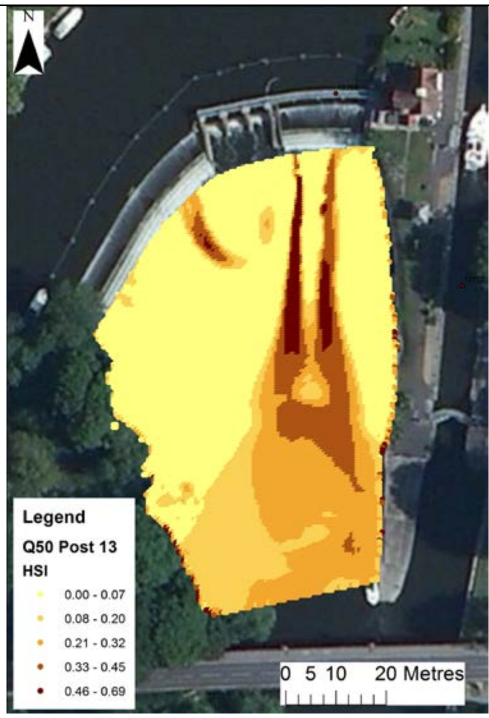
Hydromorphology	Under Q95 flow conditions, with the sluices closed, velocities remain relatively unchanged compared to existing velocities but there are significant increases in velocity for Q50 and Q20 flow conditions downstream of the main weir with increases of up to 1.3 m/s as a result of concentration of flow. This is high enough to erode and transport gravel-sized material. There are also increases of 0.2–0.4 m/s under higher flow conditions along the left and right banks further downstream. When sluices are open, there is a reduction in flow velocity for the Q50 and Q20 flow conditions downstream of the sluice gates that could allow for deposition of fine sediment. Under Q20 flow conditions the left hand bank channel section that is currently shallow may have more energetic flows when the sluice is closed and if turbine flows cause a re-direction towards the left bank. This could expose some gravel habitat where fine silts have been readily deposited in the past but could also result in the movement of some of the stored smaller gravel as velocities could reach up to 0.2 m/s. The redistribution of flows across the weir pool and higher flow scenarios could change the morphology downstream of Goring Weir. This is dependent on the frequency of higher flow events but could result in exposed gravel and transport of smaller gravels towards the left bank of the channel and a deepening of the channel immediately downstream of the main weir. There could also be increased fine sediment deposition towards the right bank as a result of reduction in flow velocity here.
Macroinvertebrates	Velocity changes from the hydropower installation will have some impact on physical habitat, and thus invertebrate communities within the weir pool. The nature and direction of this impact (i.e. towards faster flowing or slower flowing conditions) will depend on how sluice gates are operated and the management regime of the sluice gates on the weir. The invertebrate communities within the weir pool are not considered to include taxon of known conservation concern. Further, given the heavily modified nature of the system, any modifications from the hydropower scheme are likely to be minor.
Macro-phytes	The lack of macrophytes in the weir pool complex at Goring means that no interpretation of the impact of the hydropower scheme can be undertaken.

Fisheries

The lack of appreciable change in depth across the study area between the pre- and post-installation scenarios means that change to the location and extent of adult fish holding habitat is very unlikely to have population-level effects.

An absence of emergent and aquatic macrophyte stands immediately downstream of Goring Weir suggests the phytophilic spawners known to be present in the stretch (i.e. tench *Tinca tinca*) are unlikely to utilise the habitats in the weir pool complex for spawning.

Substantial increases in lithophilic spawning habitat are observed when extra flow is introduced into the weir pool complex (either by opening the sluice gates or the installation of an on-weir hydropower scheme). Habitat modelling using JHab suggests almost a ten-fold increase in the availability of hydraulic conditions suitable for rheophilic spawning. This is primarily due to the increased velocity in the weir pool complex.

