Ecologically acceptable flows in Chalk rivers

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Abstract

The term 'Chalk rivers' is used to describe all those water courses dominated by groundwater discharge from Chalk geology. Natural conditions and historical modification have generated an ecosystem, with rich and unique assemblages and with high value to society (*e.g.* SACs, SSSIs, visual amenity and fisheries. Chalk rivers are considered to be sensitive to hydrological and morphological change and there is concern that flood defence and land drainage schemes, catchment agriculture, urbanisation, climate change and abstraction are leading to a decline in river health. This report reviews tools and methods available for setting ecologically acceptable flows in Chalk rivers to help define sustainable abstraction levels.

Methods of ecological flow setting are classified into four types (1) look-up tables (2) desk (3) functional analysis and (4) physical habitat modelling. The analysis of methods of their application leads to 12 recommendations.

1. Chalk rivers are iconic English rivers. All flow-setting studies should define clear objectives for the river system with costs and benefits of different options.
2. Chalk rivers have some hydrological characteristics in common including the baseflow-dominate response. Low flows, especially in the summer are critical to Chalk river ecosystems, such as August flows for salmon parr.
3. Chalk rivers have ephemeral (winterbourne) reaches which have no flow during certain periods. A research study is needed on ephemeral river flow setting
4. Chalk river ecosystems are sensitive to flow change and setting the appropriate flow is crucial to river conservation. Information on hydromorphology and ecological dynamics needs to be combined.
5. The impact on the flow regime varies according to the type of abstraction. Different management approaches may be needed for these abstraction types.
6. Chalk rivers are characterised by high macrophyte biomass. This needs to be considered in the role of flow in creating habitat.
7. Chalk rivers are not natural. Channel morphology, macrophyte growth, and flow need to be considered together.
8. Chalk rivers are not one homogeneous river type due to management. There is a need for individual studies to define hydraulically appropriate flow regimes.
9. In Chalk rivers the relative sensitivity of habitat types is not clear. Ecological flow studies need to consider the whole reach, not just single habitats (*e.g.* riffles).
10. In Chalk rivers, flow may be linked to other factors such as temperature. Analysis is required to assess trends and changes in flow and temperature regimes.
11. Flow in Chalk rivers comes primarily from aquifers. Appropriate flow regimes may be achieved at critical times by stream support by pumping from an aquifer.
12. Chalk rivers tend to be low in fine sediment and recover slowly from artificial inputs. Simple channel narrowing is not necessarily a satisfactory solution.

Four areas for new research are proposed.

1. To develop a rapid assessment of physical habitat sensitivity to flow change for Chalk rivers
2. To investigate the response of Chalk river biota to the combined effects of flow, morphology, sediment and water quality.
3. To define any trends, changes and variations in environmental conditions in Chalk rivers
4. To examine hydro-ecological issues of ephemeral reaches of Chalk rivers

1. Background

The term 'Chalk river' is used to describe those water courses dominated by groundwater discharge from Chalk geology (Mainstone *et al*, 1998). The Chalk influence gives rise to a distinctive hydro-chemistry and flow regime, creating characteristic assemblages of plants and animals. Most Chalk rivers have been highly physically modified for many centuries, through channelisation, installation of weirs, lades and side channels and weed management. Nevertheless, this historical modification has generated an ecosystem, with rich and unique assemblages and with high value to society (such as designation as Special Areas of Conservation and Sites of Special Scientific Interest, plus their visual amenity and fisheries). Furthermore, Chalk rivers are considered to be sensitive to hydrological and morphological change and there is concern that flood defence and land drainage schemes, catchment agriculture, urbanisation, climate change and abstraction are leading to a decline in river health. Half of the top 20 rivers identified in 1993 requiring low flow alleviation (ALF) were Chalk rivers and form part of the Restoring Sustainable Abstractions (RSA) programme of the Environment Agency (Acreman and Adams, 1998). This is due to their location in south-east England, where water demand is great, and the high quality water resource of chalk aquifers. As a result many Chalk rivers have been the subject of intensive study including the Pang, Itchen, Wylye and Darent. One of major objectives for Chalk rivers has been to achieve ecologically acceptable flow regimes, by limiting abstraction to a level that maintains their ecosystems at the desired state, such that they continue to deliver their functions, services and values.

This report describes a review of tools and methods available for setting ecologically acceptable flows in Chalk rivers, so that sustainable abstraction levels and impoundment operations can be defined. Terms of Reference are given in Annex A.

2. Chalk rivers and ecologically acceptable flows

Most ecological (or environmental) flow concepts and approaches are based on the notion that a river system provides its maximum ecological functions, services and values when the flow regime is natural (Poff *et al*, 1997; Junk *et al*.,1989; Richter *et al.,* 1997) and that deviations from natural lead to ecosystem degradation. Consequently, the natural flow regime is frequently used as the baseline against which to set target flows. Likewise, Good Ecological Status, required for European rivers under the Water Framework Directive (WFD), is assessed in terms of the extent of deviation from undisturbed reference conditions, in which hydromorphology is a supporting element. Some Chalk rivers do not fit well with this paradigm and many experts feel that the natural flow regime may not the most appropriate target for an unnatural river, thus restoring UK chalk rivers to more natural conditions may lead to loss of functions, services and values; widening and deepening, for example, may mean that more than the natural flow is required. In such a case, river restoration, including narrowing, can return a river channel to the dimensions that match the natural flow regime. However, this does not mean that impacts of abstraction can be overcome by making a channel smaller than natural. This issue is compounded by some evidence for past trends in flow and future predictions of further changes. In the River Itchen study[1], for example, the issue of appropriate reference conditions was hotly debated. This concept is only starting to be realised in the international literature (Poff *et al*, 2009).

A major issue with Chalk rivers is the lack of clear reference conditions and hence indicators of modification. Some suggest that natural chalk river channels would consist of many small channels divided by vegetated bars. The most ecologically acceptable flow for such channel form may be different from that appropriate for the human-influenced channels that characterise Chalk rivers today. Furthermore, climate change prediction by UKCIP (Hulme *et al*, 2002) suggest that UK winters are likely to become wetter and summers drier, with greatest changes in the South and East, where chalk rivers occur.

3. Analysis framework

There are numerous methods that have been used to set ecological flows in rivers. A global review of environmental flow methods (Acreman and Dunbar, 2004) produced a simple four-fold classification.
(1) look-up tables – simple numbers that can be applied readily to any rivers (e.g. maximum abstraction – 30% of flow), such as produced for WFD implementation (Acreman *et al*., 2008b).
(2) desk-top - methods that require some analysis of data on the target river (*e.g.* Indicators of Hydrological Alteration (Richter *et al*, 1996).
(3) functional analysis – methods that employ explicit process links between species or communities and components of the flow regime (e.g. building block method proposed for defining flow released from reservoirs, Acreman *et al*., 2009)
(4) physical habitat modelling – methods that require hydraulic modelling of depth and velocity rather than flow, and the calculation of usable physical habitat through the use of habitat preference functions (e.g. PHABSIM – Elliott *et al*., 1999).

These method types have implications for data, time and expertise needed with generally increasing requirements from (1) to (4). Nevertheless, specific details on data employed, main results, applicability to Chalk rivers would be appropriate. Methods could also be classified according to output type: study (qualitative/narrative output), approach (quantitative broad method), tool (specific method with step-by-step guidance and software).

A pro-forma was developed to capture the information from reviews of the various documents available on methods and tools. These are provided as Annex B.

