Chalk Streams First

Dealing with impacts of groundwater abstraction on the chalk streams of the Colne and Lea valleys

Final Report

Borehole locations redacted

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Key Points

- The current draft water resource plans (WRMPs) include about 150 Ml/d of abstraction reductions in the upper Colne and Lea chalk streams, a similar amount to the reductions put forward in the Chalk Streams First proposal. This would be sufficient to almost wholly re-naturalise the chalk stream flows.
- The re-naturalised chalk stream flows would also substantially improve flows in the lower Rivers Colne and Lea, making the 290 Ml/d of additional abstraction reductions proposed for the lower rivers appear to be of questionable value and, perhaps, largely unnecessary.
- About 50 Ml/d of planned reductions would be in place by the early 2030s, enabled by the Grand Union Canal transfer and operational by 2031.
- Most of the water companies' planned reductions are delayed until after 2040, waiting for the availability of water from the proposed Abingdon reservoir and the Thames to Affinity transfer scheme.
- The reason for the delay is the water companies' assumption of only 17% recovery of London deployable output from the enhanced chalk stream flows arising from the upper catchment abstraction reductions.
- Analysis of measured chalk stream flows following abstraction reductions has found much higher flow recoveries, which are also shown by groundwater modelling.
- Therefore, it is proposed that the first phase of the Thames to Affinity transfer should be brought forward to the early 2030s, allowing all the planned 150 Ml/d abstraction reductions before 2035, without the need to wait for Abingdon reservoir.
- The uncertainty of recovery of London deployable output could be overcome by using the chalk aquifer in the re-naturalised upper catchments for a drought supply scheme similar to the existing West Berkshire Groundwater Scheme (WBGWS).
- The WBGWS-type drought scheme could more than offset the replacement supplies for all the abstraction reductions, giving about 55-60 Ml/d of deployable output increase for London, with minimal impact on the re-naturalised chalk stream flows.

Background

The Chalk Streams First proposal for re-naturalising flows in the Chilterns chalk streams was published in February 2020 and launched in May 2020 by a coalition of The Angling Trust, The Rivers Trust, WWF (UK), the Wild Trout Trust and Wild Fish.

The proposed scheme involved reducing public water supply abstraction from the Chilterns chalk stream tributaries of the Rivers Colne and Lea, meeting the Environment Agency's ecological flow indicators (EFIs). The resulting improved flows in the chalk streams would flow down to the lower Rivers Thames and Lea where it could be pumped into the existing London reservoirs. Replacement supplies would be taken from the London reservoirs and transferred back into the Chilterns via an existing and extended network of pipelines.

In essence, the Chalk Stream First (CSF) proposal allows the chalk stream flows to be largely re-naturalised, with public water supplies taken instead from much larger and less ecologically sensitive river reaches further down the Thames catchment. In this way, there could be large reductions in the damaging chalk stream abstractions, with only a relatively small requirement for costly replacement water sources.

The potential benefits of the Chalk Stream First proposal were recognised by the Environment Agency and Ofwat in 2020. The water companies were asked to investigate the proposal as part of the £470 million programme of investigations of strategic water resource options, with Chalk Streams First considered as part of the Thames to Affinity transfer option. The outcome of the investigation has fed into the draft Water Resource Management Plans (WRMPs) of Thames Water and Affinity Water, which are currently out for public consultation.

This report looks again at some of the technical aspects of the CSF proposal, particularly the amount and timing of chalk stream flow recovery from abstraction reductions. It considers case studies of four of the Chilterns chalk streams – the Rivers Chess, Ver, Mimram and Beane. It reviews the proposals for amounts and timing of groundwater abstraction reductions in the various WRMPs and Water Resource South East's regional plan. It makes proposals for changes in these plans that would allow flows in the Chilterns chalk streams to be re-naturalised faster than currently proposed and at much reduced cost.

Note: this report has been prepared by John Lawson, in consultation with Charles Rangeley-Wilson, acting as representative and liaison for the Chalk Streams First coalition: where the report goes beyond technical detail to policy recommendations, these should be considered to be the collective position of Chalk Streams First.

Relationship between river flows, groundwater levels (GWLs) and abstraction

Recorded data shows a non-linear relationship between the rise and falls of chalk stream flows and aquifer groundwater levels – ie for a given unit of rise in GWL, flows increase a lot more at high GWLs than at low GWLs. This clear relationship between GWLs and flows has been seen in many chalk streams. The GWLs rise as effective rain fills the aquifer and fall when effective rain is low, while river outflows and chalk underflows continue to drain the aquifer. With the aquifer acting as a reservoir, groundwater abstraction suppresses the rise in GWLs during periods of recharge and exaggerates the GWL decline during dry periods. The main impact of abstraction on baseflows is interpreted as coming through its effect on regional water table fluctuations and hence flows, rather than the localised impacts of borehole cones of depression which are superimposed on the rises and falls of the regional water table.

This interpretation of chalk stream behaviour has been used in CSF lumped parameter models for the Rivers Chess, Ver, Mimram and Beane, which simulate daily GWLs and flows for the past 100 years, using the Environment Agency's 100-year records of daily effective rain. These models generally give a closer fit between recorded and modelled data than does the Environment Agency's 2015 Herts Regional Groundwater Model (HRGM).

The importance of flow recovery from reduced abstraction

The amount and timing of chalk stream flow recovery is crucial for the Chalk Streams First proposal. If the amount of recovery is high and a good proportion of extra water from the chalk catchments is available to refill the existing London reservoirs in droughts, there would be comparatively little additional water resource development needed. This would allow flows in the Chilterns chalk streams to be re-naturalised within a few years and at relatively low cost.

The original CSF proposal assumed that an average of about 70% of the amounts of reduced groundwater abstraction could be recovered through enhanced chalk stream flows re-abstracted into the London reservoirs. The current WRMPs and WRSE's regional plan assume only a 17% recovery for planning purposes (albeit at low flows). Therefore, this report has examined in detail the evidence from measurements and modelling of flow recovery from actual abstraction reductions in the Chilterns chalk streams.

Assessment of measured flow recovery from abstraction reductions

Measurement of flow recovery is very difficult because of the paucity of cases of significant and maintained abstraction reductions and the difficulty of separating the effects of abstraction reductions from climatic changes, bearing in mind the time taken for GWLs and flows to respond. However, there is some reasonably clear evidence of flow recoveries:

- The Friars Wash sustainability reduction of about 12 Ml/d from the River Ver in 1992 showed that recovery varied across the range of flows: about 80% at the median flow Q50, about 30% at Q90 and less than 20% at Q99. At high flows, the flow recovery was considerably more than the abstraction reduction.

- Relative flow changes in the Rivers Ver and Chess associated with substantial and sustained changes in relative abstraction amounts over the past 50 years, showed measured changes in relative flows of a similar magnitude and pattern to the measured changes from the Friars Wash reduction.

- A similar assessment of changes in relative flows in the Beane and Rib catchments over the past 20 years, covering the period before and after the 13 Ml/d reduction in abstraction at Whitehall in the Beane catchment, gave a similar scale of recovery to the Friars Wash and Chess-Ver cases, although with more recovery at low flows and less at high flows.

The Affinity Water assessment of the much lower 17% flow recovery is based largely on the perception that a number of abstraction reductions since 2016 have failed to deliver any significant measured flow improvements. In explanation Affinity Water has proposed that semi-permeable Marl layers within the chalk provide a barrier which prevents abstraction from below the Marl layers from having any significant impact on near-surface GWLs and river flows. Affinity Water also refer to a number of short-term pumping switch-offs (signal tests), which failed to register significant measurable river flow increases. Affinity Water has concluded that this evidence shows that there would be little recovery of river flows in droughts at times when they would be needed to boost the deployable output of London's supplies.

This report has examined Affinity Water's evidence and concluded that:

- The abstraction reductions since 2016 have been mostly too small and insufficiently maintained for measurable flow increases to be detected or separable from natural flow changes.
- There was insufficient time and aquifer recharge between the abstraction reductions and the investigations into / reporting on their impacts and therefore the regional water balance and groundwater levels had not recovered enough to cause measurable flow changes.
- The signal tests were of too short a duration to affect the changes in the aquifer water balance and generate flow changes. Short term signal tests are not a reliable way of assessing flow gains from abstraction reductions in these rivers.
- The consistency of recorded GWL fluctuations in different parts of the catchments and at different depths shows that the deep aquifer beneath the Marl layers has sufficient connection to near-surface GWLs to enable abstraction to affect river flows.
- There are no instances of flow recoveries failing to materialise when they might reasonably be expected to after genuine and maintained abstraction reductions.

The conclusion is that there is sufficient evidence of measured flow changes from abstraction reductions to support the assumption that abstraction reductions lead to substantial flow recovery, including at the times when additional flow is needed for the deployable output of London's supplies.

Modelling of flow recovery from abstraction reductions

The EA's HRGM regional groundwater models and the CSF lumped parameter model both validate reasonably well against recorded historic data. They can both be used with confidence to estimate abstraction impacts and flow recoveries. The patterns and amounts of modelled flow recoveries are similar to the measured flow recoveries from the Friars Wash sustainability reduction and the Chess-Ver and Beane-Rib comparisons referred to above. The models show that at average river flows, modelled river flow recoveries are in the region of 80% of the abstraction reductions, and at extreme low flows, recoveries are typically around 30-40% of abstraction reductions. These conclusions are equally true in all four case-study rivers.

The modelled and measured flow recoveries are similar. They are far more than the 17% flow recovery assumed in recently published water company draft WRMPs and in the draft regional plan of Water Resources in the South East.

Up-date of the Chalk Streams First proposal

Under the CSF proposal, the proposed abstraction reductions would be a total of 63 Ml/d in the Colne chalkstreams and 89 Ml/d in the Lea chalk streams, as shown below.

	Recent abstraction 2019-21	**CSF proposed abstraction**	**Abstraction reduction**
Misbourne	15.8 Ml/d	6.2 Ml/d	9.6 Ml/d
Chess	15.1 Ml/d	4.1 Ml/d	11.0 Ml/d
Gade	36.2 Ml/d	11.9 Ml/d	24.3 Ml/d
Ver	25.8 Ml/d	7.7 Ml/d	18.1 Ml/d
		Colne sub-total	**63.0 Ml/d**
Upper Lea to Water Hall	48.4 Ml/d	7.2 Ml/d	41.2 Ml/d
Mimram	10.4 Ml/d	6.1 Ml/d	4.3 Ml/d
Beane	24.9 Ml/d	9.8 Ml/d	15.2 Ml/d
Rib	22.8 Ml/d	7.3 Ml/d	15.5 Ml/d
Ash	1.2 Ml/d	0.0 Ml/d	1.2 Ml/d
Stort	25.0 Ml/d	13.5 Ml/d	11.5 Ml/d
		Lea sub-total	**88.9 Ml/d**
		Total	**151.9 Ml/d**

CSF proposed abstraction reductions in the upper Colne and Lea chalk streams

The CSF modelling shows that these reductions would achieve flows that comply with the Environment Agency's proposals for Abstraction Sensitivity Bands and Ecological Flow Indicators. The flows in all the upper Colne and Lea chalk streams would be restored to near natural amounts.

In the case of the River Chess and the upper River Lea, where drought flows at present are almost totally made up of STW effluent, the re-naturalised flows would be in addition to the STW effluent, providing much more dilution.

The CSF proposed abstraction reductions in the upper catchments would substantially increase flows in the lower rivers. There would be a big increase in STW effluent dilution in droughts, particularly for the large STWs at Maple Cross and Rye Meads which at present provide almost all of the drought flows in the lower Rivers Colne and Lea.

At the historic Amwell Magna fishery in the middle River Lea, flows would benefit from all the upper catchment abstraction reductions. Summer flows would increase by about 30-50% and would no longer be almost entirely STW effluent in droughts.

CSF modelling of deployable output recovery for London's supplies

The CSF lumped parameter model has been combined with a simulation model of the London water supply system to determine the gain in deployable output for London's supplies from the total 151 Ml/d of CSF proposed abstraction reductions.

The modelled 87 Ml/d gain in London's deployable output is 58% of the 151 Ml/d abstraction reduction – a far higher gain than the 17% assumed in water company WRMPs.

Abstraction reductions in current draft WRMPs and WRSE's regional plan

The draft WRMPs for Affinity Water and Thames Water and WRSE's regional plan allow for substantial abstraction reductions in the Chilterns chalk streams. Information provided by WRSE on abstraction reductions at individual sources shows reductions in the upper chalk tributaries under the 'High' scenario of similar amounts to those proposed by CSF, although with some differences in individual rivers. It is understood that the 'High' scenario reductions have been assumed as the main planning scenario in water company WRMPs.

