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DISCUSSION PAPER FOR WWF's ITCHEN INITIATIVE

SMARTER LICENSING TO REDUCE DAMAGING ABSTRACTION FROM ENVIRONMENTALLY FRAGILE RIVERS WITH MINIMUM POSSIBLE IMPACT ON WATER RESOURCES YIELD

. RIVER ITCHEN CASE STUDY

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Background

The Itchen Initiative is a WWF project that aims to develop solutions that will enable England and Wales to meet the challenges of water scarcity, to benefit both people and nature. The Initiative is named after the River Itchen, one of the world's most beautiful and iconic rivers, now threatened with over-abstraction of water, a growing population, and climate change. The Initiative is intended to inform, in particular, Defra's 2011 Water White Paper and Ofwat's review of the regulatory arrangements.

WWF commissioned a number of discussion papers to inform the Itchen Initiative process, including this discussion paper, authored by Colin Fenn and Rob Wilby, which considers potential use of a smarter licensing regime to reduce damaging abstraction from environmentally-sensitive rivers, while minimising reductions in yield.

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1. INTRODUCTION

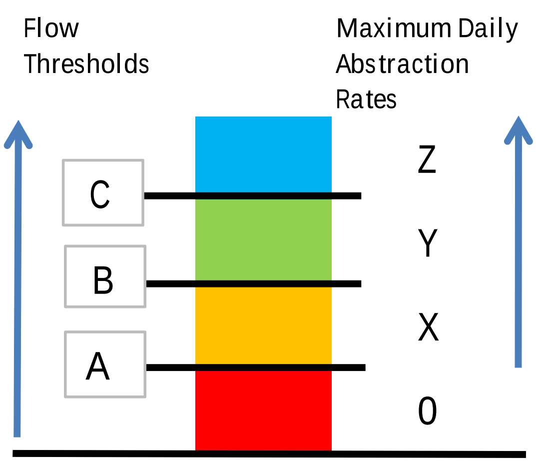
This paper describes work undertaken on behalf of WWF to examine the merits, in principle and in practice, of the use of a 'smart' rising block permitting regime to control abstraction from vulnerable rivers. In theory, a 'tiered' abstraction permitting system – with the amount authorised for abstraction being linked to flow in the river – can be used to control abstraction from currently over-abstracted (or over-licensed) run of river sources so as to provide protection to river flows where and when they need it most, but with minimum impact on water resources yield. To achieve the latter, the permit should, at the same time as preventing damaging abstraction, maintain abstraction volumes over the long run and minimise any reduction in deployable output in low flow periods. This paper examines the viability of the approach in practice, using abstraction from the surface and groundwater sources of the River Itchen at Otterbourne as a test case.

A short summary of the work, and of the results obtained, is included in the main report on WWF-UK's Itchen Initiative (WWF-UK, 2011)[1]. This extended paper provides details of the work undertaken, of the results obtained and of the conclusions reached.[2].

The rising block abstraction principle

The underlying principle of the rising block abstraction regime is that abstraction from a specific source (or group of sources) should be restricted at environmentally damaging low flows, limited at higher but still low flows and then progressively increased as flows get higher. Figure 1 illustrates the general concept, with three flow thresholds (A, B, C) and four abstraction rate bands in place. The rate of abstraction when flow is in the red, amber, green and blue bands rises, in the case shown, from zero, to X, then Y, then Z Ml/d, respectively. The red zone defines a no abstraction zone up to a hands-off flow (HOF) of A Ml/d.

Figure 1: The rising abstraction block concept *(Note that A < B < C; that X < Y < Z; that threshold A is a hands-off flow, with the red abstraction band below it being a no abstraction band).*



[1] WWF, 2011. The Itchen Initiative: Reforms to Deliver Smarter Water Management in England and Wales.
[2] A separate extended paper on the work undertaken has also been submitted for consideration for publication (Wilby et al, 2011).

The number of flow thresholds and abstraction bands may be decreased or increased according to the balance desired between simplicity and resolution. The maximum permitted abstraction rates (X, Y, Z) could be redefined as the percentages of flow which may be abstracted from each band. Different unit prices (£/Ml) could also be applied to abstraction from the different flow bands, should greater incentivisation to abstract more from high flow bands and less from low flow bands be desired. Here, the test is restricted to the use of three flow thresholds (A, B and C) and four abstraction bands (red, amber, green and blue, each with different maximum permitted abstraction rates, of X, Y and Z, respectively).

The same general approach is widely used in managing the use of reservoir stocks, and of conjunctive use schemes, with a hierarchy of control curves defining the maximum permitted rate of drawdown of stocks or abstraction from supporting river sources at different times of the year. Other than for controlling complex integrated systems like the Lower Thames resource system [3], the approach has not been applied in the particular fashion advocated – involving the use of more than a simple HOF condition - in England and Wales. It is believed that considerable scope exists for the use of the approach on a widespread basis.

To date, abstraction from rivers in England and Wales has been controlled by permitted annual and daily maximum volumes, and sometimes by the use of seasonally varying licence rates (to protect low flows during the summer). Some long-standing abstraction licences and all new (and amended) licences have HOF constraints, which prohibit abstraction when flow (or water level) falls to a prescribed value. Some of the sources that are now protected by HOFs[4] have a variable HOF provision (with abstraction being prohibited at higher than normal flow rates under defined circumstances). However, the proposed rising block arrangement provides for more flexible abstraction management than does adjustment of the HOF value alone.

Whilst sophisticated licensing regimes are currently being considered as part of the on-going Review of Consents (ROC) undertaken by the Environment Agency (EA) for the Habitats Directive, thus far there are no known instances of the rising block approach being applied to manage abstraction from rivers in England and Wales in the manner described above.

Determining values of A, B, C and X, Y, Z

The abstraction volumes and the residual flows delivered by a rising block abstraction system of the type proposed here clearly depend upon (and vary with) the values selected for the flow control thresholds A, B and C, and the permitted (maximum) abstraction rates X, Y and Z. Where the objective is to retain as much water in the river as possible (to the benefit of the river without regard to water resources yield), A, B and C would be set high and X, Y and Z low. To maximise yield (to the benefit of people and with less regard to the needs of the environment), the opposite arrangement would apply: A, B and C would be set low, and X, Y and Z high. For the rising block abstraction regime to be able to deliver a balanced outcome in regard to both environmentally-desirable residual

[3] The Lower Thames Operating Agreement (LTOA), which controls abstraction from the R Thames and from the Thames and Lee Valley reservoirs, is an example of the use of flow and/or level related abstraction and demand management in practice. To date, the approach has been limited in its application to large, complex resource schemes.

[4] These constitute 31% of all surface water sources, 1% of all groundwater sources, and 17% of all surface and groundwater sources together, across England and Wales.

flows in the river (net of permitted abstraction) and maximum possible water resources yield, the values of the flow thresholds A, B and C and the abstraction rates X, Y, and Z must be carefully optimised.

To meet the first of the joint objectives – the environmental requirement – the residual flow must be capable of supporting the ecology of the river. In practice, this means that environmentally-significant target flow values should be achieved. Of these, the magnitude of the flow that is equalled or exceeded 95% of the time, over the long run (the 95th percentile of the residual flow regime; the Q95) is deemed to be a particularly important environmental flow indicator (EFI)[5]. The Environment Agency are in the process of defining the magnitude of the Q95 corresponding to 'good ecological status' for abstraction points for all rivers in England and Wales, as part of the Catchment Abstraction Management Strategy (CAMS) in relation to the Habitats and Water Framework Directives. EFI values provide one target criterion for the residual flow regime under our rising block abstraction regime; but for only one point (albeit a fundamentally important one) in a full range flow regime. A flow duration curve that describes the target environmental flow regime (EFR) for residual flows across the whole flow range (from Q0 to Q100), including specification of the target Q95 but all other percentiles in the flow regime, too, provides a fuller and better representation of the environmental target to be delivered by the smart licensing approach[6].

The second joint objective – the yield requirement – of the rising block abstraction regime is to achieve the environmental objective whilst also delivering sufficient abstraction volumes and water resources yield, overall (across all flows, over a long run period) and in dry and drought periods. This requires that maximum use is made of water available for abstraction above the target EFR particularly in the low flow range, from Q50 to Q100, if deployable output (DO)[7] is to be maximised subject to the environmental constraint of delivering a target EFR.