1 Look-up tables

Worldwide, the most commonly applied methods to define target river flows have been rules of thumb based on simple indices given in look-up tables. Engineers have traditionally used hydrologically-defined indices for water management rules and to set compensation flows below reservoirs and weirs. Examples are percentages of the mean flow or exceedence percentiles from a flow duration curve (*i.e*. the flow duration curve is a water resources tool that defines the proportion of time that a

[1] http://www.riveritchensustainability.org.uk

given flow is equalled or exceeded). A hydrological index is used in France, where the Freshwater Fishing Law (June 1984) required that residual flows in bypassed sections of river must be a minimum of 1/40 of the mean flow for existing schemes and 1/10 of the mean flow for new schemes (Souchon and Keith, 2001). The RAM framework used for CAMS (Environment Agency, 2000) includes a table where river type is based on sensitivity to abstraction (Table 1) determined though consideration of four elements: physical characterisation; fisheries; macrophytes; and macro-invertebrates. Chalk rivers tended to be in the A band, such that only 0-5% of Q_{95} (*i.e.* that flow which is equalled or exceeded for 95% of the time) can be abstracted. Q_{95} is often as a threshold to below which little or no abstraction (hands-off flow) can take place (Barker and Kirmond, 1998).

Table 1. Percentages of Q_{95} flow that can be abstracted for different environmental weighting bands within the initial RAM framework

Environmental weighting band	% of Q_{95} that can be abstracted
A	0-5
B	5-10
C	10-15
D	15-25
E	25-30
Others	Special treatment

Specific thresholds were developed by English Nature for SAC and SSSI rivers (Table 2).

Table 2. English Nature thresholds for SAC/SSSI rivers

EW band (sensitivity)	**HD ERF**		
	Maximum % reduction from daily naturalised flow		
	> Qn_{50}	Qn_{50-95}	<Qn_{95}
Very high	10	10	1-5
High	15	10	5-10
Moderate	20	15	10-15
Low	N/A	N/A	N/A
Very Low	20	20	15

For implementation of the WFD, an expert group of UK river scientists defined a look-up table (Acreman *et al.*, 2008b); this work included Chalk rivers (Table 3), but sub-divided them into those with drainage areas greater than 100 km^2 (downstream) and those less than 100 km^2 (headwater).

Table 3. Maximum allowable abstraction from Chalk rivers as a % of natural flow to achieve Good Ecological Status under the Water Framework Directive

Chalk river type	Season	flow > Qn_{60}	Flow > Qn_{70}	flow > Qn_{95}	flow < Qn_{95}
Downstream > 100 km^2	Apr – Oct	25	20	15	10
	Nov – Mar	30	25	20	15
Headwaters < 100 km^2	Apr – Oct	20	15	10	7.5
	Nov – Mar	25	20	15	10

The WFD maximum abstraction limits have now been incorporated in to a revised RAM framework (Table 4). There is some consistency in the figures, for flow at Q_{95} suggesting 5-15% of the flow could be abstracted from Chalk rivers depending on season and sensitivity. However, the tables are not independent as many of the same river scientists were involved in their development.

Table 4. Flow standards now used in the RAM framework. These are maximum % abstractions from natural flow.

Type	**Flow > Q95**		**Flow < Q95**	
	Mar - Jun	**Jul - Feb**	**Mar - Jun**	**Jul - Feb**
Al	25	30	15	20
A2	15	20	10	15
B1, B2, Dl	20	25	15	20
C2, D2	15	20	10	15
	Oct - Apr	**May - Sep**	**Oct - Apr**	**May - Sep**
Salmon spawning & nursery (not chalk rivers)	15	20	10	15

A conference was held in York in January 2010, organised by the Atlantic Salmon Trust to present and discuss scientific knowledge of the flow needs of salmonid fish. This was followed-up by a workshop in Pitlochry in March 2010 to distil the guidance for ecological flow setting from that knowledge. In general, it was considered that there was significant evidence for the impacts of flow change on different life stages of salmonids (migration, spawning, eggs, fry, juveniles, parr adults), though much of this was for upland rivers. However, it was difficult to find precise evidence for specific flow thresholds; many of the flow-fish relationships were smooth curves or straight lines, devoid of specific 'nick-points'. Some advocated that there should be no abstraction (hands-off flow) below Q_{95}, but this was considered as expert opinion and a precautionary approach, since there was no explicit scientific justification. End-users (including water and hydropower companies) pointed-out the significant opportunity costs of small changes in abstraction limits or required environmental reservoir flow releases. End-users also supported the concept of adaptive management, although there may be few examples from Chalk rivers. Outputs from the workshop (AST guidance) and the conference (special issue of the Journal Fisheries Management and Ecology) are underway.

2 Desk-top analysis

Methods in this class involve some analysis of existing data at a site. An example of a desk-top method is the Range of Variability Approach (RVA; Richter *et al.,* 1997) using the Indicators of Hydrological Alteration (IHA; Richter *et al.* 1996). Development of the IHA approach concentrated on identification of the components of a natural flow regime, indexed by magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency (number of events), duration (indexed by moving average minima and maxima) and rate of change (Figure 1). The method used gauged or modelled daily flows and a set of 32 indices (Richter *et al*, 1996). Each index was calculated on an annual basis for each year in the hydrological record, it thus concentrates on inter-annual variability in the indices.

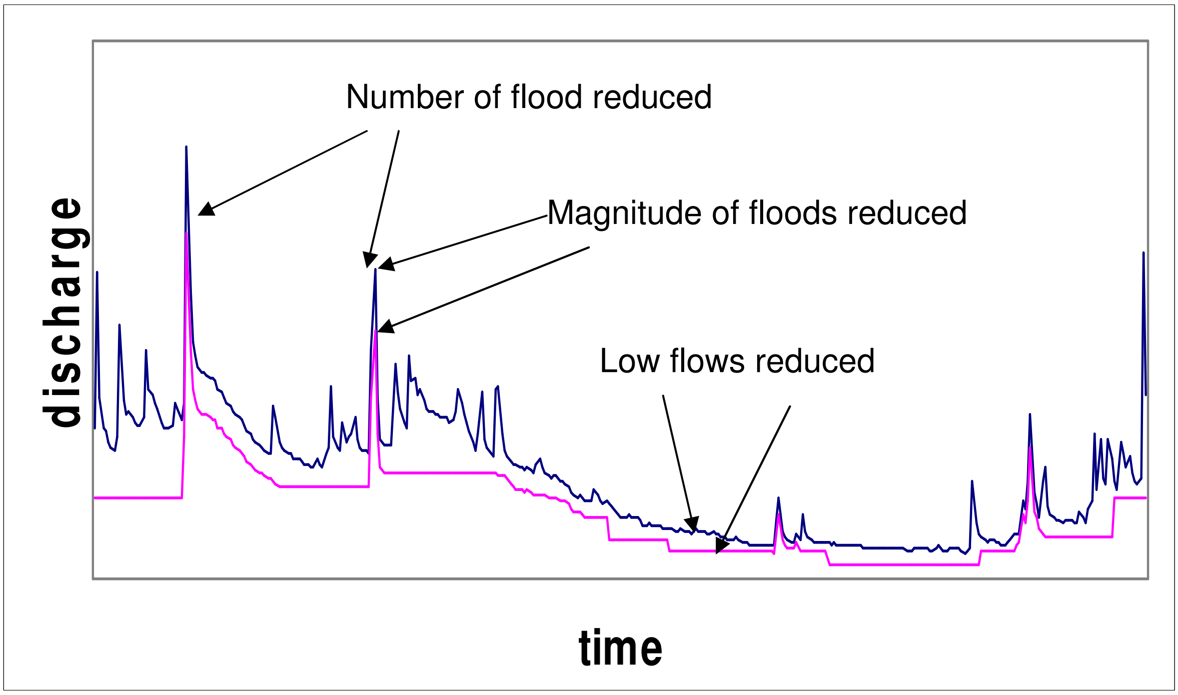

Figure 1 Indicators of Hydrological Alteration (after Richter et al. 1996)

A major question is how much deviation from natural ranges of these parameters is too much? Where no ecological information is available to answer this question, the RVA uses a default range of variation based +/- 1 standard deviation from the mean or between the 25th and 75th percentiles. This method was recommended as a screening tool for assessing whether river water bodies are likely to achieve Good Ecological Status under WFD (Acreman *et al*., 2009). Because the method includes natural variability in the flow regime, it has tended to be used to assess the impacts of past management, rather than for setting licensed abstraction levels for future management. Furthermore, abstraction from Chalk rivers tends to impact on low flows more than higher flows or floods. Thus many of the high flow parameters are of less relevance to Chalk rivers, being more applicable to assessment of altered flows downstream of reservoirs, as proposed for Scotland (Black *et al.,* 2003).