However, WRSE's figures show that most of the planned reductions will be delayed to after 2040 as below:

		WRSE High scenario DO loss	
	CSF proposed abstraction reduction	**Reduction by 2034-35**	**Reduction by 2049-50**
Colne total	**63.0 Ml/d**	**13.1 Ml/d**	**52.2 Ml/d**
Lea total	**87.6 Ml/d**	**37.3 Ml/d**	**100.0 Ml/d**
Total	**150.6 Ml/d**	**50.4 Ml/d**	**152.2 Ml/d**

Timing of water company planned abstraction reductions

The WRSE plan delays most of the abstraction reductions until after 2040, because of the supposed need to wait for construction of major new sources like the Severn to Thames transfer or Abingdon reservoir. This is the consequence of the water company assumption that only 17% of the flow recovery from abstraction reductions converts to increased deployable output from the London reservoirs. The CSF proposal is that the reductions can be achieved within 10 years without needing to wait for any major new sources, taking account of much higher deployable output recovery for the London reservoirs.

Justification of the water company assumption of 17% flow recovery

From supporting documentation to Affinity Water's WRMP, the justification of the 17% DO recovery appears to have been simply:

1. During the critical droughts of 1921 and 1934, the average natural flow percentile in the River Thames at Kingston was said to be around the 98th percentile flow.

2. Recovery of flows from abstraction reductions in the Colne and Lea catchments was an average of 17% recovery at the 98th percentile.
3. Therefore, the deployable output gain from abstraction reductions is 17%.

There are several flaws in this assessment. Firstly, average River Thames naturalised flows during the 1921 and 1934 drought recessions were at the 92nd percentile, which is a lot more flow than the 98th percentile. Secondly, the average of modelled chalk stream flows during the drought recessions are also at the 92nd percentile and not the 98th percentile. Thirdly, the measured and modelled flow recoveries in droughts at the 92nd percentile described above are a lot more than 17% and more in line with the CSF modelled London deployable output recovery of 58%.

It is proposed that groundwater modelling should be the primary means of estimating flow recoveries and the gain in deployable output for London's supplies. This is consistent with the Environment Agency's use of models to estimate the amounts of required abstraction reductions. It would seem irrational to use these models to determine the amount of required abstraction reductions and then not use the same models to estimate flow and deployable output recovery.

WRSE planned abstraction reductions in the lower Colne and Lea valleys

WRSE also propose 286 Ml/d of abstraction reductions in the lower Colne and Lea valleys – about 79 Ml/d for the Colne and 207 Ml/d for the Lea (mostly surface water abstractions for the Lea). This is nearly double the amount of the abstraction reductions from the upper catchment chalk streams. However, whereas the reductions in the upper catchments are easily justified in terms of restoring near-natural flows in iconic chalk streams, the benefits of the much larger reductions in the lower rivers are much less clear. The lower Colne and Lea are heavily modified and urbanised rivers, with impounded channels that will be less ecologically responsive to flow improvements.

Notwithstanding, the lower Colne and Lea will benefit anyway from large flow increases from abstraction reductions in the upper catchments.

It is suggested that the abstraction reductions in WRSE's plan and the WRMPs should be carefully and transparently prioritised, specifying the benefits and costs of each reduction, with due consideration of the disbenefits of the impacts of constructing the replacement sources.

It is most important that a) whatever resources are available should first be used to restore flow to the internationally important chalk streams b) plans don't become unrealistically ambitious and threaten the viability of any reductions by becoming far too costly and c) the environmental impacts of developing other sources are weighed against the environmental benefits.

Infrastructure proposals for CSF in Affinity Water's draft WRMP

Affinity Water's draft WRMP includes plans for infrastructure to deliver the replacement supplies needed to enable the proposed abstraction reductions, with several strategic resource options and a pipe delivery network, termed 'Connect 2050'.

From the perspective of Chalk Streams First, any of these strategic options could deliver the required water. However, there would be a strong preference for options that can be delivered quickly to enable the planned abstraction reductions to be in operation within the next 10 years.

Affinity Water's plan proposes that a 50 Ml/d first phase of the Grand Union canal transfer, bringing in treated effluent from Minworth STW, should be in operation by 2031. This has the potential to facilitate a considerable proportion of the planned 150 Ml/d of abstraction reductions in the Chilterns chalk streams, replacing groundwater supplies in both the Colne and the Lea chalk catchments.

Affinity Water's preferred plan includes the construction of Abingdon reservoir, the Thames to Affinity transfer and a second phase of the GUC transfer, but only making additional water available after 2040. This means that most of the planned 150 Ml/d of abstraction reductions in the upper Colne and Lea catchments will have to wait until after 2040. This explains why WRSE's plan only allows for about 50 Ml/d of Chilterns chalk stream abstraction reductions by 2035, mostly in the Lea chalk streams.

This is all extremely disappointing from the perspective of the NGOs supporting the Chalk Streams First proposal and the local people and organisations who have been campaigning for improvements for many years. It is particularly disappointing that the first phase of the Thames to Affinity transfer strategic resource option has been put back to 2040, presumably because this is the earliest date that Abingdon reservoir water is available.

The delay in construction of the Thames to Affinity transfer means that there is no opportunity to feed water from London's supplies into the Chilterns before 2040, even though by 2031 London's supplies will benefit from the 50 Ml/d of new water coming into the Chilterns from the GUC transfer – much of this will become available to fill London's reservoirs, either from increased effluent returns or from enhanced chalk stream flows from the abstraction reductions.

Therefore, it is proposed that the first phase of the Thames to Affinity Transfer should be brought forward to its earliest feasible completion date, perhaps the early 2030s. This would facilitate some more of the planned Chilterns chalk abstraction reductions to proceed quickly, particularly in the upper Colne chalk streams.

It is appreciated that there is uncertainty over the amount of flow recovery in critical droughts. One way of removing this uncertainty is to convert some of the Chilterns sources scheduled for abstraction reductions into drought-only supply schemes similar to Thames Water's existing West Berkshire Groundwater Scheme. This could only be done or trialled after construction of at least part of the Thames to Affinity transfer.

Future conversion to a WBGWS-type of drought scheme

The West Berkshire Groundwater Scheme (WBGWS) was constructed in the 1970s to augment London's water supplies during severe droughts – its planned use is about once in 25 years. The scheme abstracts water from boreholes in the chalk aquifer in the upper Lambourn, Pang, Enbourne and Loddon valleys, discharging water into those rivers from where it flows down into the River Thames for later abstraction to fill London's reservoirs. It contributes about 90 Ml/d to London's deployable output.

The WBGWS concept could be used in the Colne and Lea chalk tributaries, in combination with current proposal for reduced abstractions for day-to-day supplies. Replacement supplies would be transferred from the London supply system using the Thames to Affinity transfer and the 'Connect 2050' pipe network. An initial assessment of the WBGWS concept in the Chilterns chalk streams has shown:

1. CSF modelling of the concept for the River Ver shows the reduction of public water supplies from the current 28 Ml/d to about 8 Ml/d, combined with WBGWS-type drought support of up to 25 Ml/d, would almost re-naturalise River Ver flows and give a net increase in London supplies of about 9 Ml/d.

2. If the concept was adopted in all the Colne and Lea chalk streams, abstraction could be reduced to meet EFIs throughout and the deployable output gains from the WBGWS-type releases would more than offset the replacement supplies needed for the abstraction reductions to give a net increase in London deployable output of about 55-60 Ml/d.

3. The drought support would only be needed about once in 25 years. Drought flows in the chalk streams would be increased by the WBGWS-type releases and would be slightly less in the following year (but still much more than with abstraction at recent levels).

4. The introduction of the WBGWS concept would remove much of the doubt that currently exists over the amount of flow recovery from abstraction reductions. The net gain in deployable output of 55-60 Ml/d would make this a significant new water resource in its own right.

In principle, the conjunctive use of the chalk aquifer and the reservoirs downstream appears a much better way of using the chalk water resource, with far less impact on chalk streams than continuous pumping of water supplies directly from the chalk.

The concept should now be investigated as a matter of urgency, with the aim of implementing one or more pilot schemes in AMP8.

1. Introduction

1.1 Background to the Chalk Streams First proposal

The Chalk Streams First proposal was published in February 2020 and launched in May 2020 by a coalition of The Angling Trust, The Rivers Trust, WWF (UK), the Wild Trout Trust and Wild Fish[1]. The concept is illustrated in Figure 1:

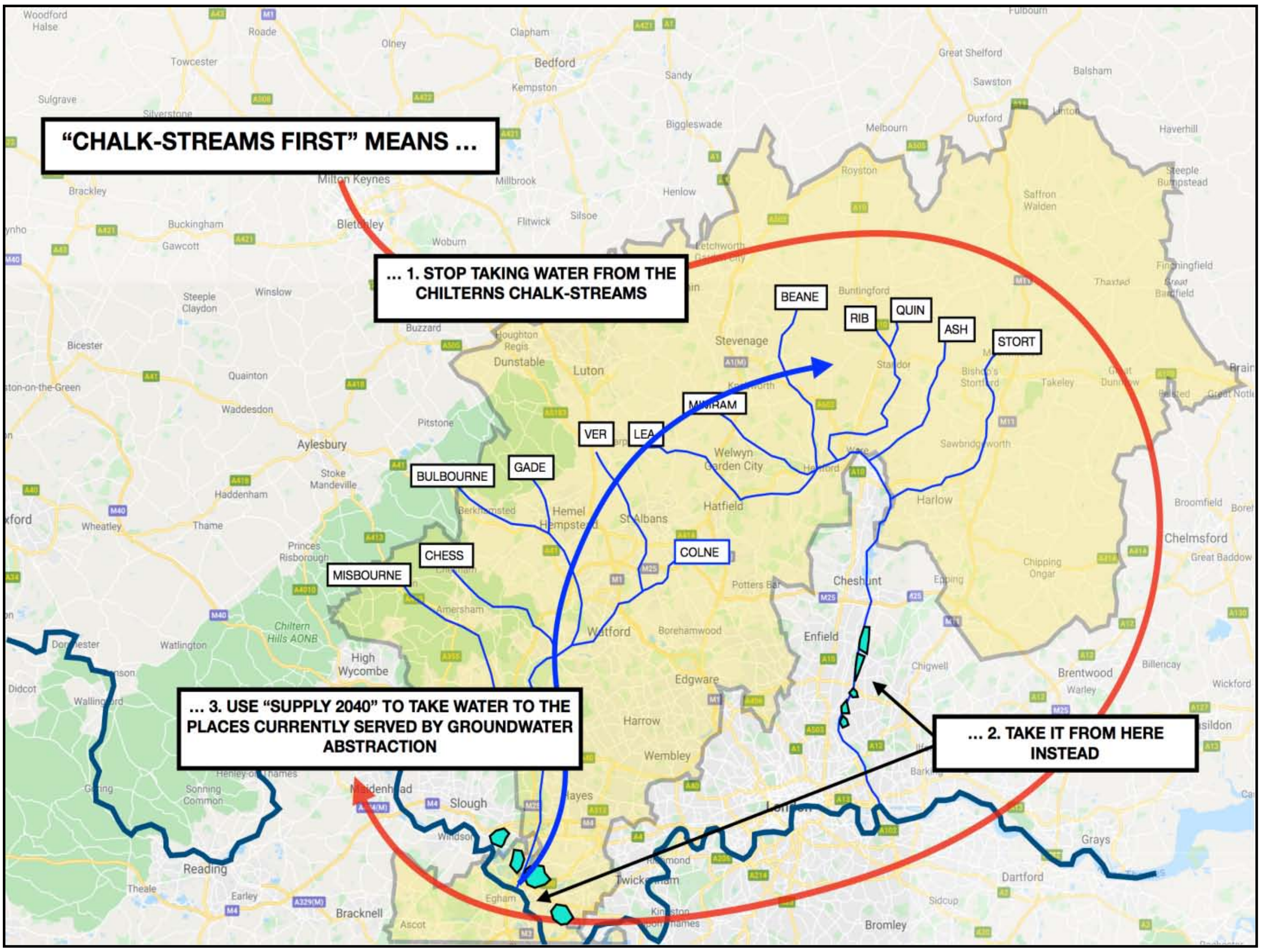

Figure 1 - The concept of the Chalk Streams First proposal

The proposed scheme involved reducing public water supply abstraction from the Chilterns chalk stream tributaries of the Rivers Colne and Lea from its present 30-40% of natural recharge (ie rain percolating into the underlying chalk aquifer) to around 10% of natural recharge. The resulting improved flows in the chalk streams would flow down to the lower Rivers Thames and Lea where the water could be pumped into the existing London reservoirs. Replacement supplies would be taken from the London reservoirs and transferred back into the Chilterns via an existing and extended network of pipelines, termed 'Supply 2040' in Affinity Water's 2019 Water Resource Management Plan.