Pre-hydropower (sluice gates closed)	Post-hydropower
	

Synthesis	The scoping process suggested that despite being potentially rare, the morphology is of poor quality, provides little direct angling amenity and is unlikely to sustain fish species only found downstream of the weir. The modelling results suggest that velocities in the weir pool complex are highly dependent on the amount of water released by the sluice gates in the centre of the weir complex. An increase in availability of spawning habitat preferred by rheophilic fish species is observed when the gates are open compared to when the gates are closed at Q50. This suggests that there may be potential to improve habitat in the weir pool complex by refining the use of the sluice gates. The operation of the sluice gates in the pre-installation phase is also vital in determining the impacts of the proposed hydropower scheme (i.e. the impact of the hydropower scheme is greatest if the gates have been treated as closed in the pre-installation analysis). Again, the macroinvertebrate and macrophyte analysis was hamstrung by the lack of site-specific data. Changes in patterns of velocity distribution following the installation of a hydropower scheme were more different and were greater in magnitude than the changes to the distribution of velocities following a flood event.

7 Conclusions and recommendations

In this chapter key findings are presented in **bold** font with a discussion provided beneath each point. Findings are presented on (1) the efficacy of the weir pool importance scoping process, (2) issues surrounding the use of 2D hydraulic modelling to detect changes in weir pool systems following hydropower installation and (3) hydropower impacts on weir pool hydraulics and ecosystems.

7.1 Determining the importance of weir pools

Existing tools cannot determine the importance of weir pool habitats but we propose a stepped process

Weir pool habitats can be evaluated with a fluvial audit that considers morphological features and is compliant with Water Framework Directive monitoring standards, but it is worth noting that there is not an existing, single applicable tool or metric that is able to describe weir pool importance.

Site-specific data is important in determining weir pool importance

The results of the scoping process were presented using two different approaches: (1) desk-based study only, (2) using available site-specific reports. The application of the process using available reports acted as a proxy for the similar information which may be gathered on a site visit. While many of the scoping process questions can be satisfactorily answered from a desk-based study, the quality of the habitat of the weir pool can only be assessed by a site-specific study incorporating a site visit. Furthermore, if site-specific ecological data (macrophyte and macroinvertebrate) is available for the weir at importance-determination stage it could be used to more robustly assess weir pool importance. For example at Romney, although the nearby fish communities appear relatively resilient, site-specific macroinvertebrate surveys revealed the presence of three species of conservation interest, thus increasing the potential importance of the weir pool complex when considering hydropower installation.

Weir pool rarity and quality are complex concepts that are difficult to quantify

While quantifying the importance of the complex of habitats downstream of a weir using absolute metrics such as the presence of an environmental designation is both simple and objective (e.g. is the site within an SSSI), quantifying rarity and quality of features is a subjective process compounded by data which might be of limited quality and resolution. The concepts and interrelationship of habitat accessibility, rarity and importance are difficult to consistently align. For example, a location that is spatially isolated (i.e. distant from similar habitat types) might be considered rare and therefore important. However, if that location is inaccessible (i.e. upstream of structures that are impassable to upstream migrants) it may also be considered to be of lesser importance, although this may change with time. Conversely, a habitat could be considered important as it is accessible; however, it might be common elsewhere in the catchment, therefore not considered rare and therefore less important.

Weir pools of 'importance' can be resilient to change

Application of the scoping process at Romney and Pershore weirs indicated that the weir pool complexes could be thought of as important. This result at any proposed hydropower site could potentially guide a developer to undertake further work to understand the ecosystem of the weir pool in more detail or carry out a predictive modelling study to determine the impacts of the hydropower scheme. However, the analysis at Romney and Pershore has shown that it is possible for a weir pool complex to be considered important, but also resilient to the impacts of hydraulic change. In the case of Romney this was because of the central location of the gravel shoal and the distance downstream of the weir structure, and for Pershore the relative position of the turbine and the gravel bar meant that the good quality gravel habitat could be sustained.

7.2 Using hydraulic models

Site-specific data on macrophytes and macroinvertebrates may be necessary for weir pools considered to be important

If a weir pool is considered important and necessitates more detailed work, site-specific surveys for relatively immobile ecological features such as macroinvertebrates and macrophytes may be required. Although the Environment Agency has extensive ecological datasets at a range of sites, it is not possible to extrapolate community-level findings for these receptors from nearby sites to a given weir pool as the habitat created by a weir pool is often different from the surrounding river.

Accurate geospatial ecology and sedimentological data is essential to consider in predictive change tool application at important weir pool sites

The value of site-specific surveys is increased with accurate georeferencing. The likely impacts from on-weir hydropower are (often localised) changes in distribution of depths and velocities. Fully georeferenced ecological data would allow a robust interpretation of modelled changes in weir pool hydraulics.