The IHA/RVA method was employed by Acreman *et al*. (2003) to assess the extent to which observed flow regimes for impacted rivers fell within the English Nature 'maximum reduction' targets (Table 2). Chalk rivers included in the analysis were the Hampshire Avon (East Mills, Knapp Mill), Nar (Marham) and the Lee (Feildes Weir). Based on an illustrative categorisation of all case study SSSI/SAC rivers as Moderate, under the RAM EW sensitivity banding, only the most heavily abstracted of the three studied regimes was found to fall outside of the English Nature targets.

Some studies have focused on ecological functioning of chalk stream headwaters. Westwood (2008) explored long-term biological and hydro-physical data from north-east and north-west areas of Thames Region of the Environment Agency. He found that both macrophytes and invertebrates demonstrate a range of periodicities in their responses to stream discharge. (1) There were immediate within-year responses to extreme events, such as high, scouring flows or periodic desiccation of the channel; when whole communities of plants and animals can be either grossly simplified or temporarily lost. (2) There was a recovery phase, which is between one and two years for both macrophytes and invertebrates. (3) There were more extended cycles of community succession and development as assemblages re-establish their long-term equilibria following perturbation. Invertebrates generally experienced longer cycles of adjustment than macrophytes, with the available evidence gathered through classification, ordination and regression analysis, suggesting a 5-6 year period for invertebrates and 3-4 year period for macrophytes. A step change was noted at community level for both invertebrates and macrophytes following the exceptional high flows of 2000-2001. For macrophytes, the positive benefits were immediate, and the proliferation of the more flow-dependent communities lasted until 2003; although some individual sites continued to defy the effects of drought even in 2006. For the invertebrates, the effect was initially more gradual but was very apparent in 2003 and has lasted in some degree up until the present.

3. Functional analysis

The third group of methods builds on explicit understanding of the functional links between the hydrology and ecology of the river system. Perhaps the best known is the Building Block Methodology (BBM) developed in South Africa (Tharme and King, 1998); its basic premise is that riverine species are reliant on basic elements (building blocks) of the flow regime that explicitly justified by the function they play in the ecosystem, including low flows (that provide a minimum habitat for species and prevent invasive species), medium flows (that sort river sediments, and stimulate movement and reproduction) and floods (that maintain channel structure and allow movement onto floodplain habitats). A flow regime for ecosystem maintenance can thus be constructed uniquely for each site by combining these building blocks, normally by a team of river physical and biological scientists. This method was recommended for setting of flow standards below reservoirs (Figure 3) to implement WFD (Acreman *et al*., 2009). The method has potential for application to Chalk rivers as a means of combining information for different life stages (*e.g.* migration, spawning, fry, juvenile fish). The disadvantage of this method is that flow regime elements may be disregarded if explicit ecosystem dependence is not known.

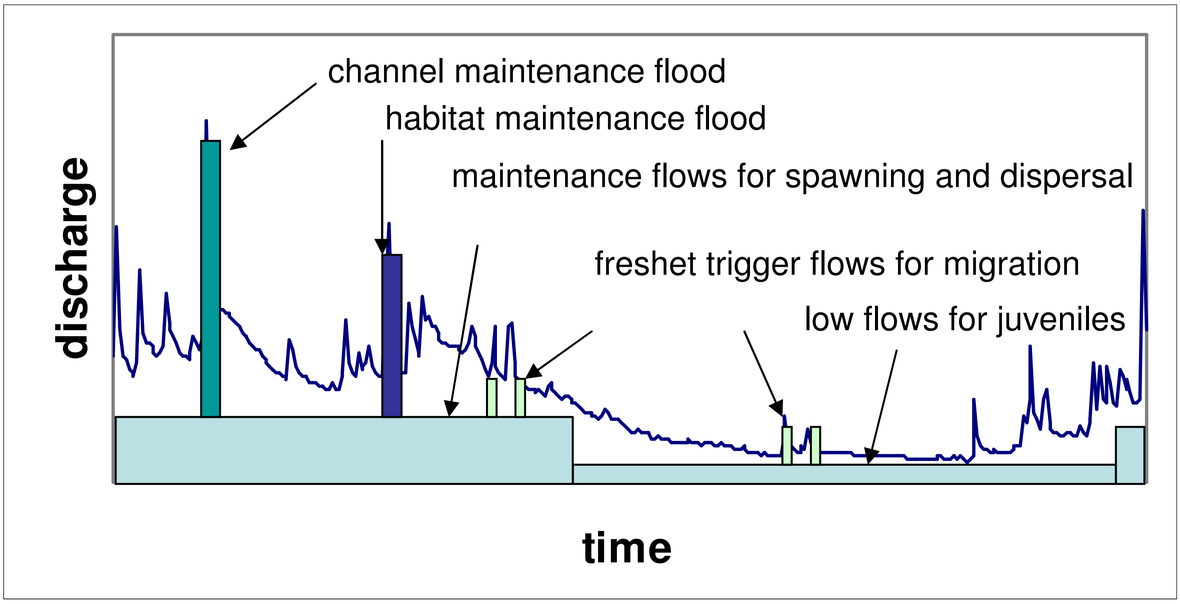

Figure 3 Building blocks for a hypothetical salmonid river

Data exist in the literature to define many of the hydrological building blocks and this method could provide a useful way of bringing together information regarding Chalk rivers. It is widely accepted that salmon preferentially migrate into rivers during periods of higher flow; this may reflect the optimal situation for maximum growth and minimal mortality (Ladle, 2002). However, there is no absolute flow at which salmon will migrate into a particular river. Furthermore, salmon migration in the River Frome has been observed to occur at flows lower than those often available (Hellawell, 1973 cited in Ladle, 2002) and this may be due to the more steady nature of Chalk river flows. The flow rates associated with salmon entry vary both seasonally and annually (Alabaster, 1970 and Hellawell, 1976 both cited in Ladle, 2002). The relationship between rate of salmon entry and river flow varies between years depending on preceding flow conditions (Smith, 1991). River flows may also be too high for salmon entry; for example, very large floods can move fish out of rivers and back out to sea. The apparent link between salmon entry into rivers and flow levels suggests that migration patterns may differ between rivers with different flow regimes.

Solomon and Lightfoot (in preparation) found that on the Hampshire Avon, August flows are critical for salmon parr, late autumn/winter flows are important for distribution of salmon and spring flows are critical for incubation (both indexed by January flow). Solomon and Sambrook (2004) reported that entry of salmon to the Avon, from the sea, is greatly reduced when flows are below Q_{95} (6.97 m^3s^{-1}).

Electro-fishing 2006 and 2007 (Bradley *et al.*, 2008) compared un-impacted (<15% flow change) with impacted reaches of the Hampshire Avon. More bullheads were found in un-impacted reaches, particularly for >0+ fish, with abstraction at Q_{95} being most significant. More >0+ trout were sampled in un-impacted reaches, whereas more 0+ trout and more lamprey were found in impacted reaches. No *Ranunculus* was found where flow reduced by more than 10%. There was little evidence of impacts on invertebrates or on algae.

A further example is this category of methods is the Lotic Invertebrate Flow Evaluation (LIFE) index (Extence *et al*, 1999, Dunbar *et al.*, 2004) that employs routine river flow and macro-invertebrate monitoring data. A metric of perceived sensitivity to water velocity scores all recorded UK taxa on a six-point scale. For a sample, the score for each observed taxon is weighted based on its abundance, and mean score per taxon is calculated. The system works with either species or family level data. For monitoring sites where historical flow time series of flows are available, the relationship between LIFE score and preceding river flow can be analysed. Metrics of antecedent flow (such as Q_{95} over the 6 months preceding the invertebrate sample) have shown good relationships with LIFE scores over a range of sites.