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[1] Chalk Streams First – A Permanent and Sustainable solution to the Chilterns Chalk Stream Crisis, February 2020 https://chalkstreams.org/chalk-streams-first/

In essence, the Chalk Stream First proposal allows the chalk stream flows to be largely re-naturalised, with public water supplies taken instead from much larger and less ecologically sensitive river reaches further down the Thames catchment. The overall loss of water resource would be quite small, because the additional demands to be met from the London reservoirs would be mostly offset by the extra water available to refill the reservoirs, coming from the enhanced chalk stream flows.

The amount and timing of chalk stream flow recovery is an important consideration in the Chalk Streams First proposal. If the amount of recovery is high and a good proportion of extra water from the chalk catchments is available in droughts, there would be comparatively little additional water resource development needed. This would allow flows in the Chilterns chalk streams to be re-naturalised within a few years and at relatively low cost. If flow recovery is low, particularly in the long droughts that are critical for London's supplies, there would be a requirement for development of replacement water supplies at increasing cost, all depending on the net loss to DO supply.

The Chalk Streams First proposal suggested that about 75% of the supplies lost from the reduced chalk abstractions would be recovered via the enhanced flows reaching the London reservoirs. This figure was based on some preliminary modelling of chalk stream flow recoveries and how they would enhance London's supplies in the critical historic droughts of 1921 and 1933/34.

1.2 Current status of the Chalk Stream first proposal

The potential benefits of the Chalk Stream First proposal were recognised by the Environment Agency and Ofwat in 2020. The water companies were asked to investigate the proposal as part of the £470 million programme of investigations, supervised by RAPID (a coalition of Ofwat, the Environment Agency and the Drinking Water Inspectorate). Under this programme, plans for major new water supply schemes, termed Strategic Resource Options (SROs), are being developed and approved by RAPID for further funding by passing a series of "Gates". Plans for schemes have recently been submitted as "Gate 2" reports and included in draft statutory Water Resource Management Plans (WRMPs) which are currently out for public consultation. If the drafts WRMPs are approved by Defra, the selected schemes will be designed and submitted to a final approval process termed "Gate 3".

Specifically, Chalk Streams First was to be considered as part of the Thames to Affinity Transfer Strategic Resource Option (T2AT), which has been jointly investigated by Thames Water and Affinity Water. The findings of this investigation are covered in the Gate 2 report on the T2AT Strategic Option[2]. The outcome of the investigation has fed into the draft Water Resource Management Plans of Thames Water and Affinity Water.

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[2] https://affinitywater.uk.engagementhq.com/strategic-resource-options

The draft WRMPs cater for regional water resource deficits estimated by Water Resources South East (a consortium of the six SE water companies) and published in their draft water resource plan for the South East. Under three different scenarios these deficits allow for differing levels of reductions in abstractions to benefit river ecology – in some cases greater reductions in the Chilterns chalk streams than those proposed by Chalk Streams First.

Although there are a few brief references to the Chalk Streams First proposal in the Gate 2 report on the T2AT scheme, there is no detail of whether or how it has been included in the T2AT scheme or the various WRMPs. In particular, there is no clear statement of the amount of flow or deployable output recovery that has been assumed to arise from the planned abstraction reductions.

However, it is understood from communications with WRSE and Affinity Water that the various plans allow for only 17% recovery of river flows and deployable output at low flows and in droughts. This very low assumed recovery potentially undermines the basis of the Chalk Streams First proposal – the costs of flow re-naturalisation will rise in proportion to how much water needs to be replaced from other sources. The re-naturalisation could be delayed by the need to wait for the construction of major new water supply schemes.

1.3 Scope of investigation

There is still much uncertainty in the assessed impacts of abstraction on chalk stream flows and the recovery of flows from abstraction reductions. Some reports for the Water Industry National Environment Programme (WINEP) have expressed doubts over whether abstraction reductions have led to any flow increases.

This investigation addresses these doubts and uncertainties. The investigation has been in two stages – an interim report in October 2022 focused on case studies of the Rivers Ver, Mimram and Beane and was discussed on 27th October at a technical workshop involving Affinity Water, the Environment Agency, consultants and academics. This final report includes the River Chess case study and reviews how the Chalk Streams First proposal has been included in the various WRMPs and WRSE's plan. It also considers how the Chilterns chalk streams might be used in a drought supply scheme similar to the existing West Berkshire Groundwater Scheme.

The scope of the investigation has covered the following activities:

1. Review of evidence of measured changes in groundwater levels and chalk stream flows arising from changes in groundwater abstraction, particularly from past sustainability reductions in case studies of the Rivers Ver, Mimram, Beane and Chess.
2. Development of lumped parameter groundwater models for the four case study rivers. Use of the models to estimate naturalised flows, abstraction impacts and flow recovery from abstraction reductions.

3. Review of available Environment Agency and Affinity Water modelling of abstraction reductions and comparison with the lumped parameter modelling.
4. Review of reports prepared by Mott MacDonald and HR Wallingford for Affinity Water on abstraction reductions and flow recovery in the case study rivers.
5. Proposals for abstraction reductions to achieve acceptable flows in the case study rivers, followed by use of lumped parameter models to estimate subsequent increases in chalk stream flows and groundwater levels.
6. Review of the incorporation of the Chalk Stream First proposal in the draft WRMPs of Affinity Water and Thames Water, and in WRSE's regional plan.
7. Consideration of the potential to combine major abstraction reductions in the Chilterns chalk streams with use of the chalk aquifer storage in drought support schemes similar to the West Berkshire Groundwater Scheme.
8. Use of an existing model of the London supply system to estimate the gain in deployable output of London's water supplies arising from increased chalk stream flows following abstraction reductions.

2. Relationship between GWLs, recharge, abstraction and river flow

Note: Chapter 2 has been written collaboratively by Charles Rangeley-Wilson and John Lawson

2.1 Sources of groundwater flow and the influence of topography, stratigraphy, spring elevation and groundwater level

Chalk stream flow is dominated by groundwater-fed baseflow issuing through springs and seepages in the valley sides and within the stream channel. The sources of groundwater flow can be categorised as point-source – notable influxes of flow emanating from solution-worn fissures and fractures in the chalk – or diffuse – more akin to seepage through and from saturated ground. R B Bradford 2002 described accreting inflows along the Lambourn valley as of these two types: *'a) local point-source inputs at identifiable springs on the floodplain and through the bed and banks of the channel,' and b) local diffuse inputs … directly into the channel bed without any obvious visual expression.'* In the upper, ephemeral reaches of chalk streams, and on the valley sides, where the alluvial deposits in the floodplain are thin / absent, these diffuse sources are not confined to the stream bed.

The distribution of these sources in and between chalk valleys is not uniform. For example, distinct flow pathways may develop along hard grounds in the chalk stratigraphy creating opportunities for significant perennial influxes where these layers meet the surface. Folds and inclines in these layers under the surface may lead water away to neighbouring valleys, creating significant differences between surface and groundwater catchments, both spatially and temporally.

In high groundwater conditions ephemeral streams may develop and continue far up the valley, arising through saturated ground and varying in linear length in relationship to the rise and fall of the groundwater level in the valley. Spring sources will switch on and off at varying groundwater levels, depending on their relative elevation.

The relationship between the dip of the stratigraphy and the river's direction of flow will also influence the relationship between groundwater and surface flow. Scarp-slope streams tend to rise where the oldest strata of chalk meet less impermeable, underlying layers of clay, mudstone and greensand: in these settings the streams may have a relatively fixed linear length and a perennial source.

Dip-slope streams – the "classic" chalk stream type – tend to rise on chalk and flow over chalk and in the same direction as the dip of the chalk stratigraphy underground. Undulations in the layering of the chalk and hard-grounds may force water to the surface only to fall away again in a downstream direction, meaning a stream may naturally gain, then lose flow.

Towards their lower reaches dip-slope streams tend to flow from the chalk onto progressively younger layers which have been deposited over the chalk. These younger surface layers can influence the connectivity between the chalk aquifer and the stream. But the proportion of the stream that flows over chalk can vary greatly: the Chess for example flows over chalk for its entire length, whereas the Wandle steps off the chalk onto London clays, silts and sands almost immediately downstream of its source in Carshalton. Variations like these will influence how a given stream acquires and retains (or loses) flow and the varying proportional split between water leaving the valley as surface flow in the stream or aquifer through-flow.

Different streams draining the same aquifer may rise and flow at different elevations, meaning the timing of the rise and fall of their flow patterns can vary in time with the rising and falling groundwater levels.

However, in spite of the many variations that might exist from one valley to the next between surface topography, bedrock stratigraphy and superficial deposits, the overarching driver of baseflows in chalk streams is the groundwater level relative to the springs and river bed stage level at any given point, as shown in Figure 2[3]:

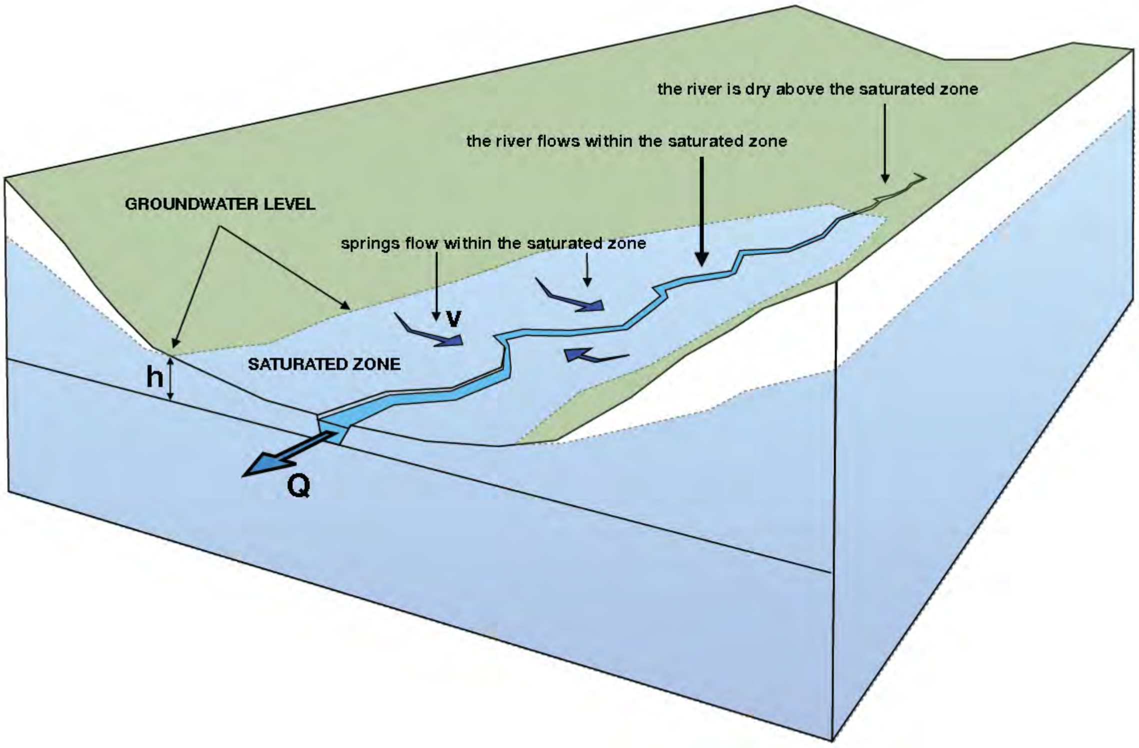

Figure 2 - Schematic representation of a typical chalk valley

As groundwater levels rise, so does the physical force of gravity (hydraulic head) driving water to the springs and seepages in the valley and stream below. In addition, as groundwater levels rise, so more and more springs start to spill water from the aquifer to the stream.

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[3] Diagram from page 36 of the CaBA Chalk Stream Strategy https://catchmentbasedapproach.org/learn/chalk-stream-strategy/

Figure 2 represents an idealised dip-slope chalk stream valley to show simply how a chalk stream flows within the saturated zone where the aquifer water-table intersects with the surface topography and the water emerges as springs and seepages in the valley sides and in the stream itself. In the upper reaches of a typical classic chalk-stream valley, the upper boundary of the saturated zone moves up and down the valley with the rising and falling groundwater level. This creates ephemeral winterbournes, which usually flow only in winter and spring.