It follows that values for A, B, C and X, Y, Z must be selected to achieve a residual flow regime that sits as close to a target EFR as possible. The reliability of the EFR chosen for use is accordingly critical. If the chosen EFR is too conservative (i.e. too high), abstractable volumes and deployable outputs will be adversely affected. If it is set too low, river flows and ecology could be adversely affected. Hence the EFR must be determined on a balanced basis, using best available data, but with due regard to the uncertainties involved in its determination and use. Herein, the intention is to determine optimal values for the flow thresholds A, B, C and the abstraction rates X, Y, Z with a view to delivering a residual flow regime that meets environmental targets with minimum possible impacts on overall abstractable volumes and low flow deployable outputs. The underlying presumption is that the larger abstraction volumes attainable from the higher bands are able to compensate for lower abstraction during low flows. This presumes that the enabling infrastructure (abstraction pumps, treatment capacity, distributions mains) exists or can be developed economically. Furthermore, it

[5] Put simply, if the Q95 of the post-abstraction (residual) flow series is equal to or greater than the value of the Q95 EFI, we can have reasonable confidence that the residual flows support the attainment of ecological objectives at that particular, environmentally-significant point in the flow range.
[6] If the residual flow regime achieves (lies on or above) the target EFR, we can again have reasonable confidence that the abstraction regime does not prejudice the achievement of ecological objectives.
[7] Deployable output (DO) is defined as the reliable yield from the source in a drought year of defined severity (or return period), subject to licence, water quality and infrastructure constraints. Being a measure of yield in a drought year, DO is highly sensitive to the abstraction rates that may be sustained in low flow spells. Generally speaking, the DO of a given source reduces as the return period of the drought event lengthens.

assumes that all of the water from the source can be used to meet demand when it is plentiful (locally, or to support demand in other areas) and augmented when it is not (from other sources or areas, or from storage).

2. WORK PROGRAMME

The programme of work undertaken sought to examine the viability and merits of implementing the rising block abstraction model using abstraction from the Otterbourne river and groundwater sources of the River Itchen in Hampshire (a high baseflow chalk stream in Southern Water's Hampshire South Resource Zone) as a first test case of its potential applicability more broadly. [8] The initial work programme encompassed four distinct activities:

- Stage 1: Derive a reliable environmentally-based target flow regime (EFR) for the River Itchen below the Otterbourne abstraction point[9];

- Stage 2: Use a reliable model of daily river flow to determine optimal values of A, B, C and X, Y and Z for abstraction from the Itchen at Otterbourne, so as to deliver a residual (downstream) flow regime that does not fall below the target EFR, and minimal possible reductions in annual average abstractable volumes (AV) and deployable output (DO), under a plausible set of climate variability and change scenarios[10];

- Stage 3: Work with Southern Water to examine the consequences of adopting the 'smart' values thus found on the water resources yield[11] profile of the source and the resource zone (RZ) to which it contributes, at different times of the year, in dry and drought years of varying severity, with and without climate change;

- Stage 4: Work with Southern Water to identify the best possible combination of 'smart licensing' values that could enable attainment of the target flow regime with minimum possible reduction in yield (that is, the least disruptive to water resources and most environmentally beneficial option).

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[8] WWF records its appreciation to Southern Water for its willingness to collaborate in this programme of work.
[9] At the Allbrook and Highbridge gauging station.
[10] For 1901-1930, 1931-1960, the standard period 1961-1990, and the recent past period of 1991-2009, and using UKCP09 and UKWIR (2006) climate change factors, so as to be able to test the performance of the proposed abstraction regimes under climatic variability and change.
[11] As has been noted under the definition of DO given above, water resources yield is generally defined as the deployable output (DO) that can be attained under defined hydrological conditions from a given source or set of sources operating under licensed limits and conditions and subject to other environmental and infrastructural constraints. Temporary losses of DO from unavoidable events like pollution incidents, floods or works failure, or from planned maintenance activities (together, outage) are deducted from DO to provide an estimate of the water available for use (WAFU) to meet demand. Water companies report DO as the annual average output attainable in a drought year of a defined severity (say 1 in 50 years, but sometimes 1 in 100 years). If the balance between supply and demand is at its lowest in a particular period of the year (e.g., when demand is at its highest, or output is at its lowest), a critical period DO (of the same drought severity) is also reported. Southern Water report deployable output for the annual average (ADO), peak demand (PDO) and minimum resource (MDO) conditions.

The aims, approaches and outcomes from each of these work stages are described in the following sections, with results and findings being presented to the extent of progress to date. Prior to the completion of this report (February, 2011), Stage 1 had been completed; Stage 2 had been completed, with various combinations of values having been tested, and two preliminary sets of values of ostensibly satisfactory values for flow thresholds A, B, C and abstraction rates X, Y, Z having been determined; Stage 3 had commenced, using the two sets of preliminary values provided from Stage 2, but not completed. Stage 4, which involves revisiting Stage 2 outputs in light of results from Stage 3, had not yet commenced.

3. AIMS, METHODS AND RESULTS

Stage 1: Determination of a target environmental flow regime

Target minimum flow values and a full range target environmental flow regime (EFR) for the River Itchen at Allbrook and Highbridge, downstream of the Otterbourne surface water and groundwater sources were derived through consideration of the environmentally-based values and curves proposed in the Habitats Directive Stage 4 Review of Consents (ROC) reports (Atkins, 2007), and related studies. The minimum residual flow values considered therein are based on assessments of the low flow tolerances of key macro-invertebrates. The resultant minimum flow values proposed by various authors are listed in Table 1 below.

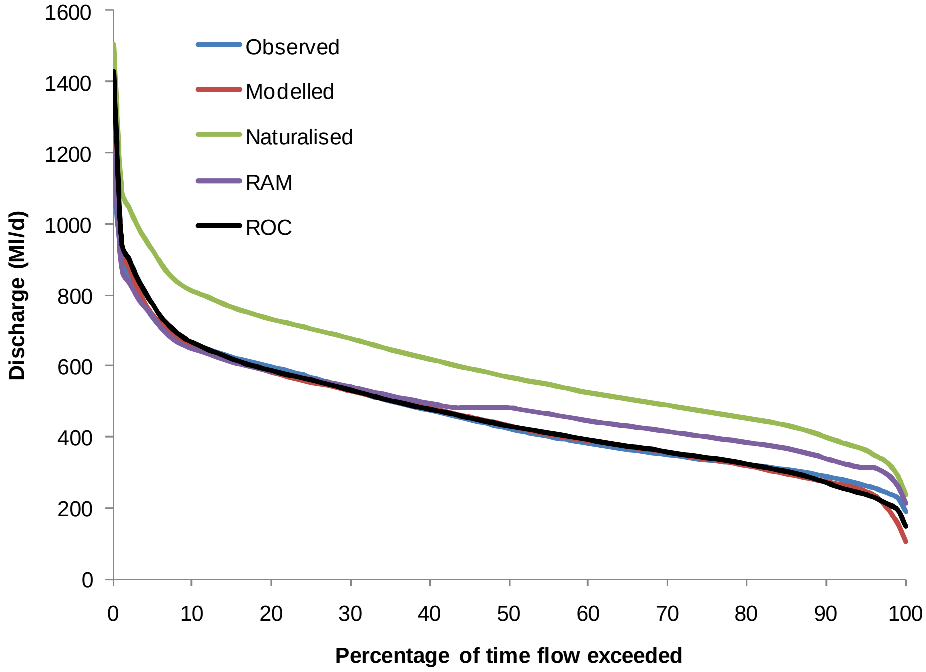
The target EFR for present purposes is taken to be the flow duration curve of residual flows corresponding to the licence terms and conditions proposed by the Environment Agency in its Stage 4 ROC investigation. This is based on a minimum residual flow (or hands-off flow) of 198 Ml/d, an annual maximum abstraction quantity of 51,138 Ml/a (from the surface and groundwater sources at Otterbourne, combined) and maximum permitted abstraction totals of 4,110 Ml, 3,940 Ml, 3,445 Ml and 2,280 Ml in the months of June, July, August and September, respectively.