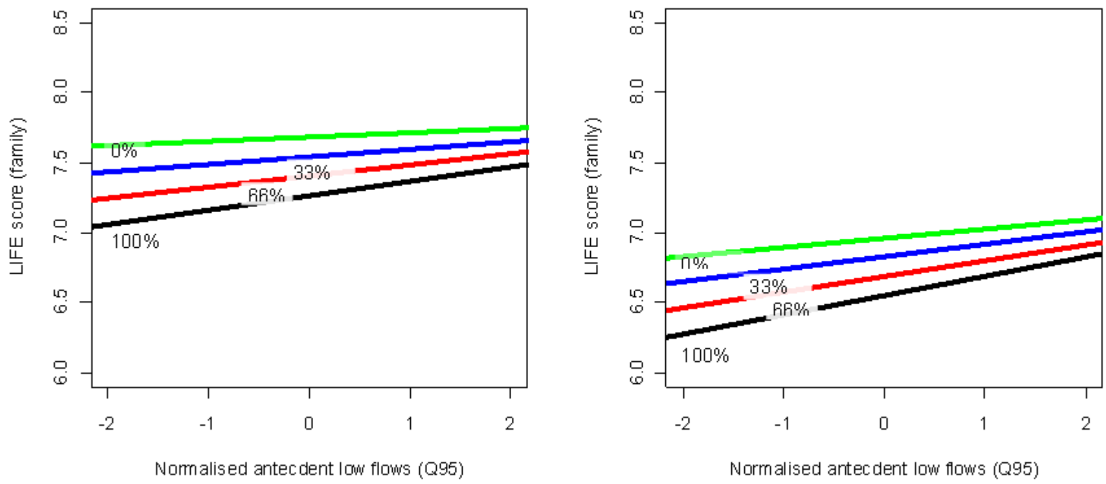

Figure 4 ***Mean behaviour of LIFE score as a function of flow for different levels of channel modification. Percentage labels refer to percentage of 500m RHS reach where resectioning observed. Upland rivers (left) lowland rivers (right).***

The slope of the line describing the relationship between flow and LIFE defines the sensitivity to flow change and thus potential impacts of abstraction. The DRIED-UP projects (Dunbar and Mould, 2008, Dunbar et al. 2010) have shown that the slope of the line has been shown to vary systematically with degree of alteration of the channel morphology as indexed by re-sectioned bed and banks sub-score of the River Habitat Survey. The results suggest that when indexed by their LIFE score, and controlling for extent of modification, upland river reaches are generally less sensitive to flow change than lowland river reaches (Figure 4). This is probably because the complex morphology of upland streams means that some suitable habitat is available even at quite low flows. In contrast, the less varied morphology of lowland reaches may mean that at comparable low flows, refugia for taxa that require higher velocities are rare. Application of the approach to the River Cray in Kent, illustrated the major effects that the habitat modification would have on achievement of a target LIFE score. Given the highly managed nature of most Chalk river channels, this approach has potential. The models produced as part of DRIED-UP may be applied to "new" locations with only flow data, or additionally with RHS and / or local biological data, resulting in a consequent reduction in uncertainty. Forthcoming work in this area funded by the Environment Agency will focus on whether there are thresholds of community change in Chalk rivers which are not apparent from consideration of LIFE score alone.

This approach can be applied broadly across all Chalk rivers and uses standard flow and macro-invertebrate monitoring data, plus RHS survey results.

Studies by Wood *et al*. (2000) on the Little Stour, Kent, showed the strong effects of historical flow on macroinvertebrate communities and illustrated the importance of site characteristics in determining response to flow and showed the strongest associated between macroinvertebrate community and flows 4-6 months prior to sampling. Wood and Armitage (2004) noted "the sequence of flows, and the transition between drought, flow recovery and non-drought conditions, is probably as important as the total volume of flow in many groundwater dominated rivers". The macroinvertebrate community generally took two years to recover from the super-seasonal droughts studied.

4 Physical habitat modelling

The above discussion has highlighted the difficulties that exist in relating changes in the flow regime directly to the response of species and communities. This is partly because organisms are unlikely to be directly impacted by flow (discharge m^3s^{-1}), though this has a dilution effect on water quality. Organisms respond to depth and velocity, and associated factors such as bed material composition, that are determined by the interaction of flow and channel geometry.

The most obvious physical dimension that can be changed by altered flow regimes is the wetted perimeter (area of river bed submerged) of the channel. Hydraulic rating methods provide simple indices of available habitat (*e.g*. wetted perimeter) in a river at a given river discharge. Graphs of discharge and wetted perimeter provide a basic tool for environmental flow evaluation (Figure 5). As a rule of thumb, shallow, wide rivers tend to show more sensitivity of their wetted perimeter to changes in flow than do narrow, deep rivers. In some cases limited field surveys are undertaken; in others, existing stage-discharge curves from open-river gauging stations are used. This approach has been studied in the USA (Espegren and Merriman, 1995) and in Australia (Gippel and Stewardson, 1998) although these studies highlighted problems in identifying thresholds (critical discharges below which wetted perimeter declines rapidly) that can be used to set minimum environmental flows. Analysis (by visual inspection) of the flow at which there is a change in slope of flow-width curves from 66 habitat modelling studies (Booker and Acreman, 2007) suggested that some thresholds occur at around Q_{95} (Figure 6), giving some support to this flow percentile as a trigger point for flow setting.

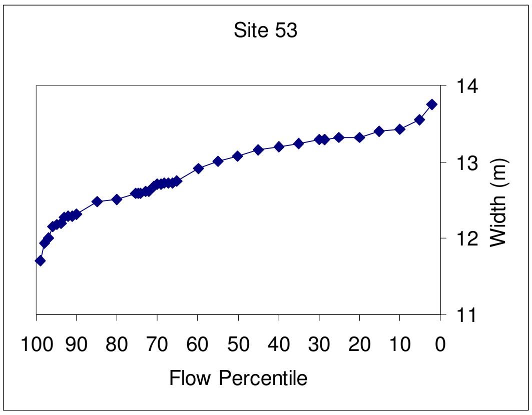

Figure 5 Flow-width relationship

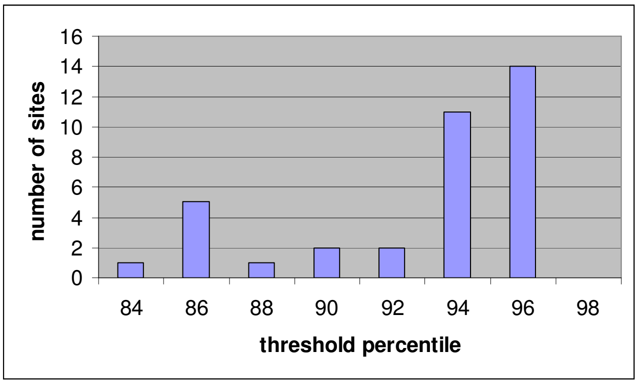

Figure 6 Flow percentiles for changes of slope of flow-width relationships

In a search for rapid assessment approaches, the concept of flow per unit width was originated in the 1960s during work primarily on salmon migration in North West by Leslie Stewart. Kilsby *et al.* (2007) aimed to test this approach for juvenile salmon habitat. Bankfull width data were not available for fish population sites, so these data were derived using a statistical model relating width to catchment area. The main finding was that fish populations were not limited if flow exceeded 0.011 $m^3/s/m$. Given that both flow (Q_{90}) and bankfull width both derived from catchment area, it is possible that this work simply demonstrated a relationship between fish density and catchment area. Over a wide range of river widths, relationships between flow and habitat are likely to be non-linear, thus there are logical reasons, following hydraulic geometry principles, why a single flow per unit width criterion may not be appropriate. Beecher (1990) noted that "Using flow as the unit of measurement in an instream flow standard does not ensure a consistent level of resource protection. Neither a flow nor an exceedance flow has a consistent relationship to habitat or production across a range of stream types or sizes." This was recognised in the (Atkins *et al.*, 2004) work as the method is recommended for small streams and applicable only in streams with a similar width to those where the threshold was derived.