Chalk aquifer groundwater level rises and falls through the year as the aquifer fills and then slowly empties. Typically, the groundwater level rises in the wetter months from November through to April when the air is cool, evapotranspiration is at a minimum and a higher proportion of the rainfall sinks into the ground; and it falls through the summer when evapotranspiration reduces percolation to the chalk, while the groundwater continues to discharge to the river and the down-slope aquifer. Therefore chalk-stream flows tend to be at their highest in late spring and lowest in the early autumn.

Groundwater abstraction notwithstanding, the total amount of winter rainfall and how much of it sinks into the ground (known as 'effective rainfall') largely determines the volume of river flows during the following summer. If groundwater levels are high in the spring after a good winter recharge, then (natural) flows will hold up well through the summer. If groundwater levels are low in the spring after a dry winter, then generally the chalk stream will be very low by the end of summer.

2.2 The non-linear relationship between groundwater level and river flows in chalk streams

While the driver of chalk-stream flows is groundwater level relative to spring and river-bed level, the relationship between groundwater level and river flows appears to be non-linear: ie. the flow rises exponentially relative to rises in groundwater level (each unit rise in groundwater level generally leads to an increasingly large unit rise in flow).

Foster (1974)[4] showed examples of non-linear flow recession curves in the Yorkshire chalk streams of the Hull catchment. When the river flow data were correlated to groundwater levels he found the relationship was non-linear, contrary to what would have been expected “had the aquifer behaved as a simple linear storage reservoir”. Foster interpreted the apparent steps in the recession as a series of linear sections caused by stratification in the chalk aquifer.

Bradford (2002)[5] examined recession of river flow in the Pang (Berkshire) and showed the

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[4] Foster, S.S.D, 1974, Groundwater storage - river flow relations in a chalk catchment, Journal of Hydrology, Volume 23, Issues 3-4, 299-311

[5] Bradford, R.B., 2002, Controls on the discharge of Chalk streams of the Berkshire Downs, UK, The Science of the Total Environment, 282-283, 65-80

relationship between groundwater level (measured at five observation boreholes) and flow at Frilsham gauging station: these showed the same non-linear relationship between GWL and flow and also – unsurprisingly – that the rises in groundwater level are more marked with distance from the river.

A non-linear GWL-flow relationship has been observed in other countries in non-chalk settings. For example, on the Gellibrand river in Victoria, Australia, Costelloe et al (2014)[6] observed an increasingly non-linear relationship between stream flow and groundwater levels as groundwater levels rose in response to recharge. Costelloe investigated whether the non-linear behaviour coincided with a non-linear increase in the intersection of the land surface with the water table, (i.e. leading to increased groundwater discharge into small tributary streams draining the valley slopes). However, the groundwater table mapping in the Gellibrand catchment suggested relatively small changes in the percentage of saturated area intersecting the land surface between high and low groundwater conditions and he concluded that interflow within and from upper catchment groundwater, persistent perched aquifers or spatially discrete zones of regional groundwater discharge was the more likely driver of non-linear flow response.

In northern Sweden, Hinzman et al (2020)[7] observed an increasing non-linearity in storage-discharge relationships over time (1950 to 2018) in 16 catchments, hypothesising that as seasonally frozen soils thaw and recede in extent as a response to global warming trends, flow path diversity and thus hydrologic connectivity increases. This enhanced hydrologic connectivity then increases the non-linearity of the storage-discharge relationship in a catchment. On the face of it, stream response to thawing in Arctic streams might not obviously relate to groundwater-flow relationships in chalk streams, but the hypothesised role of the increasing flow-path diversity could well correlate with, for example, changes in fracture density with depth (see Soley ref below) in the chalk as a factor in the non-linear relationship. The comparison with Costelloe's hypothesis of increasing interflow is also worth making.

2.3 Possible explanations for the non-linear relationship between groundwater level and river flows in chalk streams

In seeking explanations for non-linearity, it is interesting to note that in New Zealand a review of Environment Southland's spring gauging programme (2012)[8] recorded relatively linear correlations between groundwater level and river baseflows in a number of spring-supported streams. R^2 values varied between 0.4 and 0.9 with the best correlations (greater than 0.7) in the Meadow Burn and Brightwater, both of which arise from highly permeable

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[6] Costelloe, J.F. 2014. Can Seasonal Groundwater Level Rises Explain Non-linear Increases in Baseflow? HWRS

[7] Hinzman A.M. 2020. Increasing non-linearity of the storage-discharge relationship in sub-Arctic catchments. Hydrological Processes. 2020;34:3894–3909

[8] Environment Southland's spring gauging programme - Review and recommendations for future modelling. Liquid earth April, 2012.

aquifers with limited quick-flow and where groundwater levels rise and fall almost simultaneously across the entire aquifer. In the case of the Brightwater the aquifer is a deep single-sided terrace of gravel at the foot of mountains on the east side of the Mataura valley, the Brightwater being a tributary. The Brightwater arises, therefore, as a series of perennial springs at the foot of the terrace. It is less than I km in length. The Brightwater's flow variance is narrowly confined between -12% and +30% percent of the median discharge (1,640 l/s) over 11 years of recording, reflecting the almost total dominance of base-flow in the system. A possible explanation for the apparently linear relationship here between groundwater level and flow might be the topography of the Brightwater aquifer which, being a single-sided terrace of highly permeable material, acts on stream flows much as a 'linear storage reservoir*' would. (*as described by Foster in his paper on the River Hull). If so, then perhaps the differences between this topographical / aquifer setting and that of the typical English chalk stream might point to the reasons behind the non-linear relationship in chalk streams?

Foster hypothesised that stratification in the aquifer would be a neat explanation for the apparent steps in flow recession rates.

If the non-linear response to changing rates of abstraction is an inverse of the non-linear relationship between groundwater level and flow, there is some correlation between Foster's hypothesis and those advanced by Karapanos et al in the paper, 'Evidence of layered piezometry system within the Chalk aquifer in parts of SE England', where the authors describe a layered stratigraphy in the Chalk with restricted hydrological connectivity between layers caused by marl bands of regional extent. The authors refer to field observations which suggest that groundwater level and river flow responses to changes in abstraction are highly variable across the flow range.

Bradford didn't offer an explanation for the non-linear relationship in the River Pang.

Costelloe (for a non-chalk setting) hypothesised a non-linear increase in the spatial extent of the saturated zone as groundwater levels rise, but preferred the explanation of exponential rises in interflow within and from upper catchment groundwater storage areas.

Hinzman, also in a non-chalk setting, hypothesised an exponential increase in flow pathways caused by meting permafrost, which has some correlation with Costellos's preferred explanation.

The first two of these hypotheses (Foster and Karapanos) and others were discussed at a chalk groundwater workshop convened by CaBA and hosted at Affinity Water in October 2022.

At the conference and in correspondence afterwards R. Soley proposed that a highly significant contributory factor is the variable fracture density in the chalk with depth and also laterally between syncline and interfluve: ie. that deep chalk is generally relatively impermeable (note: like frozen ground) – its permeability being mostly a function of fracturing, folding and dissolution flow – but is much more permeable around the low water table elevation and above in the more fissured layers which fill as groundwater levels rise with recharge. It is also more permeable below the water table in valleys/dry valleys with long histories of groundwater flow, or where karstic horizons create flow paths to deeper depths – provided there is a means for the water to exit the aquifer lower down the slope through folded, faulted or artesian borehole pathways. In other words the Chalk's ability to absorb / retain recharge is not evenly distributed and it increases with elevation, or in areas which easily drain and fill.

At the onset of recharge the aquifer fills – through this unevenly distributed fissure network – as the capacity of the perennial springs to convey flow is exceeded by effective rain reaching the aquifer. Springs rise further and further up the winterbourne valleys as well as spreading across the valley floor and sides, which in turn speeds up the aquifer response time because there is a shorter distance for groundwater flow between the interfluve recharge locations and the winterbourne spring exit points than during summer when the groundwater system generally has a lower transmissivity and water has further to go to get to the perennial springs. The local specifics of drift cover, glacial history, folding, faulting and stratigraphy and less dissolvable marls and flint seams all influence how this general 'flow under natural gradients' story is played out locally.

Soley's explanation, therefore, combines aspects of all the previous hypotheses (but mostly encapsulated in both of Costello's non-chalk explanations), with the primary drivers being the heterogeneous spatial and vertical distribution of the fissure density combined with the increasing spatial extent of the saturated zone bringing more and more spring heads into play as the groundwater level rises. It may be that in chalk settings, especially on the dip slope with their typically long ephemeral sections, there is a greater capacity for expansion of the spatial extent of the saturated zone than on the streams Costelloe studied.

The Chalk Streams First lumped parameter model described in Section 2.4 of this report is based on a variation on this second part of the Soley explanation (but in its formulation effectively accommodates both components), proposing that in simple geometric terms as groundwater levels rise above the stage elevation of a given point on the river bed (h) in a typical chalk stream valley (assuming a V-shape), so the area of the saturated zone increases proportional to $h^{2:}$ ie. a doubling of the head of the groundwater level above the river bed equates to a four-fold increase in the area of the saturated zone. This is illustrated in Figure 3.