Table 1: Proposed minimum flows for the Itchen at Otterbourne

Target	Definition	Source
198 Ml/d	Lower 95% confidence level of the target flow based on macroinvertebrate community data (see below), equivalent to the minimum flow	Atkins (2007)
224 Ml/d	The hands off flow that is on average needed to achieve an annual summer Q95 flow of 237 Ml/d (see below)	Wilby (2010)
237 Ml/d	The summer Q95 flow below which there are significant changes in the macroinvertebrate community (lower counts of olive mayfly, anglers curse mayfly, blue winged olive mayfly and freshwater shrimp)	Exley (2006)
270 Ml/d	The minimum low flow required for salmon entry and spawning escapement in the lower Itchen	Halcrow (2004)

The ROC EFR is shown as the black line in Figure 2 below. It may be noted that the residual flow regime under historic abstraction rates (brown line) includes flows below the ROC curve in the low flow tail of the distribution, below Q98.

Figure 2: The modelled ROC flow duration curve (black line) of the River Itchen at Allbrook and Highbridge used herein as the target EFR for abstraction management purposes, alongside naturalised (green line), historically observed (blue line) and RAM (purple line) flow duration curves. The RAM (Resource Assessment and Management) flow regime is the derogated natural flow with the RAM sensitivity taken as "moderate", which specifies maximum percentage reductions from naturalised flows of 20, 15 and 10% for flows exceeding Q_{50}, in the range Q_{50-95}, and less than Q_{95} respectively). The brown line (Modelled) is the flow regime simulated by the CATCHMOD model under average historic abstraction rates



Stage 2: Determination of flow thresholds and abstraction rates to deliver residual flows close to the target EFR without detriment to abstractable volume

Approach

The 'smart licensing' approach examined herein corresponds to the principles of the rising abstraction block approach set out in section 1 above, and is based on the identification of three environmentally-significant flow thresholds (A, B, C, where A<B<C). These thresholds are used to limit the maximum permitted daily rate of abstraction at Otterbourne according to the average daily flow rate of the previous day (Q_{t-1}), upstream of the abstraction point[12], as follows:

> when Q_{t-1} is less than or equal to A, abstraction is prohibited (red band);
>
> when Q_{t-1} is greater than A but less than or equal to B, maximum daily abstraction from the river and groundwater sources at Otterbourne[13] is limited to rate X (Ml/d) (amber band);

[12] In practice, values of Q_{t-1} upstream of Otterbourne are obtained by adding the volume abstracted from the river at Otterbourne (1/3 of the total Otterbourne abstraction) to the residual flow of the River Itchen measured downstream at Allbrook and Highbridge.

[13] Rates X, Y and Z refer to total abstraction from the river and groundwater sources together. For modelling purposes, 1/3 of the abstracted amount is assumed to be taken from the river, and 2/3 from groundwater.

when Q_{t-1} is greater than B but less than or equal to C, maximum daily abstraction from the river and groundwater sources at Otterbourne[14] is limited to rate Y (Ml/d) (green band);

when Q_{t-1} is greater than C, maximum daily abstraction from the river and groundwater sources at Otterbourne[15] is limited to rate Z (Ml/d) (blue zone).

Values for A, B, C and X, Y, Z were either provided on environmentally-sound a priori grounds, or were derived by iterative (trial and error) simulations with a well-calibrated catchment flow model. Consideration was given to allowing rate X to vary seasonally, to provide protection to summer low flows. Rate Z was generally determined as $Z = Y + (Q_{t-1} - C)$, but with consideration being given to the need to preserve spate flows in the Winter/Spring period. The terms of the existing licence and those of the proposed new licence for abstraction from the river and groundwater sources at Otterbourne[16] were used as sources for the selection of possible values for flow threshold and abstraction rate values[17]. The findings of the Habitats Directive Stage 4 Review of Consents investigation (Atkins, 2007) and related studies, including the minimum residual flow values listed in Table 1 above were considered in this regard.

Most of the candidate flow threshold and abstraction rate values used were found by simulation modelling. This was done in order to achieve best possible values in respect of delivering a residual flow regime that matches the target EFR, whilst minimising any reduction in AV (and with regard to likely impact on DO, prior to Stage 3 modelling).

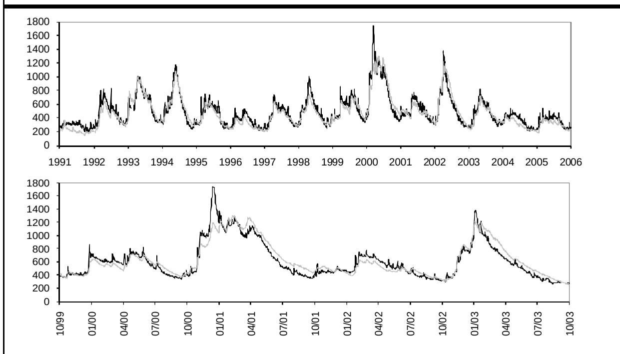
For the River Itchen, a version of the CATCHMOD model was calibrated and verified against historical climate, flow, abstraction and returns data to determine the effect of each candidate set of flow threshold and abstraction rate values on the residual flow regime of the river, post abstraction. Box 1 describes how the Itchen CATCHMOD model was built, calibrated and verified, and how it was used to test the effect of candidate licence values on flow and abstractable volumes, under past, present and possible future climate conditions. Box 2 sets out the modelling rules that were used in the simulation tests undertaken with the Itchen CATCHMOD model.

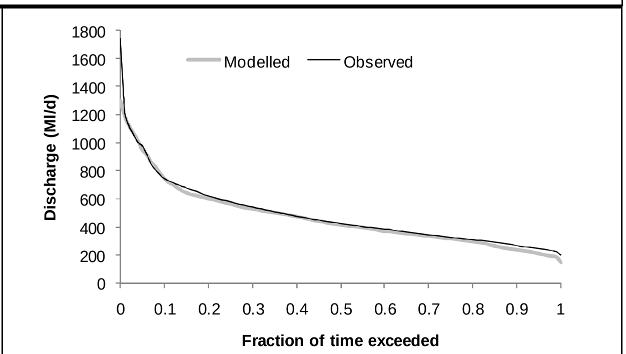
[14] As note 8 above.
[15] As note 8 above.
[16] As proposed in the Habitats Directive Stage 4 Review of Consents recently completed by the Environment Agency, and provisionally adopted by Southern Water (from 2015/16) in its final Water Resources Management Plan (fWRMP) for 2010-2035.
[17] It should be noted that the abstraction rates quoted in the ROC referred to herein relate to abstraction from the river and groundwater sources at Otterbourne in combination, and that all of the abstraction values quoted herein similarly relate to combined abstraction from the river and groundwater sources.

Box 1: Construction, calibration and verification of the Itchen CATCHMOD model, and its use in simulation modelling to define environmentally-sensitive but resource efficient licensing regimes.

Calibration and verification of the model was undertaken using daily rainfall, monthly MORECS potential evaporation, actual surface and groundwater abstraction, and gauged runoff of the Itchen at Allbrook and Highbridge. The Arle and Candover groundwater augmentation schemes were not included in the flow simulations. When tested against data not used for model calibration (1991-2006), CATCHMOD explains ~90% of the observed variance in daily river flow and reproduces the observed flow duration curve closely, except for the period of highest flows during the exceptional winter of 2000/01 (see Figures below).

For future abstraction, it was assumed that 1/3 of the total permitted abstraction from the Otterbourne surface and groundwater sources is taken from the river, with 2/3 being taken from the Otterbourne groundwater source. The Arle and Candover schemes are assumed to be inoperative. The calibrated flow model was used to quantify the annual average abstraction volumes (AV) attainable under different climate, licence and abstraction regimes, by taking given values of A, B, C and X, Y, Z and finding best possible values for the remainder of them through an iterative process designed to deliver a residual flow regime that matches the target EFR as closely as possible whilst also delivering maximum possible AV and DO values. The rules used in the modelling work, for each set of given values, are set out in Box 2 below. To find the unspecified A, B, C and X, Y, Z values, multiple simulations taking realistic trial values for each unknown value were undertaken, until the set converged on the best combination of possible values.





Observed (black lines) and modelled (grey lines) of daily flows in the River Itchen, 1991-2006

Box 2: Modelling rules for ascribing values to flow thresholds (A,B,C) and abstraction rates (X,Y,Z).