More detailed approaches link data on the physical conditions (such as water depths and velocities) in rivers at different flows (either measured or estimated from computer models) with data on the physical conditions required by key animal or plant species (or their individual developmental stages). The first step in formulating this approach for rivers was published by Waters (1976); he invented the concept of weighted usable area defined by physical variable such as depth and velocity. This led, quickly, to the more formal description of a computer model called PHABSIM (Physical Habitat Simulation) by the US Fish and Wildlife Service (Bovee, 1982). As implemented in a number of software packages, the traditional PHABSIM approach uses one-dimensional hydraulic models, adapted to handle low flow conditions and to model cross-sectional velocities. These are coupled with univariate representations of habitat suitability or preference to define how usable habitat (termed weighted usable area - WUA) changes with flow. The extent of the change will be specific to the species under consideration and it differs, frequently for different developmental stages. The physical habitat modelling approach has now been adapted in many countries including France, Norway and New Zealand, while other countries, independently, have developed similar approaches (e.g. Germany).

PHABSIM has been applied to over 90 rivers in the UK including 18 Chalk river sites. An assessment was made of the variations in WUA-Q across 66 sites with good data (Booker and Acreman, 2007). Figure 7 shows that there is as much (if not more) variation amongst Chalk rivers as across non-Chalk rivers where flow is expressed as an exceedence percentile and WUA for juvenile trout is expressed as proportion of wetted area that is usable. This suggests that in terms of response of physical habitat to flow change, Chalk rivers cannot readily be treated as one homogeneous type and that either more work is needed to understand the causes of the variations between rivers, or at an extreme, individual studies may be required to understand their sensitivity to flow alteration.

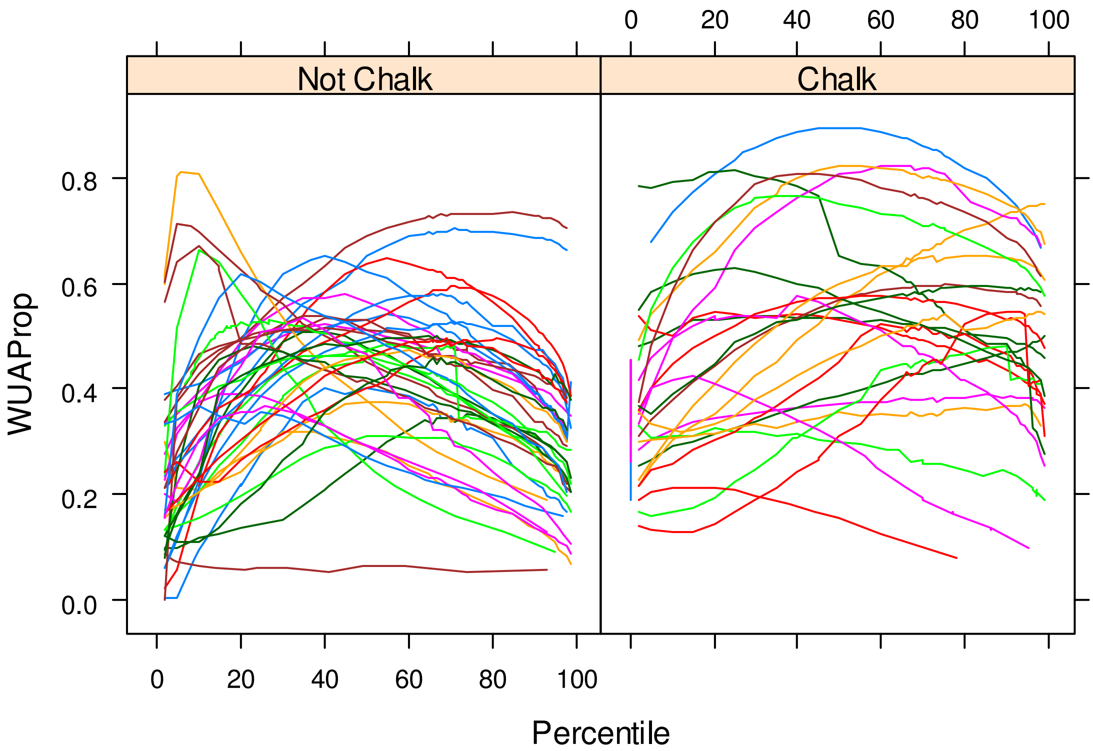

Figure 7 Variations in the relationship between Weighted Usable Area (WUA) and flow for Chalk rivers and non-Chalk rivers. Note that higher exceedence percentiles, i.e. low flows, are on the right

The relationship between physical habitat for salmonid fish, and discharge in six target areas (Upper Wylye, Chitterne Brook, River Till, Main Wylye: Longbridge Deverill to Norton Bavant, Main Wylye: Chitterne Confluence to Fisherton, and Main Wylye: Till confluence to South Newton) was undertaken by Dunbar *et al* (2000). They linked physical habitat models to flow scenarios (monthly flows from 1976 to 1994) from the SLAY groundwater model of the Wylye catchment. The main conclusion of this study was the further severe negative effects of Full Licence

Abstraction to physical habitat on the Chitterne Brook, and the potential benefits of cessation of abstraction from the Chitterne source (compared with the historical regime). The River Till also benefitted in the late summer from cessation of abstraction from Chitterne. There would be physical habitat benefits in increasing flow in the lower part of the upper Wylye. On the basis of these results, there did not appear to be a case for specific low flow alleviation on the Main Wylye downstream of Longbridge Deverill, if abstraction is not increased above historical rates. The approach demonstrated the benefits of physical habitat models in interpreting the impacts of alternate scenarios which affect flows throughout a catchment. However it required considerable input data.

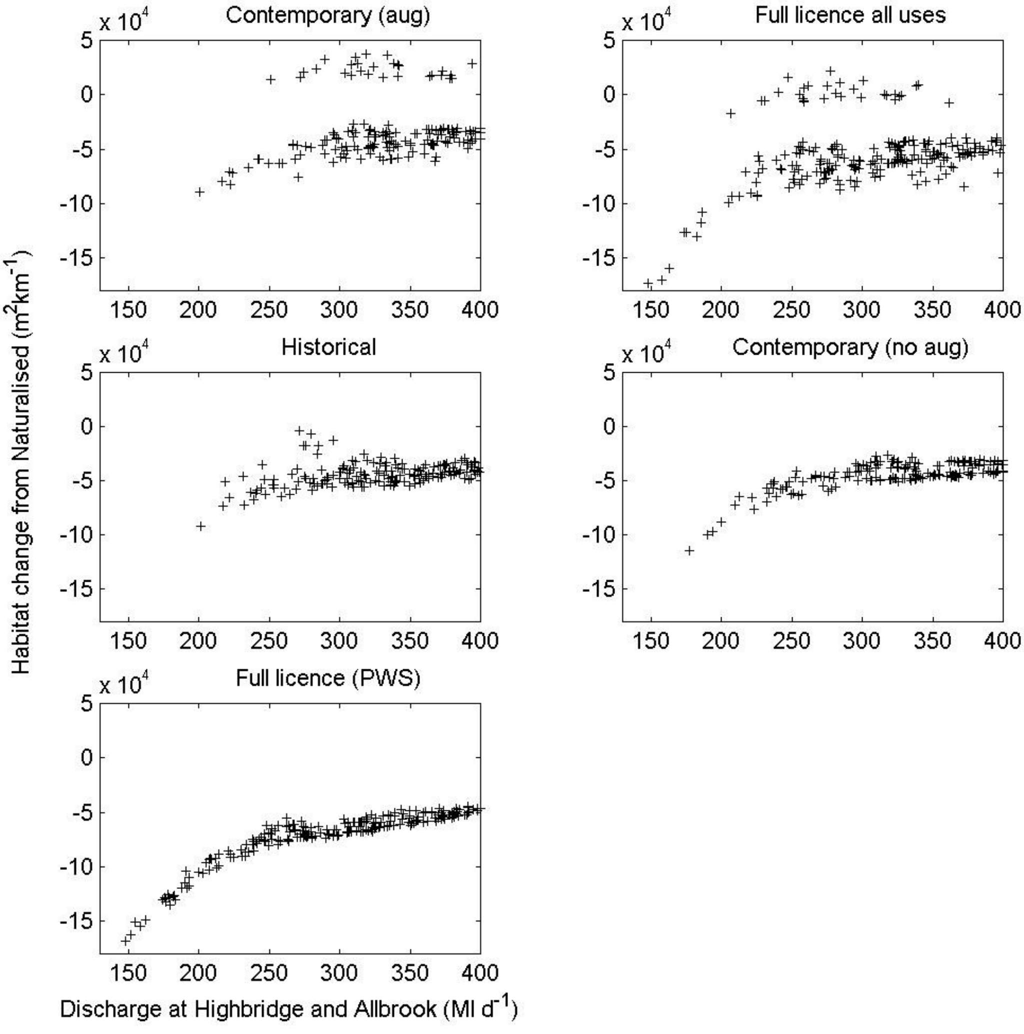

Figure 8 Physical habitat reductions from natural for different abstraction scenarios on the River Itchen.