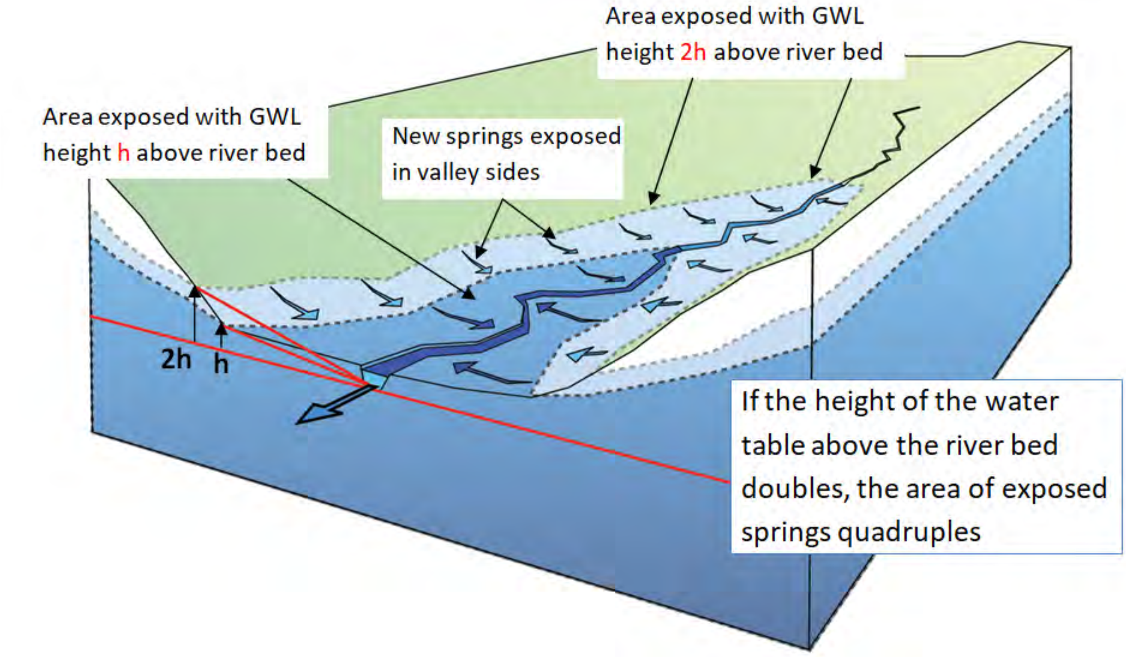


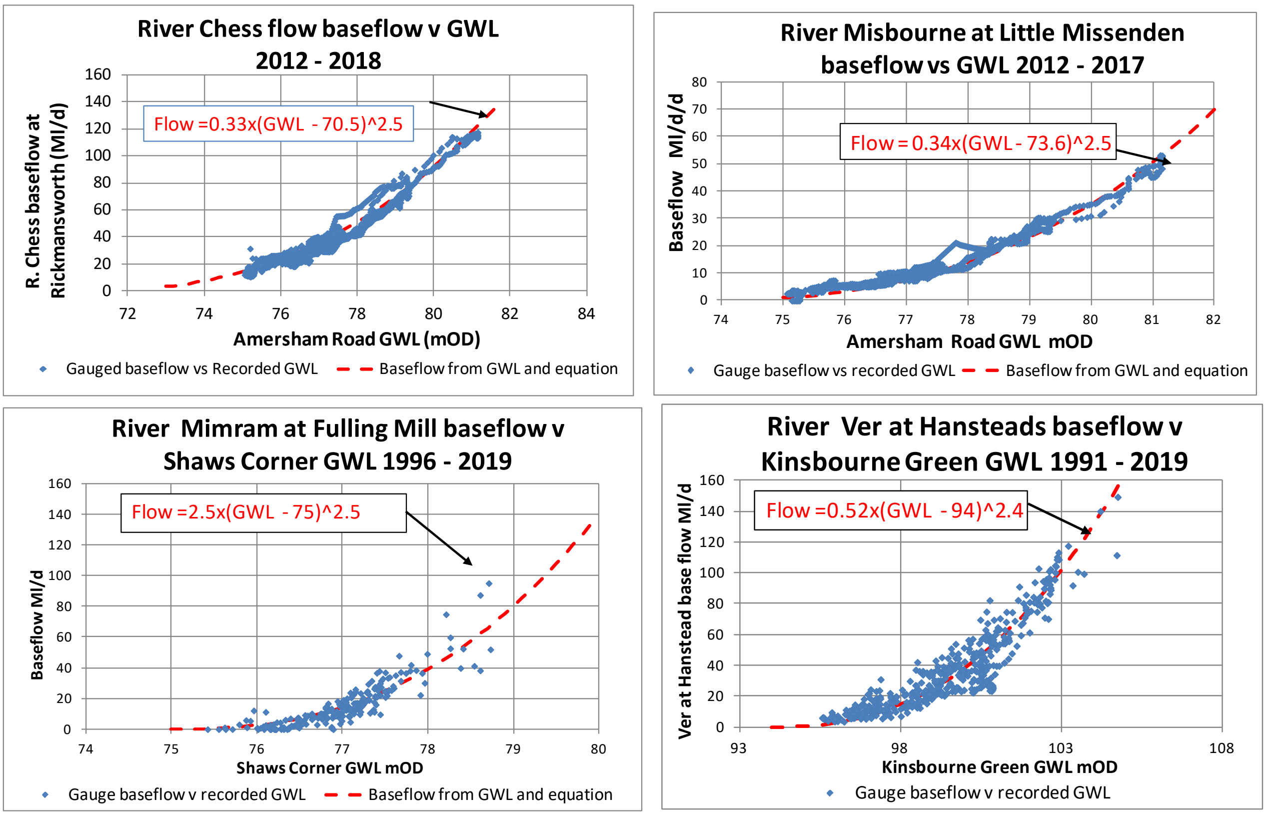
Figure 3 - Effect of rise in water table on extent of flowing springs

If the head of the groundwater (h) drives the velocity of water (v) leaving the springs, basic fluid mechanics shows that the velocity of outflow from a fissure is proportional to $\sqrt{h}$ (from $v=\sqrt{(2gh)}$, where g is gravity). With the increase in the proportional area of flowing springs proportional to h^2 the total spring outflows could be expressed as proportional to $\sqrt{h} \times h^2 = h^{2.5}$.

On this theoretical basis, the baseflow in a chalk valley would comply with an equation in the form of baseflow = a x $(GWL – b)^c$, where 'a' is a constant which encapsulates the properties which govern the permeability, transmissivity and storativity of the aquifer, 'b' is a fixed altitude somewhere in the valley bottom, and 'c' is a constant related to the shape of the valley, the spatial increase in the saturated zone and the increasing number of spring heads / volume of spring flow and the general increase in aquifer response time as GWLs rise, but generally close to 2.5.

In other words, the constants within the CSF formula are capable of accommodating both parts of the consensus of explanations of non-linearity which might be summarised as a) the topographical shape of the valley and spatial extent of the saturated zone and b) aquifer properties including spatial variations in permeability, transmissivity and storativity.

Figure 4 below shows examples of measured river baseflows and GWLs following this type of relationship in various chalk valleys, with the constants a, b and c determined by trial and error to fit to the observed data: this close relationship between river flows and groundwater levels, typically providing R^2 values in the region of 0.9 on plots like those in Figure 4, appears common to all chalk streams. Similar relationships have also been observed on the rivers Kennet, Test, Tarrant and Nar, and noted elsewhere by others.



Note: 1. Baseflows derived from gauged flows using baseflow separation software
2. Plotted baseflows usually lead GWLs by 2-3 weeks

Figure 4 - Examples of gauged baseflow vs GWL in chalk catchments

The closeness of the scatter plot fits shown above for the Rivers Chess and Misbourne suggests that river and spring flows in these catchments are almost entirely driven by the concepts of a) water table head driving flow, and b) the increasing area of outcropping springs as the water table rises, and other non-linear components such as fracture density (as above) – as illustrated in Figure 3. The increased scatter shown on plots for the Ver and Mimram suggests other factors additionally at work, for example an increasing quick-flow component deriving from deeper periglacial deposits. However, overall the Colne and Lea chalk streams appear to conform well to these concepts, as illustrated by the closeness of fits of CSF modelled flows and GWLs to recorded data, as described in Section 2.3 and illustrated on Figure 6.

Water balance, groundwater levels and the impact of abstraction

A simple way to understand the macro-scale impact of groundwater abstraction on chalk-stream flow is via the concept of water balance. Over time, in a chalk catchment without abstraction, recharge of the aquifer from rainfall equals discharge from the aquifer through stream-flow, in addition to the smaller components of flow of water underground through the aquifer (known as through-flow).

This is the basic idea in Theis's foundational 1940 groundwater paper, in which he wrote that with an aquifer-fed river system over time recharge must equal discharge, and so if you add a new form of discharge (abstraction) the former natural discharge (the river flow) must reduce to compensate and maintain the aquifer water balance. There is only one way, Theis wrote, of reducing flow in the areas of former natural discharge and that is via a reduction in the saturated thickness of the aquifer: “a lowering of water everywhere between the wells and the areas of natural discharge or recharge” (he added recharge, because technically if you lower water levels in an aquifer you can pull more water down into it).

Theis described the means whereby the former natural discharge is captured, “the lowering of the water”, via what he called the cone of depression around the abstraction well. The shape of the cone, he wrote, is determined by the properties of the aquifer, specifically the ease with which water can be drawn into the well (the transmissibility of the aquifer) and by the amount of water, per cubic unit, the aquifer releases as the head is lowered by pumping (the coefficient of storage). Once pumping starts the cone deepens and widens as water is removed from storage. Over time the cone of depression affects more and more distant parts of the aquifer. While the storativity and transmissibility of the aquifer determine the rate of lateral growth and the shape and depth of the cone, the radius of its impact is prescribed only by time: in other words the cone will keep on spreading until the abstraction is able to prevent the equivalent-to-pumping-rate volume of water from leaving the aquifer via the former routes of natural discharge.

Traditionally water level reduction within the cone of depression is conceptualised as diminishing to become effectively zero at some distance from the well, with the cone nested within an aquifer whose spatial expanse extends beyond the cone.

However, the close fit between CSF modelled and recorded ground-water levels and stream flow in the extensively abstracted chalk-stream valleys of the Chilterns suggests that in these catchments water-level drawdowns have occurred on a catchment-wide scale. It is proposed that this is the result of a combination of factors including the relatively low storativity and high transmissivity of the chalk, the multi-decadal duration of abstraction impacts, the numbers and distribution of abstraction pumps whose drawdown impacts become superimposed onto each other and the non-linear relationship between groundwater levels and flow in these chalk-stream catchments, meaning that abstraction would not prevent enough water (to compensate the Theis water balance) from leaving the aquifer if the water level drawdowns were not regional in extent. In other words it is proposed that the conventionally conceived cones of depression nest within a more extensive regional zone of drawdown or water-level decline.

2.4 Relative effects of cones of depression and aquifer water balance changes

The aquifer properties of transmissibility and storativity determine not just the size and depth of the cone of drawdown, but also the timing and dynamics of the capture of flow, depending on where the abstraction is sited relative to the stream. Theis’s principles of water balance are fundamental in that abstraction must impact former discharge *somewhere* and at *some time*, but the where and when will vary depending on the location and size of the abstraction relative to the location and (varying) rate of stream flow.

Some groundwater abstractions will intercept water that would otherwise, almost instantaneously, become stream flow. With others, the impact on stream flow can be delayed and higher in winter than summer, when that abstraction source draws proportionally more on storage than flow.

Within the conventional concept of the cone of depression, the means by which abstraction captures the former natural discharge are divided into a) interception of aquifer flow that would otherwise have contributed to the former natural discharge via springs and seepages and sometimes b) induced infiltration from the stream itself (a form of induced recharge of water which has already left the aquifer).

The cone of depression which forms around the pumping well intercepts the lateral, down-gradient flow of water from the aquifer to the stream and lowers (but does not necessarily invert) the hydraulic gradient of the water table at the aquifer/stream boundary. In some cases, however, the pumping rate can be large enough to capture water from the stream itself by creating a negative hydraulic gradient beside and under the stream.

Since a constant abstraction will inevitably become a larger and larger proportion of seasonally diminishing stream-flow, and depending on the rate of pumping versus aquifer recharge and flows in the stream, the ratio of capture between intercepted groundwater flow, induced infiltration from the stream and aquifer storage is dynamic. If the stream flow falls below the pumping rate, the abstraction will have to draw on storage.

If the stream-flow reduces to zero (as it does in a winterbourne), the abstraction will then have to wholly rely on the capture of storage, which becomes a debt to future flows. In this sense it can be seen that the ratio of capture between storage and discharge can and does vary over time, even after the initial period of aquifer reset which a new abstraction creates (typically two years).

Otterbourne, beside the lower River Itchen is an example of a stream-side groundwater source whose impact is an effectively instantaneous and direct interception of flow that would otherwise reach the river. When abstraction is switched off, flow returns to the Itchen within 2 to 3 days. Here, the flows almost always exceed the rate of pumping and so the abstraction forms a direct reduction of flow and a proportionally greater % of flow as flows recede: hence it is controlled by the Itchen hands-off-flow licence.

Other chalk groundwater sources, such as that on the Candover / Wey watershed, are sited a long way from the perennial springs of either stream and the cones of depression will have little if any impact on groundwater levels near the springs. These boreholes will have a differently timed and proportioned impact on chalk stream flows: drawing water largely from storage and thus affecting discharge and the aquifer water balance, so that groundwater levels rise less during recharge and fall more during the summer recession in the manner described in Section 2.1 and illustrated in Figure 2. These boreholes will affect river flows through general lowering of groundwater levels that drive spring flows, but with virtually no direct impact on flows via their cones of depression – the opposite of the Otterbourne stream-side source.

Both modelling and field evidence indicate that *at the catchment scale* groundwater abstraction generally has a larger impact on high flows than on low, suggesting that the non-linearity of the groundwater to flow relationship must be of underlying importance and that groundwater abstraction must impact the aquifer water balance and groundwater levels on a catchment scale and not just within the conventionally conceived cones of depression.

2.5 The significance of short-term pumping switch-offs (signal tests)

The relative effects of cones of impression and aquifer impacts are picked up by 'signal tests' – measuring the recovery of GWLs and river flows when borehole abstractions are switched off, typically for a duration of a few weeks. If the signal tests show substantial changes in river flows in a similar period to the changes in GWLs, this shows that the localised cones of depression are significantly influencing flows. However, signal tests of a few weeks' duration will not pick up changes to the aquifer water balance because it generally takes about 2 years for the water balance to fully reset after ceasing abstraction. Examples of this are shown for the Ver and Mimram case studies in Appendices A and B (see figures A17 and B24 and the accompanying text).

In the case studies for the Ver, Mimram, Beane and Chess described in the appendices, the signal tests generally showed substantial localised recovery in GWLs but little if any influence on river flows. This suggests that the influence of the cones of depression on river flows in these rivers is mostly small compared with the impacts on the water balance and the regional groundwater levels.

An exception to this was the Chesham signal test that showed a flow recovery of 58% of the reduced abstraction, as shown on Figure D24 of Appendix D and described in the accompanying text. This shows that the cone of depression from the Chesham abstraction, located close to the river channel, does affect river flows directly. Conversely, the relative lack of flow recovery shown by several other signal tests in the case-study rivers shows that in these cases the cone of depression alone was not sufficient to capture the rate of abstraction from aquifer discharge. In these cases the abstractions must have also caused - over time - a regional lowering of groundwater levels, and therefore the same time is demanded for a regional recovery in groundwater levels before flows can also fully recover.