Values for flow thresholds (A, B, C) and abstraction rates (X, Y, Z) not selected on a priori grounds were found by iterative simulations using CATCHMOD to deliver a residual flow regime (post abstraction) which matches the target environmental flow regime (EFR) as closely as possible. Optimal combinations also generate the minimum possible number of occasions when flows falls below the target minimum flow values specified in Table 1, whilst also maximising permissible abstraction volumes overall, and particularly during low flows periods (i.e. when flow is in the amber and green bands, in turn). The first priority was generally to ensure that the residual flow regime neither falls below nor lies above the target EFR in the low flow range (from say the 50th percentile of the flow duration curve (i.e. from Q50 to Q100)), so as to keep deployable output (and abstractable volume) as high as possible. Maintaining the residual flow regime above but close to the EFR in the high flow range (from say Q0 to Q50) was a second priority, in regard to delivering overall abstraction volumes that are as high as possible without infringing the target EFR. In the event of a trade off being necessary between meeting the EFR and delivering a minimum acceptable overall abstraction volume (such as that attainable under existing licence conditions), the residual flow regime was allowed to fall below the target EFR over the environmentally less critical Q1 to Q50 range, but not within the environmentally sensitive flow range below the Q50 flow.

The general optimisation strategy was altered in some runs (2a, 3a) to give precedence to minimising the number of failure occasions against target low flow values and to delivering as high an AV as possible, irrespective of the bands from which abstraction is taken. It will be appreciated that this strategy is likely to impact adversely on DO.

By allowing upstream flow on the previous day (Q_{t-1}) to determine which of the above four rules applies without the use of a secondary rule to cap abstraction rate X to the headroom between (Q_{t-1} – A), abstraction at the permitted rate can occur even when the effect of that abstraction is to take the residual flow below the applicable HOF value (A). For example, if A = 198 Ml/d and X = 130 Ml/d, the modelling rules adopted here allow for total abstraction from the Otterbourne groundwater and river sources of 130 Ml/d (with abstraction from the river of 130/3 = 43.3 Ml/d) when $Q_{t-1}$is 199 Ml/d. When Q_{t-1} is 198 Ml/d, however, abstraction is prohibited. This produces a step change in the rate of permitted abstraction around flow threshold values, and a discontinuity in the profile of residual flows. That the modelling rules and the iteratively determined values for A, B, C and X, Y, Z nonetheless ensure achievement of the target EFR serves to alleviate concern that the modelled regime might be damaging to the river. This result reflects the fact that flow range in which residual flows can fall below the 198 Ml/d HOF value by artefact of the modelling rules adopted occur so rarely in reality; the 198 Ml/d value itself is the 99.8th percentile of the (1961-1990) flow regime. The higher rates of abstraction thus permitted might be expected to support higher deployable outputs in such extreme drought events than would otherwise be achievable.

A secondary rule to prevent abstraction taking residual flows below the HOF value could otherwise be included in the modelling rules to address any concerns raised by the (theoretical) latitude extended by the rules adopted herein.

Preliminary runs and results

Five[18] CATCHMOD licence simulation runs have been undertaken to date, with each run taking different a priori values for one or more of the flow threshold or abstraction rate values, and with the design of successive runs being determined in light of the results of previous runs. Table 2 summarises the 'set' and 'found' values of A, B, C and X, Y, Z for all runs, and records the key results from each of those runs. The results from individual runs are summarised in a proforma which gives the governing values, the flow duration curve of the residual (post-abstraction) flow regime plotted against the target EFR (the ROC flow duration curve) and the abstractable volumes attainable under the modelled abstraction licence regime. The results sheet for each run undertaken to date are given in Appendix 1 to this paper.

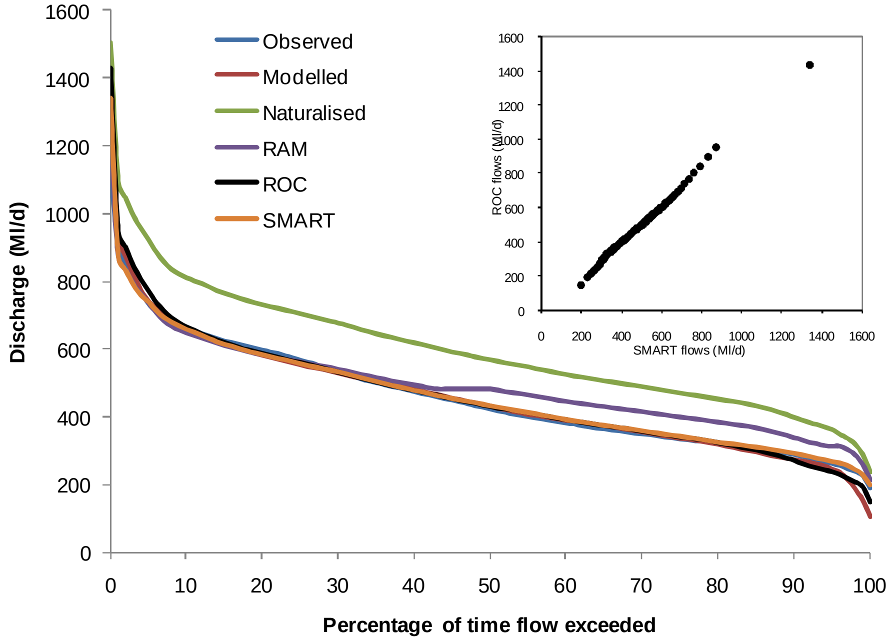
Table 2: Summary of model run parameters and results

CATCHMOD set up	**Variable**	**Run 1 (Ml/d)**	**Run 2a (Ml/d)**	**Run 2b (Ml/d)**	**Run 3a (Ml/d)**	**Run 3b (Ml/d)**
HOF threshold (red band)	A	270	198	198	198	198
Limited abstraction flow threshold (amber band)	B	**320**	237	237	237	237
Intermediate abstraction flow threshold (green band)	C	**675**	270	270	**410**	**900**
Limited abstraction rate (amber band)	X	**130**	**0**	**150**	**10**	**130**
Intermediate abstraction rate (green band)	Y	140	**0**	**0**	**70**	**140**
Unconstrained abstraction rate (blue band)	Z	Not fit	Not fit	Not fit	Not fit	Not fit
CATCHMOD results	**ROC**	**Run 1**	**Run 2a**	**Run 2b**	**Run 3a**	**Run 3b**
AV: Mean annual abstractable volumes (1961-1990) (Ml)	50398	50399	59291	59484	50904	50539
MAXAR: Maximum one day abstraction rate (Ml)	153	422	660	660	590	240
MDA: Mean daily abstraction volume (Ml/d)	140	138	162	163	139	138
EFR1: Number of days per year with flows below 198 Ml/d	5	<1	0	2	<1	5
EFR2: Number of days per year with flows below 237 Ml/d	18	6	3	4	5	17
EFR3: Number of days per year with flows below 270 Ml/d	36	20	6	7	14	38

[18] The three sets (Runs 1, 2, 3) use different combinations of flow threshold values. For each of Runs 2 and 3, two different optimisation strategies have been used, with Runs 2a and 3a seeking to minimise the number of failure days against the target minimum flows criterion in combination with the maximise AV criterion, and Runs 2b and 3b (and Run1) seeking to maximise abstraction from the amber, then green, then blue bands in turn, whilst meeting the target EFR criterion.

For Run 1, with the hands-off flow threshold A prescribed at 270 Ml/d, abstraction rate Y at 140 Ml/d and all other values determined by simulation, the residual flow duration curve matches the ROC EFR closely (see Figure 3 below), and delivers abstractable volumes as great as the ROC licence under all of the climatic scenarios modelled. The fitted values, therefore, appear to be optimal for the given set of values and rules. This indicates the possibility of environmental gain without abstraction loss in the round, and is on first inspection encouraging.