A combination of PHABSIM physical habitat modeling and analysis of flow time series data was used to estimate ecological flow needs on the River Babingley (Petts *et al.*, 1998). They recommended that the maximum abstraction at Q_{50} should be 25% of the flow, whereas overall, the environmental flow need was 60% of the total flow volume. A similar approach was applied on the River Wissey (Petts *et al.,* 1999) for trout, dace and invertebrates, which recommended a maximum abstraction of 22% of the flow and an overall environmental flow need was 77% of the volume. They added that during droughts (1 in 20 years), the minimum flow should be 22% of the mean flow. This method could be applied more widely, but figures quoted above are for the Babingley and Wissey only. Achieving minimum flows may require stream support.

As part of the Itchen Sustainability Study (Halcrow, 2004) physical habitat modelling was undertaken using a hydrodynamic model (ISIS) to which a physical habitat model was linked (Booker *et al.*, 2004). The cross-section was the fundamental unit in the study, but analysis was undertaken at broader spatial scales, including reach, management unit and the entire catchment. Various flow scenarios were used to define time series of physical habitat reduction from naturalised (Figure 8), which suggested a critical low flow threshold of 240 Ml d^{-1} (52% mean flow).

Studies of Cumbrian Rivers (Gill, 2005) employed a 'cut-down' PHABSIM approach that focused on riffles and flows needed to achieve hydraulic conditions of 0.1 m depth and 0.25 m s^{-1} velocity (derived from Hendry and Cragg-Hine, 2003). The method is based on measuring depth and velocity across cross-sections at 3 flows, with the number of observations collected limited by what can be surveyed in a day. Although this approach could be applied to Chalk rivers, there is little justification for these same thresholds, since for salmonids in Chalk rivers considerable empirical habitat suitability data exist (Dunbar *et al*. 2000) and riffles may not necessarily be the most sensitive habitat.

Confounding factors

Climate trends, change and variability

The UK Climate Change Impacts Programme (UKCIP) envisages a substantially modified future climate with intense warming in summer, wetter winters and drier summers. Annual mean precipitation over England and Wales has not changed significantly since records began in 1766. Seasonal rainfall is highly variable, but appears to have decreased in summer and increased in winter, although with little change in the latter over the last 50 years. All regions of the UK have experienced an increase over the past 45 years in the contribution to winter rainfall from heavy precipitation events; in summer all regions except NE England and N Scotland show decreases. All regions have also experienced an increase in average temperatures between 1961 and 2006 annually and for all seasons, suggesting increases in evaporation. However, the evidence for any trends in Chalk rivers hydrology in recent decades is weak. Examination of flow time series for 15 rivers across England and Wales, including the Wensum and Itchen Chalk rivers, revealed positive trends in both winter and summer flows in the Wensum since 1940 (Wilby, 2006) but not the Itchen. There is some evidence for an increase in 30-day minimum flows on the Thames since 1880, but little widespread trend in low flows over the period 1963-2002 based on 34 benchmark catchments across the UK (Hannaford and Marsh, 2006). Some positive trends over the period 1973-2002 are influenced by a sequence of notably dry years at the start of the period and were not evident over a 40-year time period. Significant trends in high flows and floods were only found in northern and western areas of the UK in a study of 87 catchments (Hannaford and

Marsh, 2007); no clear trends were found for Chalk rivers. However, flood peaks from the late 1980s onwards on the River Avon at Amesbury (Figure 9) are more pronounced that before 1988/9, with similar changes to varying degrees on other chalk rivers (Solomon and Lightfoot, 2007). Groundwater level records from Chilgrove House, Chichester, show a similar pattern, with more extreme levels (especially low autumn and high winter levels) since 1989 compared with the more stable 1962-1988 period. However, it is not clear whether this is part of cyclic or persistent behaviour, a long term trend or a step change.

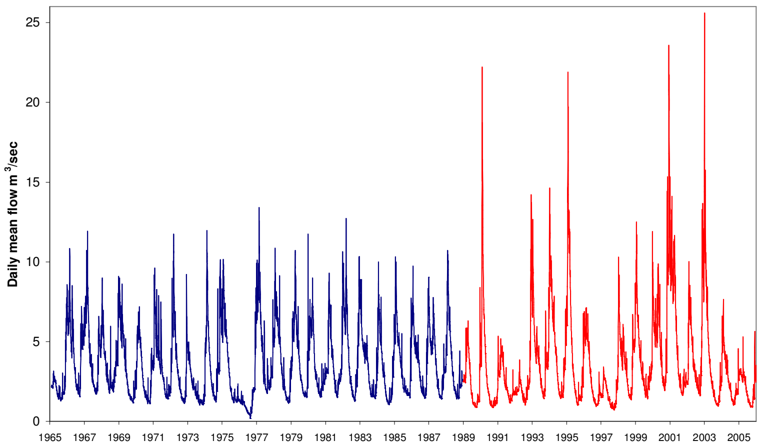

Figure 9. Daily mean flow on the Avon at Amesbury 1965 to 2005

Records of salmon catches (rods and nets) from the Avon and Frome show significant declines after 1998 compared with the previous period (Solomon and Lightfoot, 2007). However, it is unclear where there is a direct causal effect of change in hydrology or the two changes result from another process, such as alterations in the regional climate; for example the North Atlantic Oscillation also show differences in behaviour between the 1960s and 1990s.

Bloomfield *et al*. (2003) predicted a potential increase in minimum Chalk groundwater levels by 2020, but a decrease by 2080, with a likely reduction in Chalk river flows in late summer. More recent studies of the Chalk aquifer of the Marlborough and Berkshire Downs and South-West Chilterns (Jackson *et al*., in review) show a spread of predictions for annual groundwater recharge range from a 26% decrease to a 31% increase by the 2080s. The ensemble average suggests there will be a 4.9% reduction in annual groundwater recharge, with higher recharge rates occuring during winter but for a shorter period of time. During February, baseflows are predicted to change by between -9 and +51%, with the ensemble average suggesting a 5% increase in flow. The effects of climate change are shown to depend significantly on the type of land-use.

Temperature

Solomon and Sambrook (2004) found that salmon migration was related strongly both to temperature and flow, because these two variables are highly correlated. Thus it is difficult to dis-entangle cause and effect.

In a study of Wessex streams, including many on Chalk geology, river temperatures are rising (Durance and Ormerod, 2009), but any apparent relationships between macroinvertebrates and temperature were probably spurious due to overriding effects of changes in water quality and discharge.

Water temperature is increasing broadly across the UK, though this may be due in some situations to anthropogenic activities, such as effluent or power station discharges. A currently unpublished study of benchmark (fairly natural) catchments confirmed this general finding with river temperatures rising faster than air temperatures and autumn and winter river temperatures rising more than spring and summer temperatures (Simpson *et al*. unpublished).