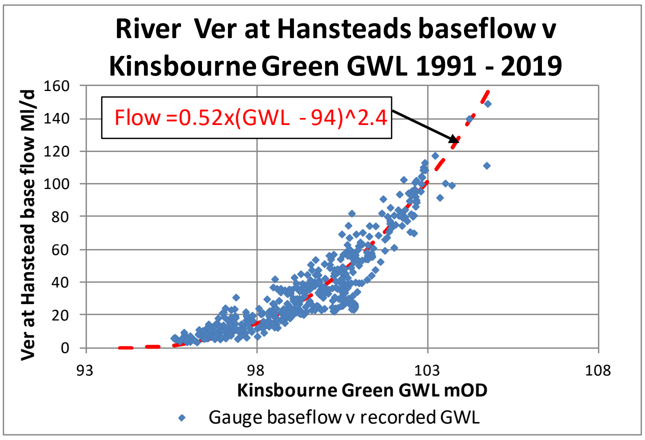
Evidence to support the relative insignificance of cones of depression in the Colne and Lea tributaries is the excellent fit of the CSF modelling with recorded data, even though the CSF model does not take any account of borehole locations and their cones of depression.

2.6 The varying % impact of abstraction on flow

It has been observed that, during droughts, flow recovery from an abstraction reduction is much lower than the amount of the abstraction reduction. At high GWLs in winter, flow recovery can be substantially more than the abstraction reduction. Examples of this can be seen in the measured flow recoveries from abstraction changes for the River Ver, as shown in Section 3.2. It can also be seen in measured relative changes in flow and abstraction for the Rivers Chess and Ver and for the Beane and Rib – see Sections 3.3 and 3.4.

The reduced flow recovery in droughts can be readily explained mathematically by the non-linear relationship between groundwater levels and river flows in the form of the equation $baseflow = a\ x\ (GWL - b)^{c}$, where c is typically about 2.0 to 2.5, as described earlier, with examples in Figure 4. Assuming that changes in GWL are directly proportional to changes in aquifer inflow or outflow, the rate of change in flow with change in GWL is proportional to $(GWL\text{-}b)^{c-1}$: since c>1 then there will always be greater reduction in flow for higher GWLs.

This can be illustrated for the River Ver as shown below:



Assuming flow = 0.52x(GWL - 94)^2.4

GWL change	River flow change
From 95 to 96 mOD	2.2 Ml/d increase
From 96 to 97 mOD	4.5 Ml/d increase
From 97 to 98 mOD	7.2 Ml/d increase
From 98 to 99 mOD	10.3 Ml/d increase
From 99 to 100 mOD	13.6 Ml/d increase

Figure 5 - Explanation of low flow recovery from abstraction changes in droughts

Put more simply, as can be seen in the chart above, rises in GWL yield higher and higher amounts of flow per unit of rise. It therefore follows that a unit reduction from high GWLs causes a significantly greater reduction in flows than the same unit reduction from low GWLs. The variability of flow recovery from abstraction reductions, depending on prevailing GWLs, is simulated by the CSF lumped parameter modelling, as shown later in this report.

In chalk stream catchments, as discussed above, the relationship between groundwater level and flow is non-linear. For all the reasons set out – which can be summarised as a) heterogeneous aquifer properties of various sorts and b) catchment topography and the spatial extent of the saturated zone – flow climbs exponentially as groundwater levels go up. This actually means that abstraction has a smaller impact on low flows than high: the opposite of what most people would imagine.

In some reports and papers this is described as if the abstraction has less actual impact on flows at low flows. And when the groundwater level drops below the river bed and therefore the river is dry, those same reports and papers state that the abstraction can no longer be having an impact on flow – because there is no flow. This is misleading and ignores the component of time.

What this ‘lesser impact at low flows’ means, in effect, is that when groundwater levels reduce to below a given point, the abstraction must progressively start to take water from aquifer storage. The abstraction is still removing water from the aquifer and still lowering the groundwater level, but this lowering has no (or much less) effect on flow at that location … at that time.

The impact will still ultimately be exerted on flows and the aquifer still conforms to Theis’s principle that over time discharge (of whatever sort) cannot exceed (or be less than) recharge. Abstraction at low flows is in fact <u>an accumulation of debt to future flows</u>: over the full flow cycle the impact of abstraction on aquifer outflows will be exactly 100% of the abstraction rate. In reality, the impact on surface river flow is less than 100% because water also leaves the aquifer via other routes – throughflow in the chalk within the valley and, in some cases, into adjacent chalk valleys.

2.7 The CSF lumped parameter model

The relationship between GWLs and flows described in Sections 2.1 to 2.3 is used in the Chalk Streams First (CSF) lumped parameter model. The model was developed originally for assessing abstraction impacts on the River Kennet and then used to assist in the promotion of the CSF proposal for re-naturalising flows in the Chilterns chalk streams. The model is described in Appendix E to this report. The principles behind the CSF model are:

a) that chalk stream baseflows are driven by the hydraulic head of the regional water table, as shown schematically in Figure 2, and by the relationship between river flows and groundwater levels shown in Figure 4.

b) that the hydraulic head of the water table is determined by the aquifer storage within the catchment, which rises due to recharge from rainfall and falls due to river outflows, throughflows (within the aquifer) and abstraction.

The CSF model gives good fits between modelled and observed historic flows and GWLs. An example is given below for the River Ver model (selected because there is available flow gauge data for winterbourne sections of the Ver):

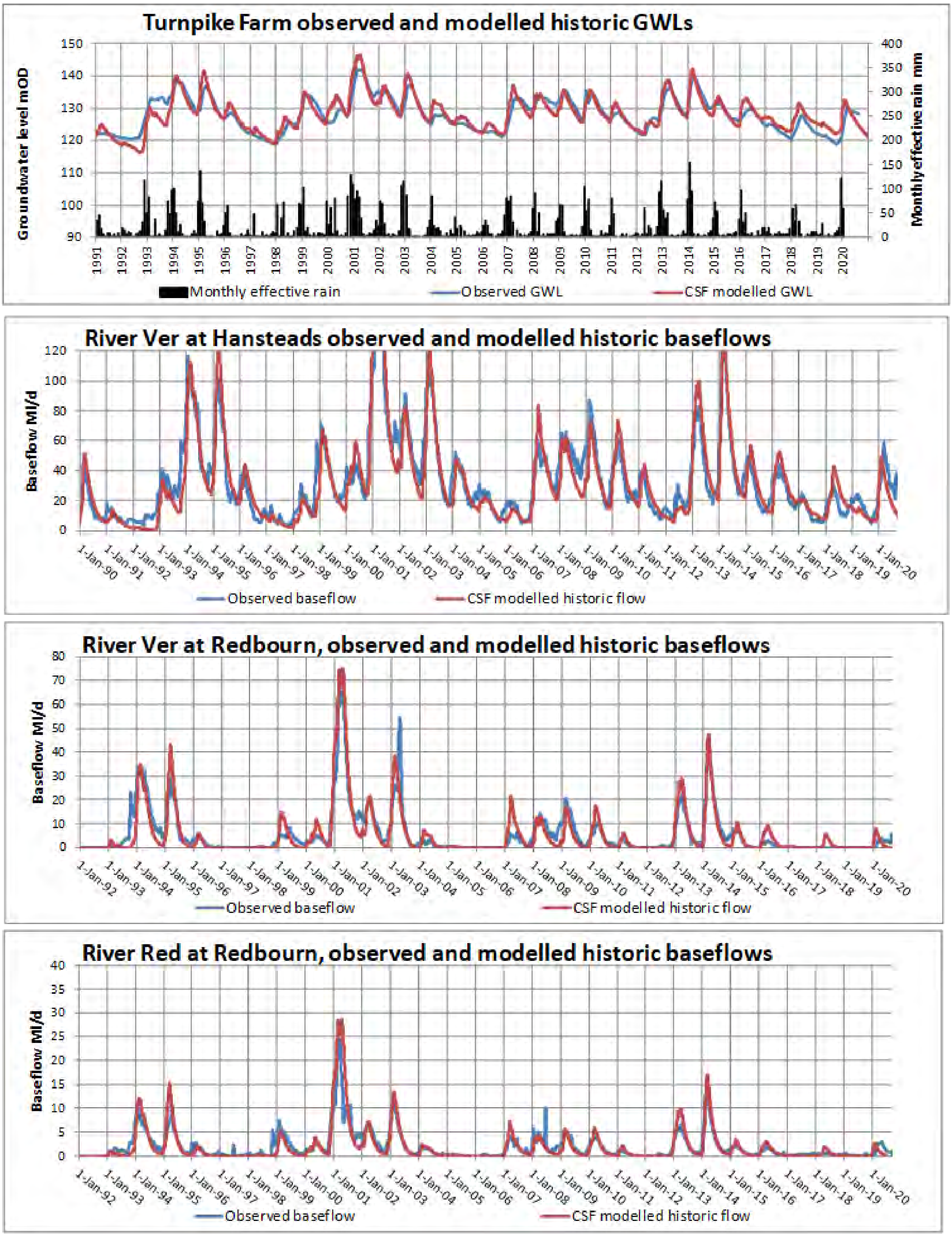


Figure 6 - CSF model validation plots for the River Ver catchment

Validation data for the Mimram, Beane and Chess versions of the CSF model are shown in the report appendices.

The CSF model computes the daily aquifer storage within the catchment by simulating the water balance of recharge from effective rain and outflows from river flow, throughflow and abstraction.

The daily aquifer recharge is calculated from the daily effective rainfall records for the catchment, as provided by the Environment Agency or water company, with an arbitrary allowance for time lag of up to 30 days (see more details in Appendix E). The daily computed aquifer storage is converted into daily GWLs at an observation borehole location within the catchment, using a specific yield set to give a best fit of modelled daily flows and GWLs. River baseflows are calculated from the modelled GWLs using formulae like those shown in Figure 4, with no allowance for lead or lag. Underflows are calculated using formulae based on Darcy's Law.

Despite the simplicity of the concepts underlying the CSF model, not taking account of borehole locations and ignoring the local effects of cones of depression, the CSF models of the Colne and Lea tributaries gives mostly excellent fits between observed and modelled GWLs and base flows. This suggests that in these catchments the relationships between GWLs, river flows and abstraction are dominated by the effect of abstraction on the aquifer water balance rather than localised impacts of the cones of depression or the detailed hydrogeology surrounding the boreholes.

2.8 Abstraction as % of recharge (A%R)

Groundwater abstraction as a % of recharge (A%R) has been proposed as a simple and easily comprehensible way to assess the amount and acceptability of groundwater abstraction in a catchment. A recent report on A%R suggests that, as a minimum target for sustainable chalk stream flows, abstraction in a chalk catchment should not exceed 10% of groundwater recharge in the catchment (A10%R)[9]. Keeping within 10% would get close to the EFI for ASB2-3 (see below) in most chalk catchments, although 5% would be a better fit for the CSMG standards applied to designated rivers. It has been proposed that the A%R target would protect the upper and winterbourne reaches of chalk streams more effectively than EFI, which is often measured at the water-body boundary and downstream of major discharges which might benefit only a small proportion of the stream.