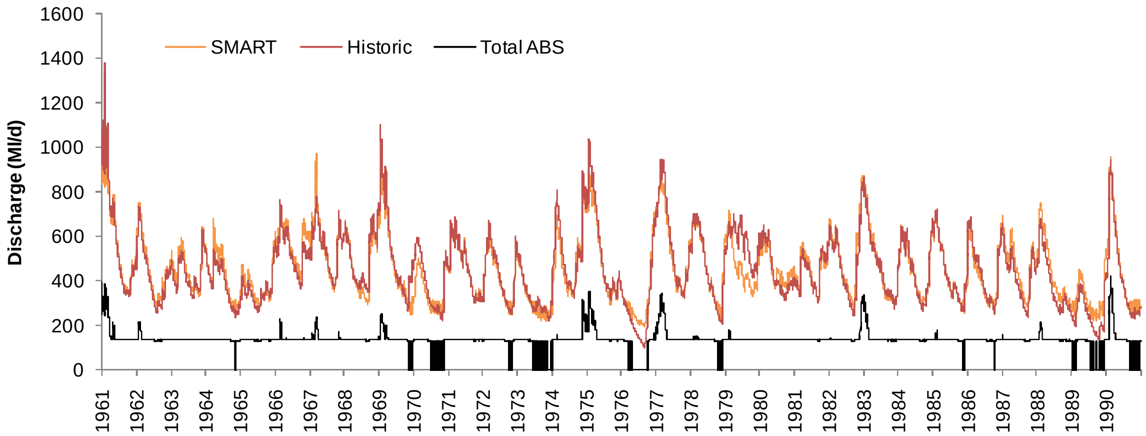
Figure 3: Flow duration curves for the Itchen at Otterbourne under different licence conditions, and under the Run 1 optimisation rules. The curves plotted are: historic abstractions (modelled); zero abstractions (naturalised); Resource Assessment and Management (RAM) derogation of natural flow; proposed abstraction regime with hands-off flow and summer limits (ROC); flow bands and limited abstraction with Run 1 values (SMART). Note that the RAM sensitivity of the River Itchen was taken as "moderate". This specifies maximum percentage reductions from naturalised flows of 20, 15 and 10% for flows exceeding Q_{50}, in the range $Q_{50\text{-}95}$, and less than Q_{95} respectively. The inset scatter graph compares the quantiles of the ROC and SMART flow duration curves.



The time series of historic actual flows at Allbrook and Highbridge plotted against the residual flows associated with the Run 1 SMART licence values (Figure 4) shows little difference between the two residual flow series, in the round. The SMART licence regime does however maintain higher residual flows in the river than does the historic abstraction regime under extreme low flow periods, whilst allowing higher abstraction and lower residual flows during intermediate low flow spells. The abstraction series under the SMART licensing regime is shown on the same plot. It shows 15 instances (of varying duration) when abstraction falls to zero in the 30 year (1961-1990) period. These episodes will impact on DO. So too will their equivalents in the ROC licensing regime. Whilst the abstraction series of the ROC abstraction scheme is not shown, it too includes multiple spells of zero abstraction. The Run 1 SMART licensing values have been passed to Southern Water for assessment of DO under its terms and conditions, using their in-house DO assessment models, for comparison against DO assessments under other licensing regimes. There is particular interest in the outcome of the SMART run when compared with the ROC regime proposed for adoption by the

Environment Agency from 2015/16 (Southern Water, 2009). The results of the DO determinations are awaited with considerable interest[19].

Figure 3: Modelled daily river flow at Allbrook and Highbridge under historic (red line) and Run 1 SMART licence (orange line) conditions, for the 1961-1990 standard period. The black line shows the combined groundwater and surface abstraction time series under the smart licensing regime.



Two further runs using the minimum flow values listed in Table 1 as guide values for flow thresholds A, B and C have also been undertaken. Run 2 used lower, less precautionary, flow thresholds than that used in Run 1, with A = 198 Ml/d, B = 237 Ml/d and C = 270 Ml/d values (with the selected values being three of the ecologically-critical values defined in Table 1). Run 3 used a still less precautionary set of values, with A = 198 Ml/d and B = 237 Ml/d, with C as well as X and Y being determined through iterative simulations. All 'floating' values were found by optimisation modelling. For Runs 2a and 3a, the optimisation strategy adopted gave precedence to minimising the number of days when the residual flow falls below the operative target minimum flow values, and then to maximising AV, without any priority being given to taking available water from the lower flow bands. For runs 2b and 3b, the general optimisation strategy prevailed, with the first priority being to take water from the amber band to the maximum extent consistent with not infringing the target EFR, and then from the green and blue bands in turn, so as to maximise the value of DO as well as maximising AV. The results from Runs 2a, 2b, 3a and 3b are given in Appendix 1, alongside those from Run 1.

Taking the Run 2 values of 198 Ml/d, 237 Ml/d and 270 Ml/d for A, B and C respectively, it proved impossible to find any values for X and Y (and then Z) able to deliver a residual flow regime close to the target EFR, under either of the two optimisation strategies investigated. The best combination of given and determined values in Run 2a delivered a residual flow duration curve that lies above the target EFR in the low flow range from the Q60 to Q100, and below the target EFR throughout the high flow range from Q1 to Q60. This indicates (on the one hand) that all available (non-damaging) yields in the low flow range are not being exploited to the full, at the inevitable cost of lowering DO more than need be. On the other hand, more water is being taken from higher flows than the EFR prescribes. The results from Run 2b, using the same flow threshold values but seeking to maximise the use of 'undamaging' yield from the amber and green bands, are marginally better (in terms of fitting the EFR and using the yield potential at low flows) than those from Run 2a, but the fit to the

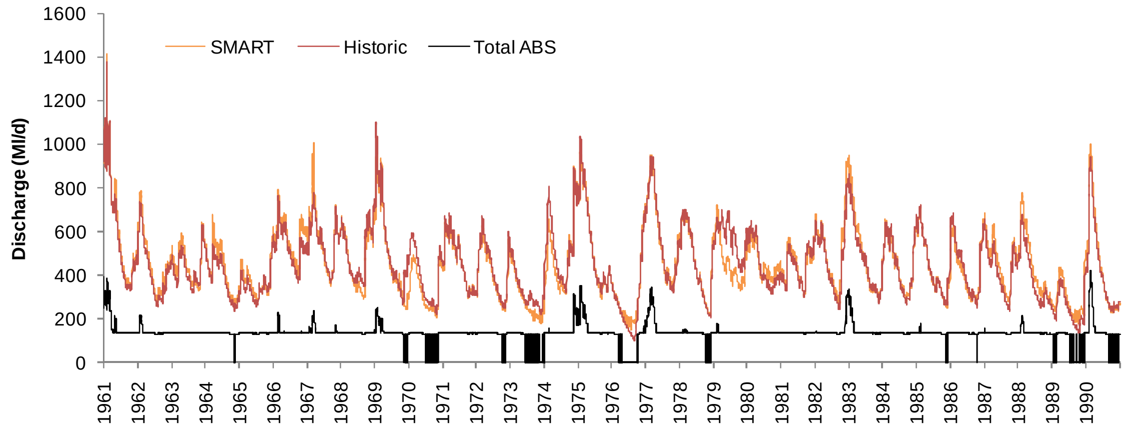
[19] DOs are to be determined for the ADO, MDO and PDO conditions, for a range of return periods, to enable the yield implications of different licence values to be identified as thoroughly as possible.

target EFR remains poor. The conclusion is that using the minimum flow values from Table 1 to define the A, B and C flow thresholds fails to deliver an acceptable outcome.

For Runs 3a and 3b, values of 198 Ml/d and 237 Ml/d are taken for flow thresholds A and B, with C, X, Y and Z being determined by optimisation, again using the minimise failure days and maximise abstraction from the amber band priorities, respectively. The results from Run 3a are superior to those from Run 2a, but whilst delivering good performance on failure days and AV, the untapped resource from low flows (from Q64) is likely to reduce DO needlessly. Run 3b provides a near optimal fit in all respects, being close to the target EFR throughout its range (and thence delivering highest possible DO, given the 'fit the target EFR' constraint) as well as delivering an AV marginally greater than that of the ROC licence and a low number of days when residual flows fall below target minimum flows. The only downside to the Run 3b combination of values is that the permitted abstraction from the amber zone exceeds that from the ROC licence during summer months.

The overall performance decision between Run 1 and Run 3b appears to hinge on the abstraction regime during low flows. Pending the direct determination of DO by Southern Water, for both the Run 3b and Run 1 values, the abstraction time series for run 3b may be usefully compared with that from Run 1. The data from Run 1 are shown in Figure 3 above, whereas those from Run 3b are shown in Figure 4 below. The data for Run 3b include 14 separate instances when abstraction falls to zero, which is barely different to the results from Run 1. Direct determination of the DO's attainable under Run 1 and Run 3b values are accordingly required to determine which of the two sets of values (Run 1 versus Run 3b) is the better, and whether either of the two delivers DO's better than the ROC values (or otherwise acceptable DOs).

Figure 4: Modelled daily river flow at Allbrook and Highbridge under historic (red line) and Run 3b SMART licence (orange line) conditions, for the 1961-1990 standard period. The black line shows the combined groundwater and surface abstraction time series under the smart licensing regime.