From a fisheries perspective, the availability and quality of gravel substrate is vital for lithophilic spawning fish species. If a weir pool complex is thought to be important for spawning fish a substrate survey would indicate the extent and quality of suitable substrate. In the case study at Goring, poor quality of the gravels (due to fine sediment infilling) was only identified by a site-specific survey.

Fish are more mobile than macroinvertebrates and macrophytes and are more likely to move to find suitable habitat, so site-specific fish surveys may be less critical if data are available from nearby monitoring sites. The key fish habitats in weir pools are the spawning gravels used by rheophilic spawning fish species. If juveniles and adults of a given species of interest are observed nearby, it may lend weight to the importance of the weir pool for spawning fish. However, even a site quite close to a weir pool may not reproduce the same set of species in low gradient heavily impounded rivers where even a few hundred metres downstream of the weir the river reverts to its lentic form and supports species typical of that type of habitat.

An understanding of the hydrology and hydraulics of the weir pool complex before installation of the hydropower can help us understand likely impacts. For example, the review at Goring highlighted that while the upstream and downstream water levels at Goring Weir are well understood and controlled, no information was available on the discharge through the sluice gates. Our analysis showed that the changes associated with a hydropower scheme could be highly dependent on the way in which the sluice gates are operated.

Hydraulic model outputs require good input data

Confidence in model predictions is increased by high quality input data on channel morphology. In each of the case studies, ADCP depth soundings were used as the basis for the bathymetry of the river channel. ADCP has advantages over traditional survey methods in the resolution, speed of survey, and ability to undertake the survey from the bankside, but it cannot survey depths below 0.6 m. This limits modelling of changes in shallow, marginal areas of weir pools. Depths can be estimated using nearby levels and LIDAR data. This may be particularly important where shallow gravels provide suitable spawning habitat for lithophilic fish species. However, as these areas are likely to be less than 0.6 m in depth, they may not be captured by ADCP. For example, at Romney, the gravel shoal 80 m downstream was of particular interest; however, due to the shallow nature of the water over the shoal the topography of the shoal could not be sampled by the ADCP. Therefore in both the previous 3D modelling study (ARUP 2013) and the current study, the bathymetry of the shoal was estimated, reducing confidence in the modelled depths and velocities over the shoal. At Romney the shoal is a considerable distance downstream of the turbine; however, in other cases if shallow areas are closer to the turbine, further survey could provide useful additional information.

The detailed understanding of weir pool complex hydraulics developed at baseline stage will also add considerable value to the modelling process as, especially at complex sites, there will be greater certainty over the model inflows. For example, a more detailed understanding of the flows over the weir and through the sluice gates at the Goring site would have allowed more relevant scenarios to be run rather than the envelope of change which was undertaken. This may have allowed a more robust interpretation, rather than one heavily influenced by the uncertainties associated with the discharge of the sluice gates.

2D modelling has limitations but is an appropriate tool to use

Model calibration data were available for the Pershore and Goring case study sites (appendix sections 4.5.3 and 5.5.3). In each case there were confounding factors which meant that, despite calibration being achieved to a satisfactory level, absolute confidence should not be placed in the model calibration. Sensitivity tests conducted showed that in general the scale of change in modelled predictions as a result of hydropower installation was higher than the uncertainty due to model parameters. This gives confidence that any changes predicted by the model are reasonable and not unduly influenced by model parameterisation.

It is difficult to compare outputs of 2D and 3D modelling

The velocity predictions produced by the 2D model are depth-averaged (i.e. one velocity representing the whole column of water in a given cell). This velocity will not be representative of near-bed velocities which would be of particular relevance to determining impacts on macroinvertebrates and fish spawning habitat. 3D modelling can provide predictions of velocities at intervals up the water column.

We were able to compare 2D and 3D model outputs at Romney. Both studies showed that the installation of the hydropower scheme on Romney Weir had very little influence on the hydraulics of the key location of interest (gravel shoal). The 3D model predicted higher velocities than the 2D model. This could have been due to a number of factors from the different model grids used to different roughness parameterisations. Furthermore, only basic map outputs rather than georeferenced outputs were available from the 3D modelling study (showing velocities at a small range of depths). Thus the 3D results were difficult to compare with the depth-averaged output from the 2D modelling.