Channel morphology and plants

As discussed above, Chalk river channels have been managed for many centuries, through channel dredging, plant management and the presence and operation of structures including weirs, sluice gates, and mill streams/leats. In many locations, altered morphology for multiple different reasons affects physical conditions. The role of macrophytes in shaping the physical conditions and responding to them, and our lack of knowledge of these extremely complex interactions is a major limitation. Chalk rivers are characterised by high macrophyte biomass, due to the favourable physical conditions and natural water chemistry; these macrophyte significantly influence Chalk river hydraulics. Water levels may be higher in summer than in winter, even when flows and lower due to the presence of macrophytes. Macrophytes also create spatial variations in velocity than alter sediment transport, directly provide habitat and create a diversity of physical habitat conditions in their vicinity (Franklin *et al*., 2008).

These complexities make flow setting for macrophytes extremely challenging. Habitat modelling has been applied to macrophytes, such as *Ranunculus*, using observational habitat preference function (e.g. requirement for 0.2m/s velocity), but because of the hydraulic feedbacks involved, great care is needed. Alternative approaches tend to gravitate towards the extremes, empirical analyses of historical macrophyte data and flow (e.g. Wilby *et al*. 1998) are extremely useful, but may be limited in ability to extrapolate in space (e.g. to other catchments) and time (*e.g.* future flow scenarios). More detailed considerations of the flow, and turbulence patterns around individual plants (Naden *et al.,* 2006) have a physical basis, but computational and data requirements make them currently applicable only to small scales and short time periods.

Historically, macrophytes have not been used as part of the national agencies' biomonitoring programmes. There are examples of individual catchments or groups of catchments with time series of data (*e.g*. Chiltern winterbournes, Test and Itchen), but at national scale, there is a general lack of time series of macrophytes as would be required for the development of widely-applicable flow-response models.

Suspended sediment concentrations in Chalk rivers tend to be an order of magnitude lower than those of many other UK lowland river systems (Heywood and Walling, 2003) and recover slowly from artificial inputs. Chalk rivers are sensitive to increased silt input from the catchment or from poaching of river banks by cattle. This poaching has also widened channels creating shallow, slow velocity conditions with limited capacity to carry sediments. These velocity reductions may be perceived as a flow problem, but are in fact a morphology issue. Studies of the River Piddle (Game Conservancy, 1996) showed that fencing to stop cattle poaching can lead to channels regaining their narrower widths, increased velocities and removal of sediment, resulting in significant increases in the wild trout population. Similar results were found on the Wiltshire Avon (Shaw, 2009) where cattle poaching had also created wide, shallow, silty rivers. From a sparse and species-poor community, the experimental reach (fenced, groynes and brushwood structures) was characterised by abundant and predominant stands of water cress within 2 years. Here, fencing the river also led to vegetation re-growth, channel narrowing, increased velocity and removal of fine sediment.

Conclusions and recommendations

1 Chalk rivers are iconic English rivers. They support highly diverse macro-invertebrate, macrophyte communities and iconic fish species such as salmon. Many are designated under national and European legislation. They have evolved from a complex combination of anthropogenic divers, such as fishing, water meadows and milling, some of which no longer occur.
Recommendation: All flow-setting studies should define clear objectives for the river system including water supply, industrial archaeology, recreation and nature conservation (including of species and approximate abundance taking account of predicted change elsewhere for organisms that also use other habitats). Costs and benefits of different options may need to be defined.

2. Chalk rivers have some hydrological characteristics in common with each-other including a baseflow-dominated flow response with a pronounced annual cycle of lower flows in late summer-autumn and higher flows in spring. This also generates high persistence in flows; for example in dry years flows below (long-term) Q_{95} will persist for long periods whilst they may not occur in wet years.
Recommendation: Low flows, especially in the summer are critical to Chalk river ecosystems, such as August flows for salmon parr; these dataset should be collated to provide inputs for the building block approach.

3. Chalk river ecosystems are sensitive to flow change and setting the appropriate flow is crucial to river conservation. Chalk river ecosystems can recover within 2-5 years after major droughts. This does not mean that they are necessarily robust to abstraction, as recovery requires a return to natural flows.
Recommendation: Information on hydromorphology and ecological dynamics needs to be combined. This could be achieve partly by extend the DRIED-UP project (see below)

4. The impact on the flow regime varies according to the type of abstraction. Groundwater abstractions may change the timing of flows, such as delaying recovery of higher flows in the autumn/winter. In contrast, direct river abstraction alters the flow on the day of abstraction.
Recommendation: Different management approaches may be required for different abstraction types to achieve the same flow regime.

5. Chalk rivers have ephemeral (winterbourne) reaches, which have no flow during certain periods. When wet, these reaches can provide considerable habitat for flowing water species of macrophytes and macroinvertebrates, and exceptional incubation conditions for salmonids and their variable flow regime can provide niches for rare taxa. Different streams have different lengths of winterbourne with different characteristics, including different periods of flow.
Recommendation: A research study is needed on ephemeral river flow setting

6. Chalk rivers are characterised by high macrophyte biomass, due to the favourable physical conditions and natural water chemistry; these macrophyte significantly influence Chalk river hydraulics. Water levels may be higher in summer than in winter, even when flows and lower due to the presence of macrophytes. Macrophytes also create spatial variations in velocity than alter sediment transport, directly provide habitat and create a diversity of physical

habitat conditions in their vicinity. Locations of macrophyte growth can be highly patchy, controlled by local physical conditions. Flow plays a critical role in mediating nutrient transfer to macrophytes and acts to mitigate the effects of epiphytic algae on flow-sensitive species. Time series data on macrophytes is far rarer than for macroinvertebrates, but does exist.
Recommendation: Macrophyte growth needs to be considered when consider the role of flow in creating habitat. Further research is needed to understand links between macrophytes and flows (DRIED-UP for plants) and to understand their role in shaping and responding to physical conditions.

7. Chalk rivers are not natural. Chalk river channels and water resources have been managed for many centuries, through surface water and groundwater abstractions and returns and through channel dredging, plant management and the presence and operation of structures including weirs, sluice gates, and mill streams/leats. For Chalk rivers, it is difficult to define reference conditions and the reference or most appropriate flow regime may not necessarily be the natural flow regime, particularly as our climate changes. In many locations, altered morphology for multiple different reasons affects physical conditions. The role of macrophytes in shaping the physical conditions and responding to them, and our lack of knowledge of these extremely complex interactions is a major limitation.
   Recommendation: Channel morphology, macrophyte growth, and flow together create physical habitat, hence need to be considered together when assessing flow impacts. A study of Chalk rivers is requied based in the 'Dried-up' methodology, to assess significance of morphology.

8. Morphologically and ecologically, Chalk rivers are not one homogeneous river type. This is at least partly due to the historical anthropogenic changes to their morphology. Evidence from the RAPHSA project suggests that there is as much hydraulic habitat variation between Chalk rivers as between other river types.
   Recommendation: There is a need for individual studies to define hydraulically appropriate flow regimes, and further work (extending the RAPHSA study) to understand the broad-scale relationships (i.e. the wide variation in chalk stream responses may be explainable with the right knowledge).

9. Many Chalk river channels do not have pronounced pool-riffle sequences particularly in higher reaches, due to natural conditions and anthropogenic impacts. In studies of other river types, it has been assumed that riffle habitat is most sensitive to flow change. In Chalk rivers the relative sensitivity of different habitat types is not clear.
   Recommendation: Ecological flow studies need to consider the whole reach and not just single habitats, such as riffles.

10. In Chalk rivers, flow may be linked to other factors such as temperature through multiple mechanisms, thus it is difficult to unambiguously conclude causes/effects, such as stimulants for salmon migration or juvenile population dynamics. Evidence of alterations to temperature and flow suggests that Chalk river ecosystems may not remain the same in the future.
    Recommendation: Further analysis is required to assess trends and changes in flow and temperature regimes of Chalk rivers. Relationships between flow and other variables need to be considered.

11. The support of the flow regime in Chalk rivers from aquifers provides a means of mitigation. However, historically, many stream support schemes have been used for amenity and dilution purposes, not optimally for supporting the chalk stream ecosystem (examples from Itchen and Wylye at least). Furthermore, water quality, including temperature, may be different in support water pumped directly from the ground than the water that would naturally be in the river.
    Recommendation: Appropriate flow regimes may be achieved at critical times by stream support by pumping from an aquifer.