Stage 3: Determination of the impacts of candidate abstraction limits and conditions on DO

The effects of each of the proposed 'smart licensing options' on the deployable output of the affected source(s) will be determined using Southern Water's in-house DO calculation models. In all cases, the intention is to define the impact of the change in licensing conditions on annual average DO, on critical/peak period DO (PDO) and on DO in the period of minimum resource availability (MDO), for events of 1:10 year to 1:200 years occurrence (or, put another, DOs of 90% to 99.5%

reliability)[20] under historic and projected climate regimes. That way, the effect of the proposed licensing regime (compared to the existing licensing regime, and the proposed ROC based licensing regime) can be determined across a range of event severities and for annual average, peak demand and minimum output periods. This will enable full characterisation of the impacts of the licence change on the profile of source output.

The licence values from Run 1 and Run 3b of the CATCHMOD modelling work have been passed to Southern Water for direct evaluation of the DO consequences of the adoption of those values, using the company's own models.

Stage 4: Determination of smart licensing arrangements to maximise environmental protection and minimise water resources impacts

The final phase of the workstream will be iterative, using the results of Stage 3 to revisit Stage 2 with a view to determining that combination of smart licensing options that provides greatest gain to the environment at least cost to yield and to the supply-demand balance.

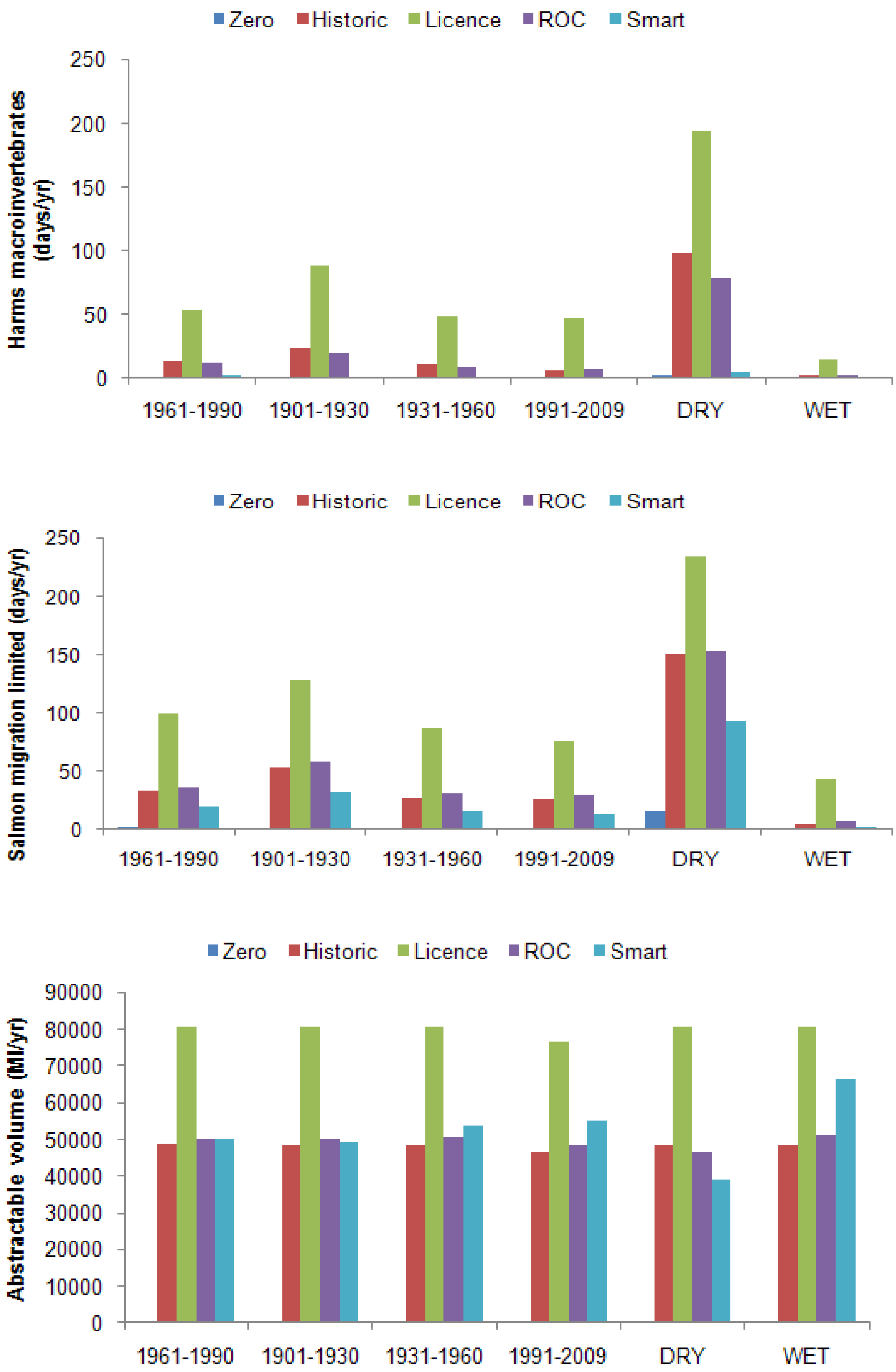
4. CONCLUSIONS

On the basis of the results obtained to date, it is evident that it is possible to find SMART licence values able to deliver a residual flow regime that matches a target environmental flow regime without reducing long run average abstractable volumes (compared to existing licence terms), under a range of climate scenarios.

The benefits of being able to do so, by comparison with the environmental and yield outcomes of other licensing regimes, is apparent from the data shown in Figure 5 below. The bar charts show the performance (for specified baseline periods) of a 'Zero' abstraction regime; an 'Historic' average abstraction regime; the existing 'Licence' regime; the proposed 'ROC' licensing regime; and the Run 1 'Smart' licensing regime examined herein, for two key environmental criteria and one key yield criterion. The upper diagram shows the performance of the respective abstraction regimes in terms of the number of resultant low flow days that might harm macro-invertebrates. The middle diagram shows the resultant number of low flow days hindering salmon migration. The bottom diagram shows the resultant annual average of the long run abstractable volume attainable under the various regimes. Each set of bars shows the results for four different historical periods and for two future 2020 climate scenarios (being 'dry' and 'wet', variants of plausible future climate for the 2020s).

[20] A 1:10 years event, for example, has a (long term average) recurrence interval of 10 years; an annual probability of occurrence of 10%; a deployable output that is likely to be attainable in 90% of all years, and not attainable in 10% of all years. In technical terms, the reliability of a deployable output in an event of n years recurrence interval is 1-(1/n). The DO attainable in a 1:50 years event has a reliability of 98%; in a 1:100 years event, it is 99%, and so on.

Figure 5: Results from the Run 1 ‘smart abstraction licensing’ approach compared to other licensing approaches. (Note: ‘Zero’ is no abstraction; ‘Historic’ is the average abstraction over the baseline period 1961-1990; ‘Licence’ is the existing abstraction licence; ‘ROC’ is the licensing regime proposed by the Environment Agency in their Review of Consents work; ‘Smart’ is the approach examined herein, using the Run 1 values stated in the text. Each set of bars shows the results for different historical periods and for ‘dry’ and ‘wet’ variants of plausible future climate for the 2020s).



The charts results show that compared to historic abstraction, to the existing licence, and to the proposed licence under the ROC, the Run 1 'smart licensing' design delivers fewer low flow days that potentially harm macro-invertebrates (upper diagram) and fewer of the low flow days limiting salmon migration (middle diagram), without loss of abstractable volume compared to the ROC abstraction in all but the driest scenarios (lower diagram). It would appear from these results that the tiered licensing approach has some merit, in relation to delivering both environmental and total abstraction goals.

As to whether it is possible to find a set of SMART licence values that can deliver environmental enhancements and abstractable volume parity, whilst also delivering acceptable deployable output values (at the same or similar levels to the ROC licence proposed for introduction from 2015/16, particularly) remains to be determined.

That being the position, it is pertinent to consider, irrespective of the outcome of those further studies, whether we should be seeking to maximise the use of environmentally benign water resources, taking yield when it is most available, according to environmental capacity. Here, the challenge would be to find ways to maximise the value of water taken according to its environmental as well as its hydrological availability. This could be achieved by using water from sources or areas with different yield patterns as conjunctively as possible, by resting and using sources sympathetically at low flows, or making use of storage and 'spot' transfers of water at high flows.

It is considered that such matters should be on the agenda, if we are to use environmentally-friendly water to the maximum, and minimise the use of environmentally-damaging water.