An advantage of 3D modelling is the ability to derive velocity close to the river bed and at user defined intervals up the whole water column. Velocity close to the bed would be more appropriate than depth-averaged velocity for understanding impacts on macroinvertebrates and fish spawning habitat. But this requires a very small grid resolution (0.1 m), to capture the habitat patchiness and complexity which characterises macroinvertebrate communities. This would lead to huge data requirements and run times, impractical for most proposed hydropower schemes, and the outputs still require interpretation.

Habitat models can add value in certain circumstances

Habitat models (such as CASiMiR and JHab) can synthesise hydraulic model outputs into more ecologically meaningful metrics where hydraulic change is significant. This was the case at Romney, where the lack of hydraulic change over the gravel shoal made habitat modelling redundant. However, the power of this type of tool was shown at Goring where the scale of increase in lithophilic spawning habitat as a result of gate operation could be quantified, and at Pershore where the resilience of the spawning habitat was confirmed. These tools were used sparingly, however, because they may not be widely available and generally focus only on fish habitat. It is possible to create habitat rules for individual species of macroinvertebrate, but it is hard to represent the diversity of invertebrate communities (D. Mould, personal communication) (2014).

7.3 Hydropower impacts

Study sites for this project were limited by data availability

Hydraulic modelling requires bathymetric data which was only available for a limited number of sites. From a list of possible case study sites we chose three with the most comprehensive available data. All three are from similar river types (i.e. low energy, navigable rivers). We hoped to have a more diverse range of case study sites, but no suitable data were available. The lack of diversity limits the transferability of the findings; however, weir pools are likely to be of most value in these low energy, lowland rivers.

Every effort has been made to extract the maximum number of findings from this study, but it should be noted that the findings below are based on a maximum of three, and often only one, of the case study sites. Therefore caution must be exercised in extrapolating to other hydropower schemes, including alternative technologies. However, the approaches outlined in this study can be used in a variety of settings.

Habitat quality may be improved by careful management of water level control structures at low flows

The Goring case study highlighted that allowing more flow though the sluice gates at the 50th percentile could improve the quality of the hydraulic spawning habitat for rheophilic fish. This increase in discharge could generate sufficient velocities to clean and sustain better quality gravels, which according to the baseline surveys available are affected by fine sediment. However, the velocities could also have the potential to transport smaller gravels away. Further work might usefully look at optimising the operation of control structures to improve instream habitat, particularly during low flows.

The impact of a hydropower scheme on velocity availability within a weir pool could be greater than a flood event (single site study)

The Goring case study allowed the comparison of the impact of a flood event against changes caused by the installation of a hydropower scheme. The analysis showed that the Christmas 2013 flood event only slightly changed the availability of depths and led to very little change in the availability of velocities in the weir pool complex. While the impact of the hydropower scheme was also the same using both the pre-flood and post-flood grids in the model, larger differences were observed between the pre- and post-installation depth and velocity availability than the differences generated by the flood event. All other model parameters remained the same, so it appears that the key driver influencing the availability of velocities in the weir pool complex is the size and position of inflows, and any concentrations of flow due to low spots on the weir, fish passes etc.

The 2D model software used a fixed grid (i.e. the same grid is used on the pre- and post-installation scenarios) but even during a flood event, the changes to the bathymetry of the weir pool complex are insufficient to cause changes to the distribution of velocities in the complex. This indicates that to assume a static topography is not unreasonable, as changes to the hydraulics in the weir pool are likely to be driven by the change in distribution of the inflows rather than changes to the bathymetry caused by the hydropower scheme. There is insufficient information available to this study to be able to conclude whether this finding can be transferred to other sites/situations.

On-weir hydropower schemes can lead to a redistribution in velocities and little change to modelled depths

The availability of depths did not change greatly as the same grid was used both pre- and post-installation and the flow in the model was the same pre- and post-installation. In general, on-weir hydropower schemes led to a spatial redistribution of the velocities in the weir pool complex, but very little overall change in velocity availability.