The assessed values of A%R for about 55 selected chalk streams across the country are shown in Figure 7:

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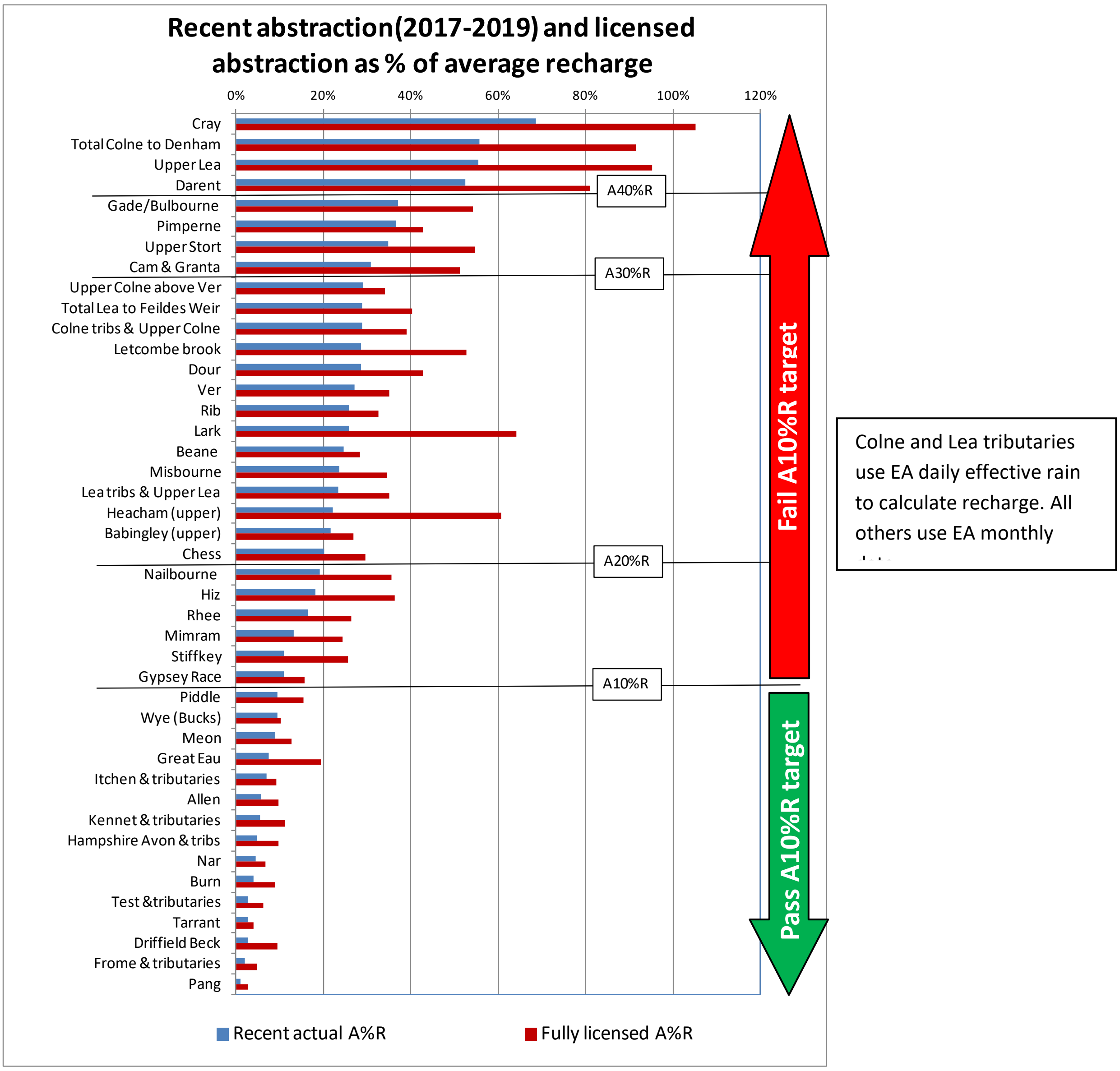
[9] A%R, Abstraction as a % of recharge in chalk streams, page 7, December 2021 https://chalkstreams.org/ar-abstraction-as-a-of-recharge-in-chalk-streams/



Colne and Lea tributaries use EA daily effective rain to calculate recharge. All others use EA monthly

Figure 7 - Values of A%R in 55 selected chalk streams

Most of the well known Wessex chalk streams meet the A10%R target, but there are widespread failures elsewhere, particularly in the chalk tributaries in the Colne and Lea catchments, as shown in Table 1:

	Misbourne	Chess	Gade/ Bulbourne	Ver	Upper Colne above Ver
Catchment area km^2	95.0	105	184	132	183
Baseflow index	0.90	0.95	0.88	0.88	#N/A
Av. annual recharge	78.3 Ml/d	67.3 Ml/d	96.5 Ml/d	85.5 Ml/d	118.5 Ml/d
Abstraction in 2017-19	17.5 Ml/d	16.5 Ml/d	53.4 Ml/d	28.1 Ml/d	41.5 Ml/d
Abstraction as %recharge	22.3%	24.6%	55.4%	32.8%	35.0%
Reduction to achieve A10%R	**9.6 Ml/d**	**9.8 Ml/d**	**43.8 Ml/d**	**19.5 Ml/d**	**29.6 Ml/d**
GW consumptive licence total	25.6 Ml/d	24.2 Ml/d	78.0 Ml/d	36.3 Ml/d	48.7 Ml/d
Licence A%R	32.7%	36.0%	80.8%	42.4%	41.1%
Licence reduction for A10%R	**17.8 Ml/d**	**17.5 Ml/d**	**68.3 Ml/d**	**27.7 Ml/d**	**36.9 Ml/d**

a) Colne chalk tributaries

	Upper Lea (to Water Hall GS)	Mimram	Beane	Rib & Quin	Ash	Stort
Catchment area	150 km2	136 km2	175 km2	152 km2	89 km2	280 km2
Baseflow index	0.82	0.93	0.76	0.60	0.55	0.48
Av. annual recharge	87.1 Ml/d	79.0 Ml/d	101.6 Ml/d	88.2 Ml/d	51.7 Ml/d	162.5 Ml/d
Abstraction in 2017-19	48.4 Ml/d	10.4 Ml/d	24.9 Ml/d	22.9 Ml/d	1.2 Ml/d	25.0 Ml/d
A%R in 2017-19	55.6%	13.1%	24.5%	25.9%	2.4%	15.4%
Reduction to achieve A10%R	**39.7 Ml/d**	**2.5 Ml/d**	**14.8 Ml/d**	**14.0 Ml/d**	**0.0 Ml/d**	**8.8 Ml/d**
GW consumptive licence total	82.9 Ml/d	19.2 Ml/d	28.7 Ml/d	28.7 Ml/d	4.8 Ml/d	35.6 Ml/d
Licence A%R	95.2%	24.4%	28.3%	32.6%	9.2%	21.9%
Licence reduction for A10%R	**74.2 Ml/d**	**11.4 Ml/d**	**18.6 Ml/d**	**19.9 Ml/d**	**0.0 Ml/d**	**19.4 Ml/d**

b) Lea chalk tributaries

Table 1 - A%R and reductions needed for A10%R in Colne and Lea chalk streams

This illustrates the scale and location of abstraction reductions needed to achieve acceptable flows in the Colne and Lea chalk streams.

3. Measured impacts of abstraction on river flows

3.1 The difficulty of measuring abstraction impacts

Groundwater abstraction impacts can be a combination of the local effects of the cones of depression (or direct hydraulic connection to a nearby river) and the accumulated impacts via the aquifer water balance. Although it may be feasible to measure the local and downstream effects of cones of depression through short duration pumping switch-offs (‘signal tests’), impacts from changes to the aquifer water balance are more difficult to measure because they take a long time to build up, so are difficult to separate from seasonal weather-related changes.

Short pumping switch-offs, combined with local monitoring of river flows and GWLs, can be expected pick up any impacts arising from the cone of depression of the borehole or a direct hydraulic connection to a nearby river.

However, short duration switch-offs are not an effective way of measuring the effects of the abstraction on the aquifer water balance, which take many months to accumulate. This is especially the case if the switch-off is undertaken during a dry summer, hoping to avoid significant rainfall affecting the test. As explained in Section 2.3, at times of low GWLs, flow recovery is only a small percentage of abstraction change so becomes even more difficult to measure. If a short switch-off induces no measurable flow impact, it shows no local impact (at the time of the off: ref as above, the abstraction can draw on flows or storage at different times) from the cone of depression, but it says nothing about possible long term flow and GWL impacts through accumulated effects on the aquifer water balance.

CSF modelling suggests that it can take about two years for impacts on the water balance to take full effect – see examples of switch-offs in the Ver and Mimram catchments in Appendices A and B, Figures A17 and B24. If the switch-offs are long enough to accumulate a significant change in the aquifer water balance, there will inevitably be natural weather-related changes over the same period and it is difficult to separate the abstraction induced changes from natural effects.

There are perhaps just two ways that long term abstraction impacts or flow recovery can be realistically measured:

- by comparing accumulated measured flows or flow durations over periods of several years with substantial abstraction differences between the periods, but similar amounts and patterns of rainfall and recharge
- by comparing relative flows and GWLs in nearby rivers in periods before and after substantial abstraction changes – this method avoids the need to identify periods with similar rainfall and recharge

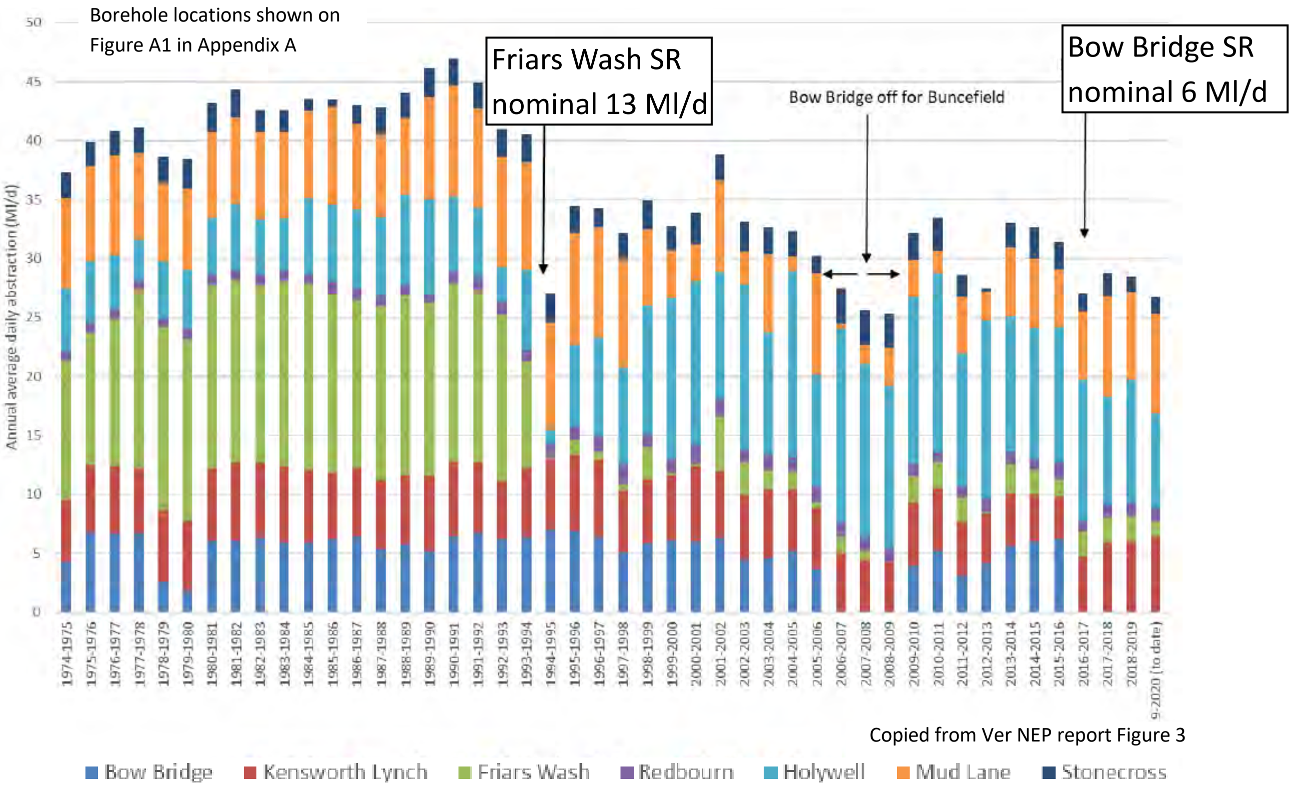
Both these methods need a) substantial abstraction changes that are consistently maintained and b) good records of river flows and groundwater levels. In practice, it is difficult to find examples of consistently maintained abstraction changes accompanied by good flow and GWL records. An additional difficulty arises with the comparison of flow durations in a single river before and after an abstraction change, which requires the following:

- Similarly lengthy periods, at least 10 years each, containing comparable droughts
- Substantial and sustained differences in abstraction between the two periods
- Continuous gauged flow records in each period
- Similar total effective rain and recharge over each period

In the four chalk streams considered for this report, there is only one abstraction change that meets the criteria for flow duration comparisons on a single river – the Friars Wash sustainability reduction on the River Ver in 1992. This case is described in Section 3.2. There are examples of relative flow changes between the Chess and the Ver and the Beane and Rib, described in Sections 3.3 and 3.4. There has been a substantial nominal abstraction reduction in the Mimram catchment, but it has not been maintained, as described in Section 3.5. There have also been several short term signal tests described in the case study appendices and summarised in Section 3.6.