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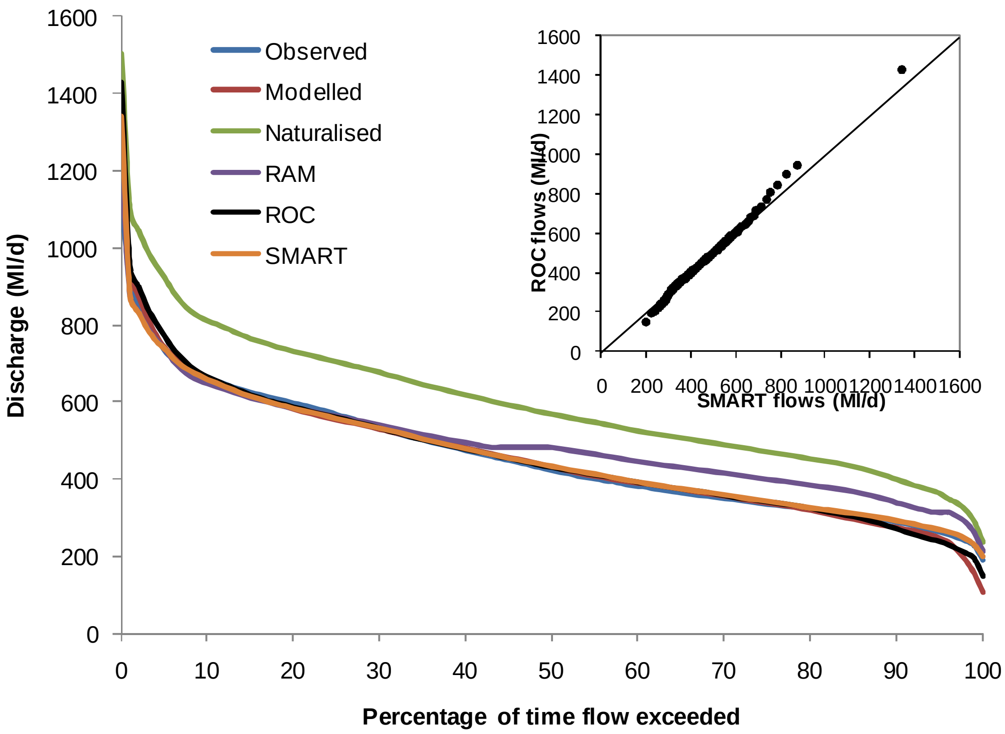
Appendix 1: Summary of results from SMART licence value determinations using CATCHMOD

Run 1 Smart licence values

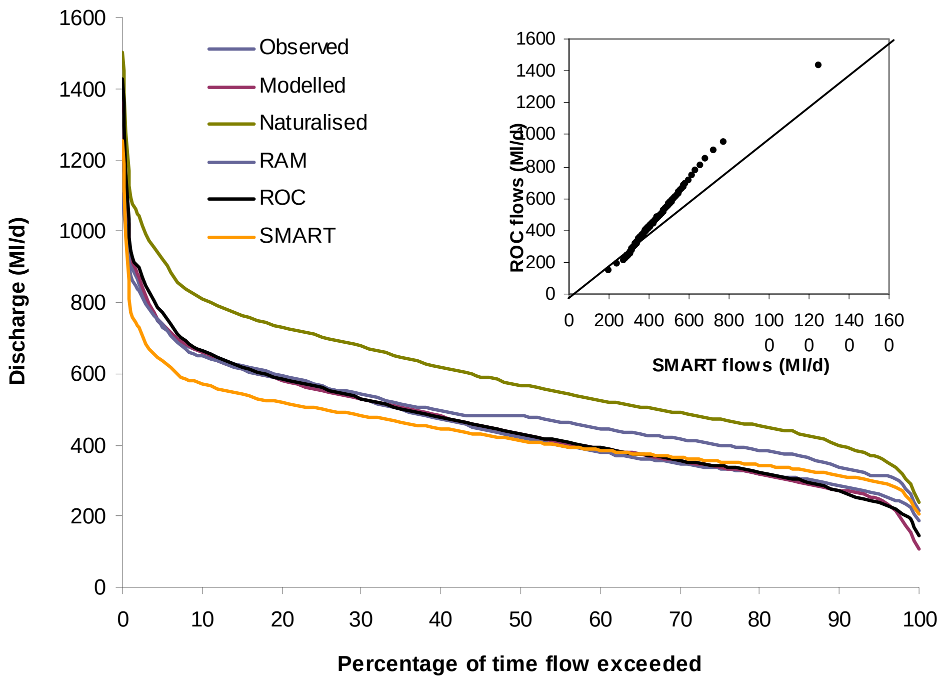
CATCHMOD set up	Variable	Value (Ml/d)
Hands-off flow threshold (red band)	A	270
Limited abstraction flow threshold (amber band)	B	320
Intermediate abstraction flow threshold (green band)	C	675
Limited abstraction rate (amber band)	X	130
Intermediate abstraction rate (green band)	Y	140
Unconstrained abstraction rate (blue band)	$Z = Y+(Q_t\text{-}C)$	Not fit
CATCHMOD results	**Variable**	**Value**
Annual mean abstractable volumes (1961-1990)	AV	50399 Ml
Maximum one day abstraction rate	MAXAR	422 Ml
Mean daily abstraction volume	MDA	138 Ml
Number of days per year with flows below 198 Ml/d	EFR1	<1
Number of days per year with flows below 237 Ml/d	EFR2	6
Number of days per year with flows below 270 Ml/d	EFR3	20



Comments: This is model configuration was described in the draft manuscript. A conservative hands-off flow threshold (270 Ml/d) is applied to meet the estimated requirement for salmon migration.

Run 2a Smart licence values

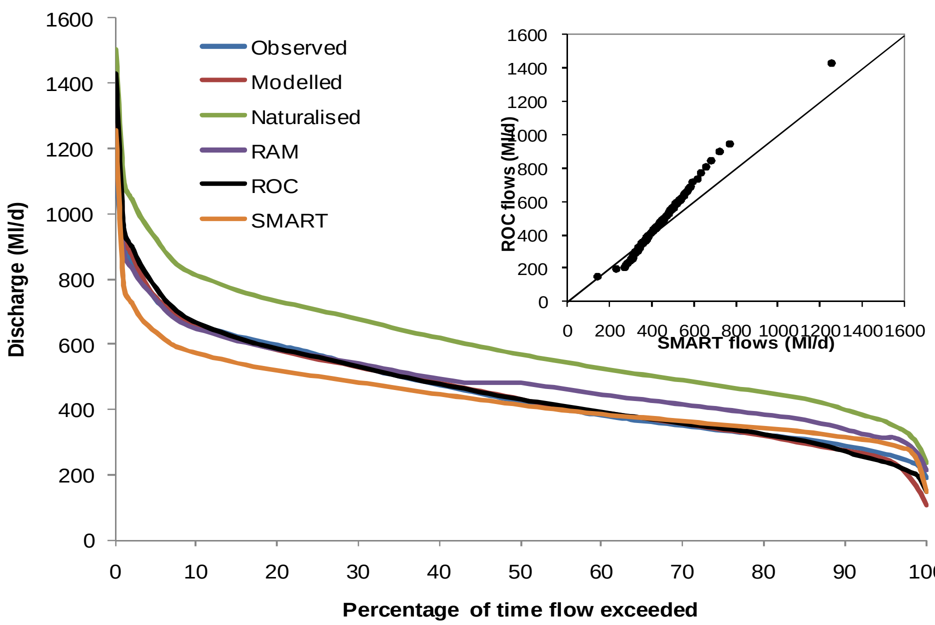
CATCHMOD set up	Variable	Value (Ml/d)
Hands-off flow threshold (red band)	A	198
Limited abstraction flow threshold (amber band)	B	237
Intermediate abstraction flow threshold (green band)	C	270
Limited abstraction rate (amber band)	X	0
Intermediate abstraction rate (green band)	Y	0
Unconstrained abstraction rate (blue band)	$Z = Y+(Q_t-C)$	Not fit
CATCHMOD results	**Variable**	**Value**
Annual mean abstractable volumes (1961-1990)	AV	59291 Ml
Maximum one day abstraction rate	MAXAR	660 Ml
Mean daily abstraction volume	MDA	162 Ml
Number of days per year with flows below 198 Ml/d	EFR1	0
Number of days per year with flows below 237 Ml/d	EFR2	3
Number of days per year with flows below 270 Ml/d	EFR3	6



Comments: Even when setting X and Y = 0 (equivalent to a single hands off flow requirement of 270 Ml/d) the AV still exceeds that achieved under ROC license conditions (50,398 Ml/yr) but the EFR (198 Ml) is easily met. The high AV occurs because the *Z* rate applies to 98% of the flow duration curve. An additional parameter (*W*) could be used to constrain the blue band abstraction rates to better match licensed volume as in: $Z = Y + W (Q_{t-1}+C)$. But this would add further complexity to the license conditions.