Even though the total availability of velocities remains largely unchanged the spatial distribution of the velocities is likely to change. The potential impact of the scheme on the spawning habitat, macroinvertebrates and macrophytes is therefore site specific, dependent on the exact location of the communities/habitat in relation to the turbines. Without spatially referenced ecology and substrate information, it is difficult to tease out the ecological impacts of on-weir hydropower schemes. For example, as the location and quality of the gravel feature at Romney and Pershore was known, a direct assessment of the potential impact of an on-weir hydropower scheme on the gravel feature could be made, while it was impossible to assess the potential impacts on the macroinvertebrate community at Pershore due to insufficient data.

In the case of these heavily modified systems, the changes to flow from hydropower seemed minor relative to existing modifications (e.g. bank reinforcement, flow controls, channel barriers) that will have already influenced the ecosystem. A strong emphasis on the current system condition in any decision-making process is suggested.

Inter-site variability limits the ability to develop a simple a set of prescriptive rules about hydropower impacts on weir pools

The complexity of the case study sites allied to the fact that the sites are relatively similar in character, means that it is impossible, through the use of conclusions from this study, to provide prescriptive rules for when considering new hydropower developments.

There could be scope for a process which sits between the scoping process and detailed modelling, but the study has shown that because weir pools are so complicated and site specific, any such process needs more research than was possible in this project. More weir pool sites would need to be investigated, and these sites would need to be of different river types, before patterns in the impacts of hydropower schemes on weir pools could be detected.

Depleted reach hydropower schemes result in more change than on-weir schemes

A hypothetical depleted reach (i.e. where the turbine outflow is located some way downstream of the toe of the weir) hydropower scheme was simulated at Pershore Weir. The impact of this type of scheme was greater than the on-weir scheme, with decreases in depths, velocities and wetted area. In particular the drying out of the gravel bar adjacent to the left hand bank could result in a large reduction in the available spawning habitat for lithophilic fish.

If a depleted reach hydropower scheme is proposed, the potential impacts are likely to be widespread within the weir pool complex, and the reduction in flow is likely to impact on the shallow regions (of particular interest for fish spawning) before affecting the deeper areas of the weir pool complex. The turbine flow used in the Pershore depleted reach scenario was marginally higher and abstracted at lower flows than that which would be allowed under the revised (December, 2013) guidance (Environment Agency, 2013).

Placement of hydropower (left bank/right bank) does not always give rise to differing changes

At Romney Weir, the as-designed hydropower scheme (located adjacent to the right hand bank) was modelled alongside a mirror hydropower scheme located on the left hand bank to explore the potential influence of scheme location on either side of the channel. The analyses showed that the overall availability of depths and velocities were independent of scheme placement, while there were differences in the location of the areas of high and low velocity. If fully georeferenced ecological data were available it may have been possible to better tease apart the impacts of the two hydropower placements for macroinvertebrates and macrophytes. However, in this one case, with a relatively straight channel downstream, the placement of the scheme on either bank led to very similar impacts on instream hydraulics and ecology.

The impact of hydropower schemes on macrophytes was generally small

Macrophyte data are limited in weir pool locations, but where they are available weir pools appear to have limited macrophyte flora. This is a result of the high energy conditions in weir pool environments, which physically limits establishment and persistence of many species, and the high levels of bankside modification, which are often (but not always) present in areas where weirs are located and can further limit the growth of riparian vegetation in marginal areas.

Given that all aquatic macrophytes have preferred flow velocity and depth tolerances within which they will grow, any permanent change beyond the tolerance limits could result in their loss from the weir pool habitat. However, given that most aquatic macrophyte species have broad tolerances within which they can persist, the impact of this is considered to be very minor, particularly as the modelled changes in flow velocities and depths are, in general, quite small.

Displacement of non-native (macrophyte) species may be an issue

Due to the redistribution of velocities it is possible that displacement of a species may occur from one area to another. At Romney, a non-native invasive species (waterweed, *Elodea* species) may be displaced by increased flow velocities and new populations could then become established downstream. However, this may not be significantly different to natural dispersal. The presence of non-native invasive species may need to be considered in relation to hydropower schemes, for example, existing weir pools complexes have been known to act as a barrier to the upstream migration of signal crayfish, keeping them separate from native species (albeit temporarily) T. Bond (personal communication) (2015).