12. The hydrology of Chalk rivers determines sediment transport. Chalk rivers tend to be low in fine sediment and recover slowly from artificial inputs. Chalk rivers are sensitive to increased silt input from the catchment or from poaching of river banks by cattle has widened channels creating shallow, slow velocity conditions that may be perceived as a flow problem, but is a morphology issue.
    Recommendation: Alterations to channel morphology may cause low velocity issues, however, simple channel narrowing is not necessarily a satisfactory solution for reduced flows caused by abstraction.

Specific research proposals

1. RAPHSA

Physical habitat modelling (such as PHABSIM) is a widely used technique for assessing the implications of changes to river flow and channel morphology for aquatic species, particularly salmonid fish. The disadvantage of the approach is the investment in time and expertise needed to collect field data and run the models. Since some 90 PHABSIM studies had been undertaken in the UK by 2005, a study was undertaken (Acreman *et al.*, 2008a) to develop a method of rapid assessment of physical habitat sensitivity to abstraction (RAPHSA), which required less input. The RAPHSA database contained 23 Chalk river studies (Figure 7), but the resulting models to produce rapid estimates of habitat-flow curves were defined using the entire dataset. An extension to the RAPHSA project is required to explore the variations in hydraulic habitat in Chalk rivers and to construct more focused rapid habitat assessment method. Work would include comparison of model utility and performance with other approaches, such as Gill's (2005) rapid hydraulic method.

2. DRIED-UP 4

This review has highlighted the need for further work on the links between flow, morphology and the macroinvertebrate and macrophyte communities of Chalk rivers. The DRIED-UP project has demonstrated these links for a wide range of river monitoring sites across England and Wales. Sites on Chalk rivers are present in the DRIED-UP dataset, but because of the way the project has evolved, there are some areas where the model lacks data notably in the Agency South West Region. The dataset could, with moderate effort be expanded. In 2010, work funded by the Environment Agency and Natural England will examine the specific response of the Chalk stream macroinvertebrate community to flow and morphology, with the aim of evaluating whether flow thresholds, associated with significant community change, exist. This will include an evaluation of the evidence for multi-year response to flow, which because of the strong temporal correlation of Chalk stream flows, needs to be statistically rigorous. Further work on the community changes associated with entry to and exit from drought conditions will be focused on the DRIED-UP dataset in its entirety and hence will include Chalk stream sites.

In contrast to macroinvertebrates, far fewer data exist for macrophytes, especially time series. The work of Wilby *et al*. (1998) and Westwood (2008) has shown that Chalk stream macrophytes respond significantly to flow; furthermore they are an essential component of the habitat for other groups of biota. There is a pressing need to assemble high quality time series of macrophyte surveys, such as from the Test and Itchen and the Chiltern Chalk streams, into a single dataset, along with associated abiotic data, in order to develop generic models of macrophyte response.

There is also a need to investigate the response of chalk stream biota to the combined effects of flow, morphology, sediment and water quality. This will require the assembly of more comprehensive datasets, and is not currently funded.

3. Trends and variations in environmental conditions

The extremes in environmental conditions have a significant influence over Chalk river communities and there is a need to examine how these have changed and are likely to change when considering protective arrangements. Past records of flow from Chalk river gauging stations and groundwater levels show changes in regime at the end of the 1980s. These hydrological changes coincide with reductions in salmon catches. However, it is not clear whether such changes are part of long term trends, persistence, cyclic behaviour or a long-term step change. Further analysis is thus required to assess trends in flow (particularly floods and low flows) and temperature regimes of Chalk rivers and to predict likely future conditions. Inter-relationships between flow, temperature and other variables need to be considered. Robust statistical techniques need to be applied to various time series to determine whether any changes are significantly different from natural variations. Regional patterns or consistency between behaviour of different records are important in defining significance and possible causal mechanisms, such as NAO.

4. Ephemeral rivers

Chalk rivers are often characterised by headwater reaches that are temporarily dry. These reaches are spatially and temporally diverse and may contain totally dry areas, remnant pools and saturated hyporheic zones. The existence and character of these areas varies spatially and temporally depending on hydrological (mainly groundwater) conditions, and this leads to a wide dynamic diversity of plants and animals. The picture is complicated by different components of the river ecosystem (*e.g.* macrophytes and invertebrates) exhibiting different periodicities in their responses to stream discharge and recovery after droughts. Further studies of ephemeral headwater reaches of Chalk rivers are required to define whether existing reference condition approaches are suitable for such variable ecosystems, and to develop generic methods for the assessment of flow-related stress in such systems.

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TERMS OF REFERENCE

Project purpose

To ensure that the tools available for the setting of ecologically acceptable flows on Chalk rivers are optimised and include knowledge of current issues arising from research and predicted consequences of climate change.

Objectives

The project will:

- Provide a brief account of available hydro-ecological tools for setting ecologically acceptable flows on Chalk rivers, identifying the species and or biological groups which these tools consider. Identify where these tools have been applied (i.e. generate a metadataset), the data owners, and the availability, nature and location of datasets.
- Where possible express the flow thresholds determined by these studies as deviations from naturalised flows.
- Seek and record the views of local EA FRB, RSA and ecology staff and other appropriate practitioners as to the adequacy or otherwise of these tools where they have been applied.
- Identify gaps in knowledge and research needs associated with application of existing methodologies
- Identify confounding environmental factors in characterising relationships between abstraction stress and biological status (temperature, pollution status, channel morphology etc) and evaluate the susceptibility of available methodologies to these factors.
- Make prioritised recommendations for appropriate R+D, taking account of likely climate change scenarios.

Activities

Task 1. Science collation

CEH staff to collate past research and studies of flow setting in chalk rivers and related river systems, plus recent methodological developments and scientific concepts. Budget constraints on this phase of the project mean that this will be limited to readily accessible material.

Output: data base of:

- hydroecological studies, approaches and tools
- species and or biological groups which these tools consider.
- where tools have been applied and targets established

Task 2. Define analysis framework

CEH staff to develop a framework for the different approaches and tools, possibly based on global reviews of environmental flow methods, but refined to best structure reflect their application to chalk rivers. Work could also be classified as study (qualitative/narrative output), approach (quantitative broad method), tool (specific method with step-by-step guidance and software).

Output: a framework suitable for database management, analysis, reporting and guidance

Task 3. Review selected material
CEH, in collaboration with Environment Agency and Natural England will select a sub-set of tools and approaches for more detailed analysis, focusing on those most relevant the Agency and NE needs, perhaps using representative approaches based on the framework from Task 2. These tools and approaches will be evaluated according to, for example, needs for: data, time, costs, expertise, whether target flows were established and if datasets can be used more widely.

Output: initial brief desk-based review of selected material

Task 4 Academic workshop
CEH will convene a scientific workshop as part of the review of recent scientific developments, concepts and methods. This will include staff from EA ecology science programme, Harriet Orr (climate change), Paul Wood (Loughborough), David Hannah (Birmingham), Steve Ormerod (Cardiff), David Solomon, Nigel Holmes, Jonathan Grey (QM), Chris Westwood (Plymouth).

Output: further review of material and CEH synthesis by academics

Task 5 Reporting
CEH will produce a brief report that will include:

- Advantages and disadvantages of different available approaches and tools
- gaps in knowledge and research needs associated with application of existing methods
- confounding environmental factors in characterising relationships between abstraction stress and biological status (temperature, pollution status, etc) and evaluate the susceptibility of available methods to these factors.
- prioritised recommendations for appropriate R+D , taking account of likely climate change scenarios.

Output: report

Task 6 Stakeholder workshop
CEH will convene a stakeholder workshop to assess the usefulness/suitability of tools and approaches for setting ecologically acceptable flows. This will include staff from Environment Agency Hydro-ecology Working Group (HEWG), Natural England, BAP Chalk River Steering Group.

Output: review of suitability of tools and approaches

It was agreed that initial focus would be on Tasks 1, 2, 3 and 5, with academic and stakeholder workshops being held later if additional funding is available.