Run 2b Smart licence values

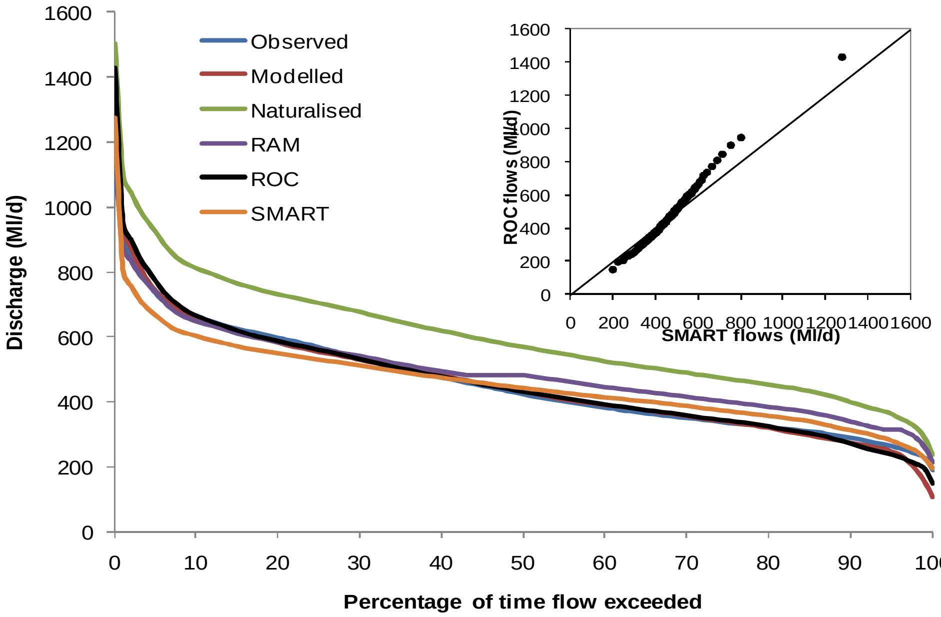
CATCHMOD set up	Variable	Value (Ml/d)
Hands-off flow threshold (red band)	A	198
Limited abstraction flow threshold (amber band)	B	237
Intermediate abstraction flow threshold (green band)	C	270
Limited abstraction rate (amber band)	X	150
Intermediate abstraction rate (green band)	Y	0
Unconstrained abstraction rate (blue band)	$Z = Y+(Q_t-C)$	Not fit
CATCHMOD results	**Variable**	**Value**
Annual mean abstractable volumes (1961-1990)	AV	59484 Ml
Maximum one day abstraction rate	MAXAR	660 Ml
Mean daily abstraction volume	MDA	163 Ml
Number of days per year with flows below 198 Ml/d	EFR1	2
Number of days per year with flows below 237 Ml/d	EFR2	4
Number of days per year with flows below 270 Ml/d	EFR3	7



Comments: As with run 2, it was not possible to achieve a residual flow regime in which <u>all</u> low flows (in the range Q50 to Q100) exceed ROC. The minimum flow (Q100) does meet the objective for X≤150 Ml/d if Y=0 Ml/d, but all flows above Q64 are below target. This is because the unconstrained rate of abstraction applies over too much of the flow regime (i.e., Q>270 Ml/d). Note that flows only fall within the amber and green bands on average 2 days per year each, so the B and C thresholds have negligible effect.

Run 3a Smart licence values

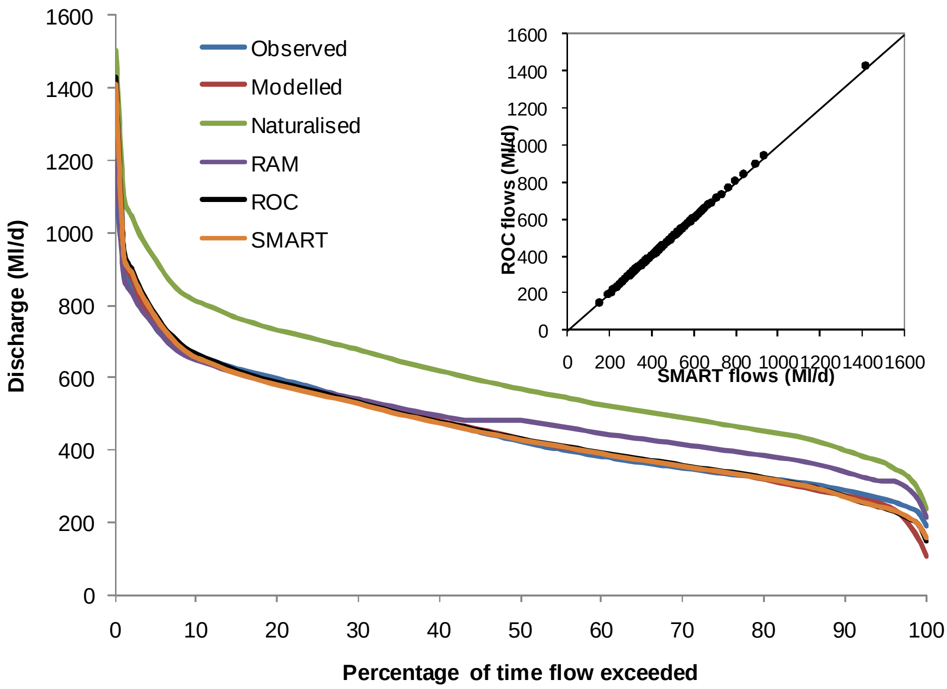
CATCHMOD set up	Variable	Value (Ml/d)
Hands-off flow threshold (red band)	A	198
Limited abstraction flow threshold (amber band)	B	237
Intermediate abstraction flow threshold (green band)	C	410
Limited abstraction rate (amber band)	X	10
Intermediate abstraction rate (green band)	Y	70
Unconstrained abstraction rate (blue band)	$Z = Y+(Q_t\text{-}C)$	Not fit
CATCHMOD results	Variable	Value
Annual mean abstractable volumes (1961-1990)	AV	50904 Ml
Maximum one day abstraction rate	MAXAR	590 Ml
Mean daily abstraction volume	MDA	139 Ml
Number of days per year with flows below 198 Ml/d	EFR1	<1
Number of days per year with flows below 237 Ml/d	EFR2	5
Number of days per year with flows below 270 Ml/d	EFR3	14



Comments: Mean annual AV (50,904 Ml) slightly exceeds ROC but the maximum one day abstraction rate is lower than in the version 2 run. The AV is found to be much more sensitive to the value of *C*, than *X* or *Y*. Mean annual frequencies of days with flows less than environmental targets (198, 237 and 270 Ml/d) are much lower than the existing ROC simulation, and significantly lower than under simulated historic abstraction. Version 3 looks like a promising set of license conditions in that comparable AV is achieved with less frequent low flows compared with ROC.

Run 3b Smart licence values

CATCHMOD set up	Variable	Value (Ml/d)
Hands-off flow threshold (red band)	A	198
Limited abstraction flow threshold (amber band)	B	237
Intermediate abstraction flow threshold (green band)	C	900
Limited abstraction rate (amber band)	X	130
Intermediate abstraction rate (green band)	Y	140
Unconstrained abstraction rate (blue band)	$Z = Y+(Q_t-C)$	Not fit
CATCHMOD results	**Variable**	**Value**
Annual mean abstractable volumes (1961-1990)	AV	50539 Ml
Maximum one day abstraction rate	MAXAR	240 Ml
Mean daily abstraction volume	MDA	138 Ml
Number of days per year with flows below 198 Ml/d	EFR1	5
Number of days per year with flows below 237 Ml/d	EFR2	17
Number of days per year with flows below 270 Ml/d	EFR3	38



Comments: Mean annual AV (50,539 Ml) slightly exceeds ROC but the maximum one day abstraction rate is much lower than in version 2, 2b and 3 runs. Mean annual frequencies of days with flows less than environmental targets (198, 237 and 270 Ml/d) are comparable to the ROC simulation. Permissible abstraction rates for the amber band exceed those for ROC during July to September.