There are few data on weir pool macroinvertebrate communities

The case studies highlighted a lack of data on invertebrate communities in the altered habitats around weirs, including the weir pool, mainly because routine monitoring is deliberately designed to avoid sampling in habitats that are not representative of the wider river reach. Although some sites have baseline surveys taken at a single point in time, this is not sufficient to be able to measure community response to any change in these environments caused by the installation of hydropower schemes. Data on invertebrate communities needs to be supported by field data on the hydrological and morphological changes from hydropower schemes, so that any macroinvertebrate responses can be explained and understood.

7.4 Recommendations

7.4.1 Conceptual framework

Here we propose a risk-based conceptual framework to help guide considerations about the potential value and sensitivity of weir pools in the face of hydropower development based on the findings of this project.

At all three case study sites the distribution of velocities changed but the overall availability of velocities did not. This suggests that impacts on adult fish are likely to be minimal but the impact on less mobile ecological features (macroinvertebrates and macrophytes, and rheophilic spawning habitat) could be different. However, in all three case studies ecological data were insufficient to infer localised ecological impact from the hydropower scheme. The case studies were all in similar lowland, navigable rivers and results may not be transferable to other rivers.

In the current Environment Agency guidelines for hydropower (Environment Agency 2013b), a decision tree is provided to support weir pool assessment (Figure 7.1). Many of the questions asked mirror those considered here. Where this report can add value is in the determination of the third question in the decision tree: Will this change in flow result in a change in status of the waterbody or prevent achievement of WFD objectives?

The risk-based conceptual framework (Figure 7.2) is proposed to highlight the potential tools/approaches which could be used depending on the stage of the application and the environmental risk. The risk is a function of the importance of the weir pool (assessed using the importance scoping tool discussed in section 3.2.1) and nature of the hydropower scheme. The environmental risk assessment will be iterative, depending on the results of any analyses and any alterations made to the scheme design. The framework is conceptual rather than prescriptive, as the impacts of hydropower schemes are likely to be highly site specific, with local understanding (provided by the Environment Agency and the developer) essential in shaping the assessment process.

The blue boxes in the framework indicate a scoping phase should be conducted early in the process for all sites with a weir pool as this will provide context for considering hydropower impacts. Consideration of the impacts of the scheme will need to be undertaken alongside or immediately after the application of the scoping tool. A number of key questions can be asked about the nature of the hydropower scheme (Table 7.1).

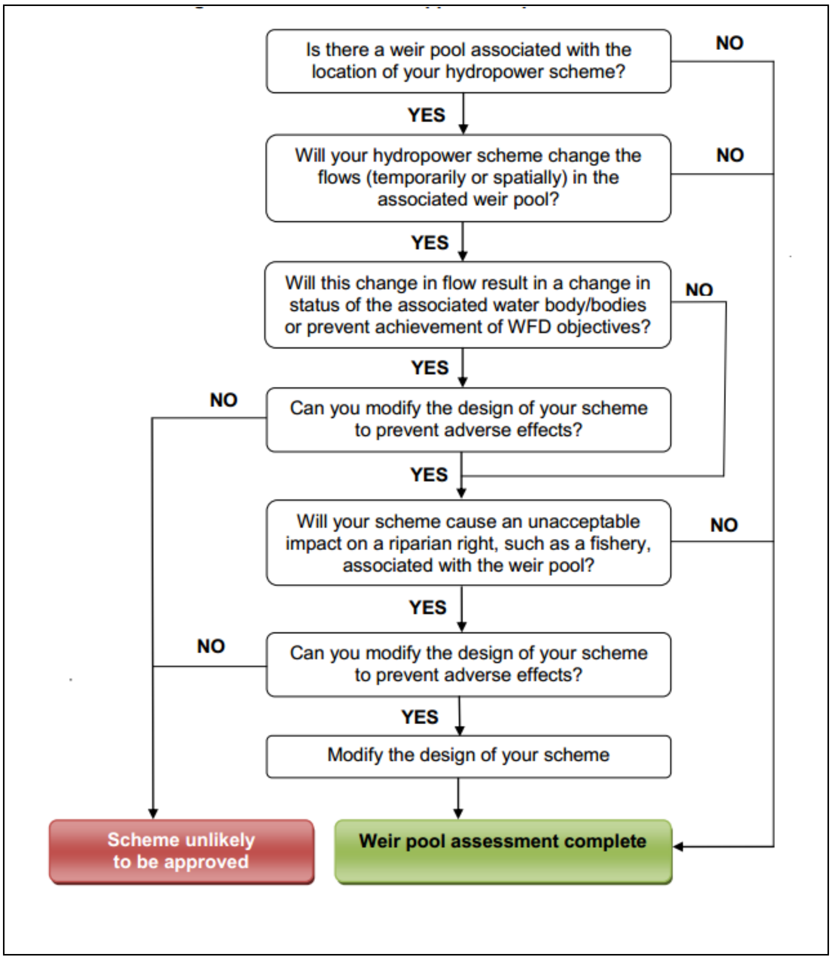


Figure 7.1 Decision tree to support weir pool assessment (Environment Agency 2013b)

Table 7.1 Key questions

Question	Risk outcome
Does the turbine take a large proportion of the flow?	Higher risk if the turbine takes a large portion of the flow. Use Environment Agency guidance.
Does the scheme change predominant flow directions in the weir pool complex (i.e. change of bank)?	Higher risk if the proposal changes the predominant flow direction in the weir pool complex. Of particular interest would be whether the change in flow patterns is likely to influence key features of interest (e.g. move higher flow areas closer to or away from key features). This needs to be considered for changes in low and high flows for gravel features, potentially resulting in increased fine sediment deposition or gravel entrainment respectively.
Is the hydropower likely to change the velocities in the weir pool complex?	For example putting a turbine and fish pass on a vertical drop weir is likely to be higher risk than on a weir with a sloping face as the change in velocities is likely to be greater.
Is the turbine close to an area of interest (e.g. a gravel bar)?	If the proposed turbine is close to an established gravel feature, this would increase the risk; if the

	feature was some distance downstream the risk would be lower.
Does the hydropower scheme create a depleted reach?	Depending on the proportion of flows to be abstracted, a scheme which results in a depleted reach may be higher risk.

Little further work may be required following the scoping phase and consideration of the nature of the hydropower scheme. This may occur where the habitat in the weir pool is poor (e.g. no gravels, gravels heavily silted) or because similar habitat is ubiquitous in the surrounding reaches of the river. In this case, expert judgement could be used to determine that the scheme would have minimal impact on the weir pool habitat.

If, however, there is a risk the installation of a hydropower scheme could still impact upon the weir pool habitat, some sampling could take place in the weir pool (green boxes in Figure 7.2). Depending on the features of interest, this may include biological or sediment sampling or ADCP survey. We strongly recommend georeferencing data to add value if modelling studies are required at a later stage.

The process could be halted following this sampling stage, for example if the sediment is found to be unsuitable for the species/life stages of interest or the ecological community unremarkable, or the hydraulics of the system are sufficiently robust to absorb the changes brought about by installing a hydropower scheme.

If, following the scoping and sampling phases, the weir pool is still considered to be at risk, it may be necessary to undertake some predictive, hydraulic modelling of the system (red boxes in Figure 7.2). As discussed in section 5.4, various approaches could be used, ranging from fixed bed 2D modelling to physical modelling, but 2D modelling may well be an adequate option.

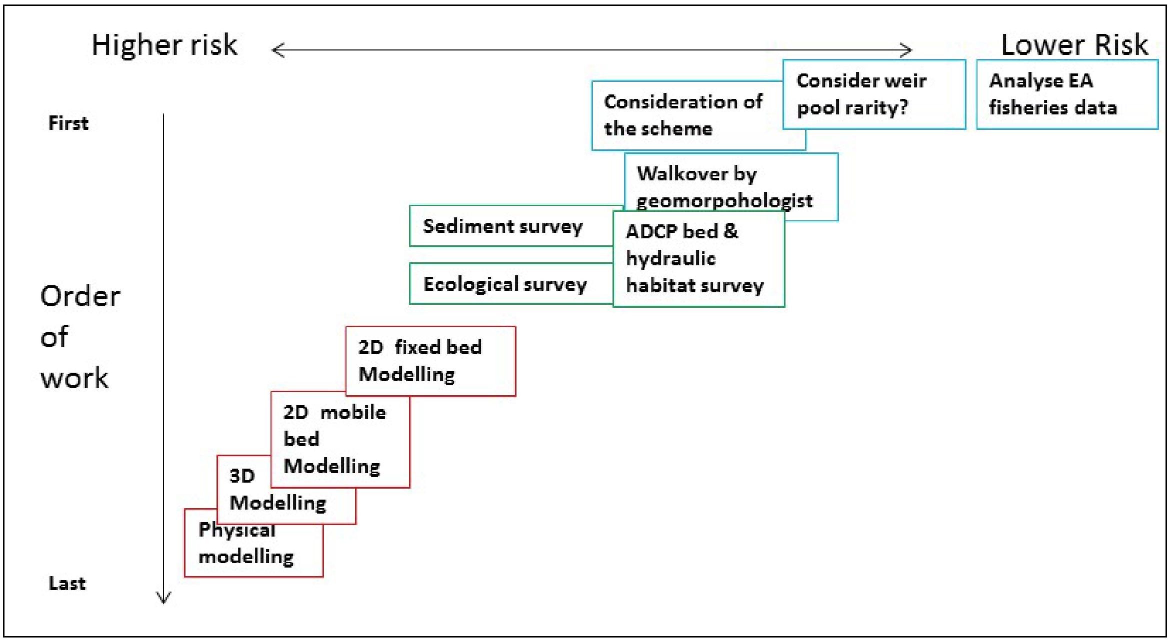


Figure 7.2 Weir pool conceptual workflow framework

7.4.2 Recommendations for further work

- There may be value in identifying sites where more detailed ecological data are available for weir pools. Modelling scenarios for sites other than large lowland rivers may indicate different impacts if data on bathymetry were available.
- Some evaluation of pre- and post-monitoring data from sites where hydropower structures have been installed may help to indicate potential impacts on weir pool macrophytes, macroinvertebrates and fish.
- Water level control structures could potentially deliver additional benefits beyond flood risk management or navigation functions.
- The differences in operating envelope between hydropower technologies may warrant further investigation with regard to potential impacts on hydraulics and weir pool ecology. The focus of this study on hydropower deployed in England led to an emphasis on Archimedean screw turbines, as these are the most common form of hydropower technology currently being considered. The choice of turbine technologies is driven by site-specific issues and is dependent on a number of factors (including available space and river hydrology).

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List of abbreviations

1D: one dimensional

2D: two dimensional

3D: three dimensional

ADCP: Acoustic Doppler Current Profiler

ASPT: average score per taxa

BAP: Biodiversity Action Plan

CFD: computational fluid dynamics

CGU: channel geomorphological unit

CHAT: Catchment-scale Habitat Assessment Tool

DEM: digital elevation model

DRAPHT: Direct Rapid Assessment of Physical Habitat Toolkit

EC: European Community

FCS2: Fisheries Classification Scheme 2

FHAT: Functional Habitat Assessment Tool

HEFT: Hydro-Ecological Flow Thresholds

MIMAS: Morphological Impact Assessment System

NERC: Natural Environment and Rural Communities Act

PHABSIM: Physical HABitat SIMulation model

Q: discharge (m^3/s)

RAPHSA: Rapid Assessment of Physical Habitat Sensitivity to Abstraction

RAT: River Assessment Tool

RICT: River Invertebrate Classification Tool

RoR: run-of-river

SAC: Special Area of Conservation

SSSI: Site of Special Scientific Interest

UK-TAG: UK Water Framework Directive Technical Advisory Group

WALES: Water Abstraction Licensing using Ecological Scoring methodology

WFD: Water Framework Directive

WRA: Water Resources Act

Glossary

Benthic	associated with the bed of the water-body
Cyprinid fish	belonging to the genus Cyprinidae (carp and minnow-like species
Eurytopic	generalist fish species such as roach and bleak
Lentic	of slow-moving water
Limnophilic	associated with still water conditions or habitats
Lithophilic	fish preferring to spawn in gravel
Lotic	of fast-moving water
Macroinvertebrates	small animals without backbone visible to the naked eye (<0.5mm) that live on and under submerged rocks, logs, sediment, debris and aquatic plants
Macrophyte	aquatic plants that grow in or near water
Phytolithophilous	Fish species that deposit their eggs on aquatic plants or gravel/cobbles.
Phytophilic	Fish species that deposit their eggs on aquatic plants
Rheophilic	fish species that prefer to live in fast-moving water, such as chub and dace
Riparian	Of river banks and margins
Salmonid Fish	species belonging to the family Salmonidae

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