3.2 Measured impacts of River Ver abstraction reductions

Changes in abstraction in the Ver catchment since 1974 are shown in Figure 8:


Borehole locations shown on Figure A1 in Appendix A

Friars Wash SR nominal 13 Ml/d

Bow Bridge off for Buncefield

Bow Bridge SR nominal 6 Ml/d

Copied from Ver NEP report Figure 3

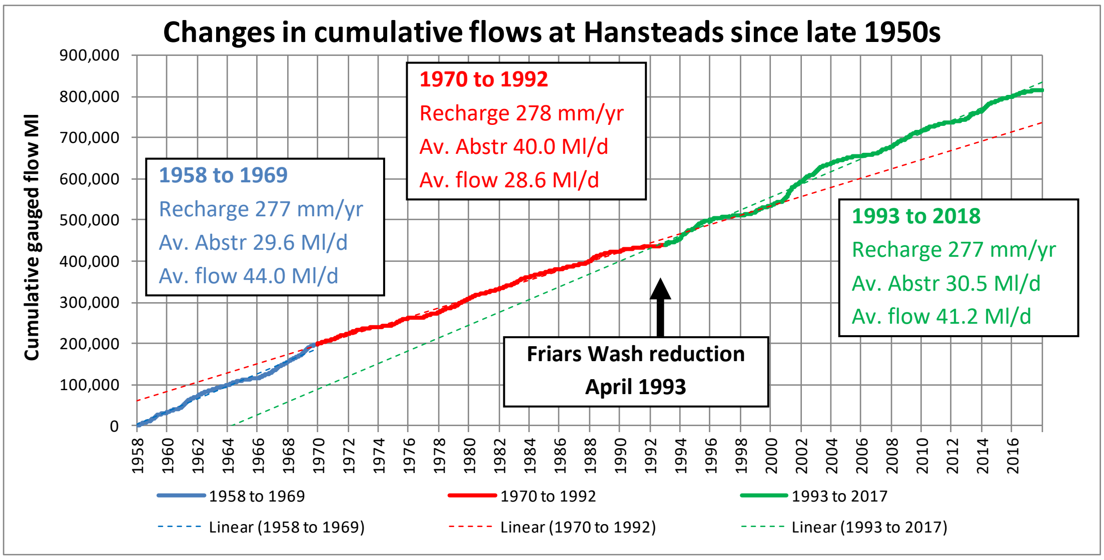
Figure 8 - Changes in abstraction in the River Ver catchment

This shows the timing and relative magnitudes of the Friars Wash and Bow Bridge sustainability reductions (SRs). The abstraction changes shown in Figure 8 illustrate the difficulty of finding substantial and sustained abstraction changes that allow meaningful assessments of flow changes. Although there was a clear 13 Ml/d drop in the Friars Wash abstraction in 1993-94, it was soon offset by some increases in other Ver abstractions. The 6 Ml/d switch-off of the Bow Bridge in 2016 was immediately offset by some increases in other Ver abstractions, giving only perhaps a 2-3 Ml/d net reduction.

Changes in average River Ver flows following the Friars Wash reduction

Although total Ver abstraction has varied somewhat since 1993, the Friars Wash reduction was a step change in abstraction which has been sustained for nearly 30 years, so it has provided the opportunity to observe the long term effect on river flows and GWLs.

The long term effect on flows in the lower Ver at the Hansteads gauging station (located close to the Ver/Colne confluence) was demonstrated in the Environment Agency's 2018 review of the Friar's Wash reduction[10] by plotting cumulative flows since the late 1950s, as replicated in Figure 9:



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[10] Friars Wash Review, PowerPoint slides, Geoff Angell, Environment Agency, 2018

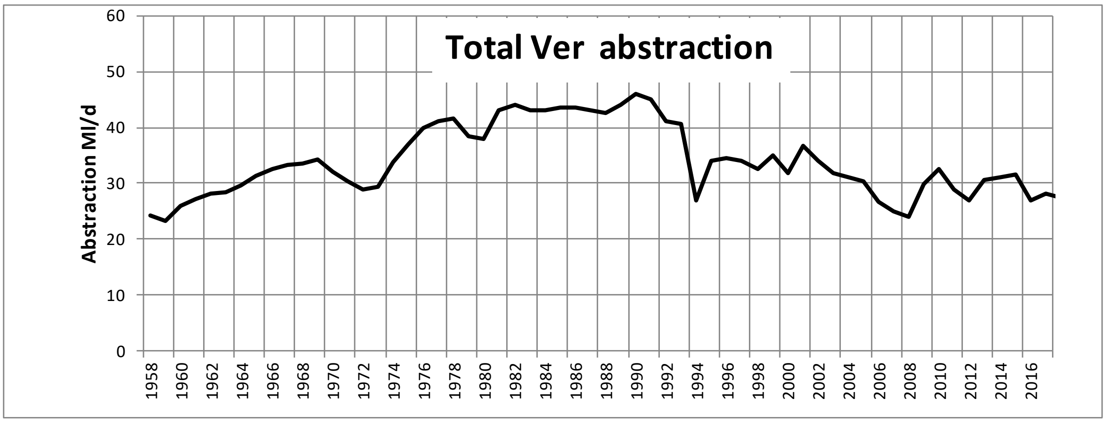


Figure 9 - Changes in Hansteads accumulated flow 1959 to 2018

The upper plot in Figure 9 shows a reasonably clear and sustained rate of accumulation of flow after the Friars Wash reduction in April 1993. Comparing the period 1970-92 with the period 1993-2018 after the Friars Wash reduction:

- Catchment recharge was virtually identical in the two periods
- Average abstraction reduced by 9.5 Ml/d
- Average flow increased by 12.6 Ml/d

A similar picture is seen for the periods before and after the rapid increase in abstraction in the early 1970s, comparing the period 1958-69 with the period 1970-1992:

- Catchment recharge was virtually identical in the two periods
- Average abstraction increased by 10.4 Ml/d
- Average flow decreased by 15.4 Ml/d

In both cases, the change in gauged river flow was more than the change in abstraction, so the changes in gauged flows, if correct, cannot all be due to the abstraction changes. For example, the drought of 1976 might have distorted both of the comparisons (although the average recharges were virtually identical in the three periods compared).

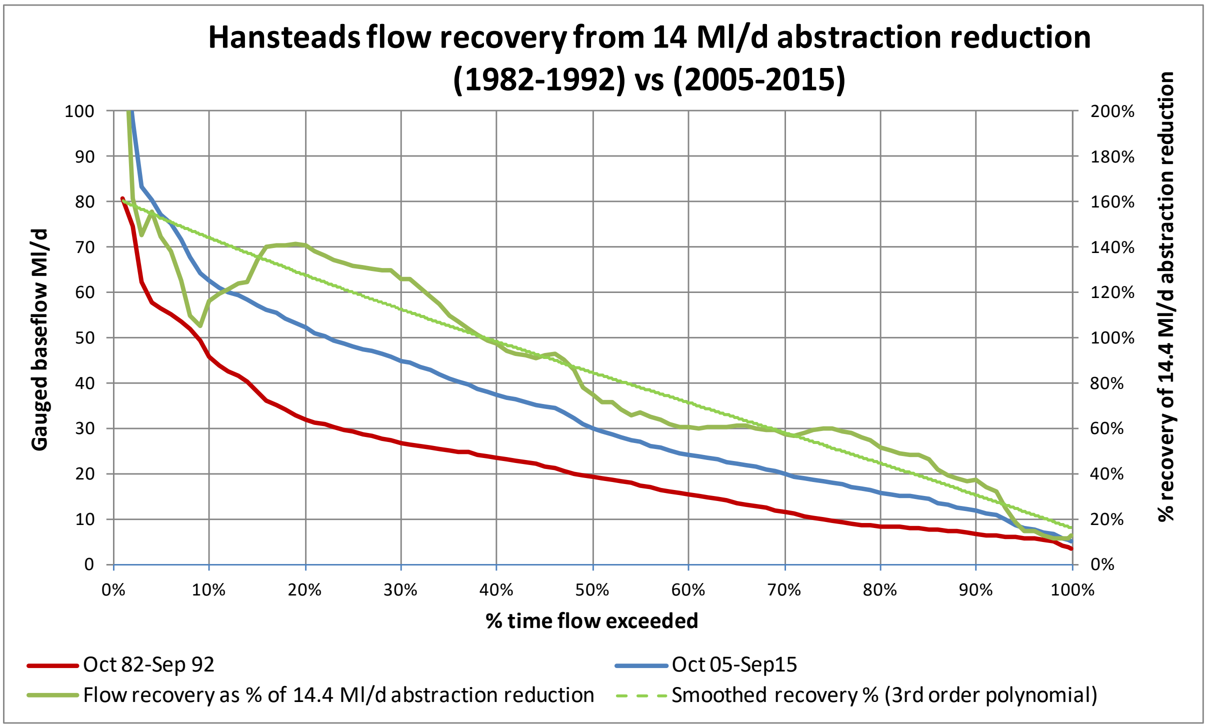
Nevertheless, this analysis, based on measured flows not modelling, does suggest that a high proportion of the abstraction reduction translates into an increase in river flow. The magnitude of the abstraction changes and the long period over which the flow changes were measured adds confidence to this finding.

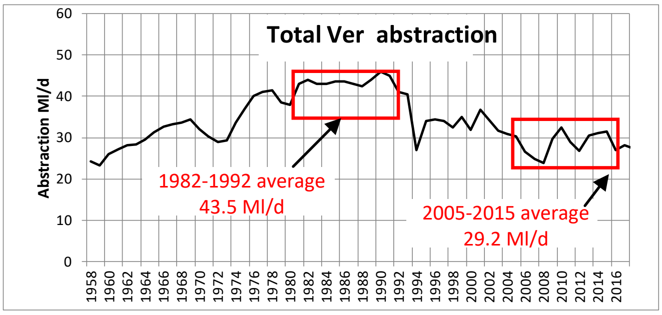
However, this method of analysis only shows changes in average river flows due to abstraction changes and provides no information on how abstraction reductions would increase flows in droughts.

Changes in flow duration curves following the Friars Wash reduction

Comparison of flow duration curves for periods before and after abstraction changes provides an indication of abstraction impacts across the spectrum of river flows, including droughts. A valid and meaningful comparison of flow duration curves requires two periods, at least 10 years each, with similar rainfall, similar droughts and good flow records.

The Environment Agency's review of the Friars Wash reduction identified a pair of suitable periods: (Oct 1982 - Sep 1992) and (Oct 05 - Sep 15) with similar total effective rain and recharge over each period. The same periods were examined in Mott MacDonald paper on groundwater impact factors[11]. The flow duration curves for these periods have been plotted in Figure 10 (with gauged flows converted to baseflows):





	Oct 82-Sep 92	Oct 05-Sep15	Difference
Average Er mm/year	262	265	3.2
Average abstraction Ml/d	43.5	29.2	-14.4
Average flow Ml/d	22.9	35.4	12.5

Figure 10 - Measured Ver baseflow recovery from Friars Wash SR, (1982-92) vs (2005-15)

This plot shows that the 14.4 Ml/d reduction in average abstraction following the Friars Wash reduction led to a 12.5 Ml/d increase in average flow – an average recovery of 87% of the abstraction reduction. The amount of the recovery varies a lot in percentage terms across the range of flows: about 80% at the median flow Q50, about 30% at Q90 and less than 20% at Q99. At high flows, the flow recovery is considerably more than the abstraction reduction. The average amount of flow recovery to the river is only around 80%, because

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[11] Groundwater abstraction factor impact analysis, Figure 3.10, Mott MacDonald, May 2021

some of the gained flow in the water balance leaves the catchment as throughflow, either to the lower River Colne or to the adjacent chalk valleys. An explanation for low recovery at low flows and high recovery at high flows is given in Section 2.6 and Figure 5.

The effect of the 6 Ml/d Bow Bridge switch-off

As can be seen from Figure 8, there was no clear change in overall Ver abstraction when Bow Bridge pumping station was switched off in April 2016. The total Ver abstraction had already fallen from about 32 Ml/d to 27 Ml/d in autumn 2015. The Bow Bridge switch-off in April 2016 was largely replaced by an increase in the Mud Lane abstraction, with the total remaining around 27 Ml/d. Therefore, there was no step-change in overall abstraction which would have allowed comparison of before-and-after flow duration curves as for the Friars Wash reduction in 1993.

Even if there had been a clear 6 Ml/d drop in total abstraction in April 2016, the GWL and river flow changes would have been too small to be distinguishable from natural variations due to climate, especially bearing in mind that groundwater levels and flows were unusually low throughout the Chilterns from 2015 to 2019. This is illustrated by CSF model simulation of what the GWLs and baseflows would have been without the 6 Ml/d Bow Bridge sustainability reduction, as shown in Figure 11:

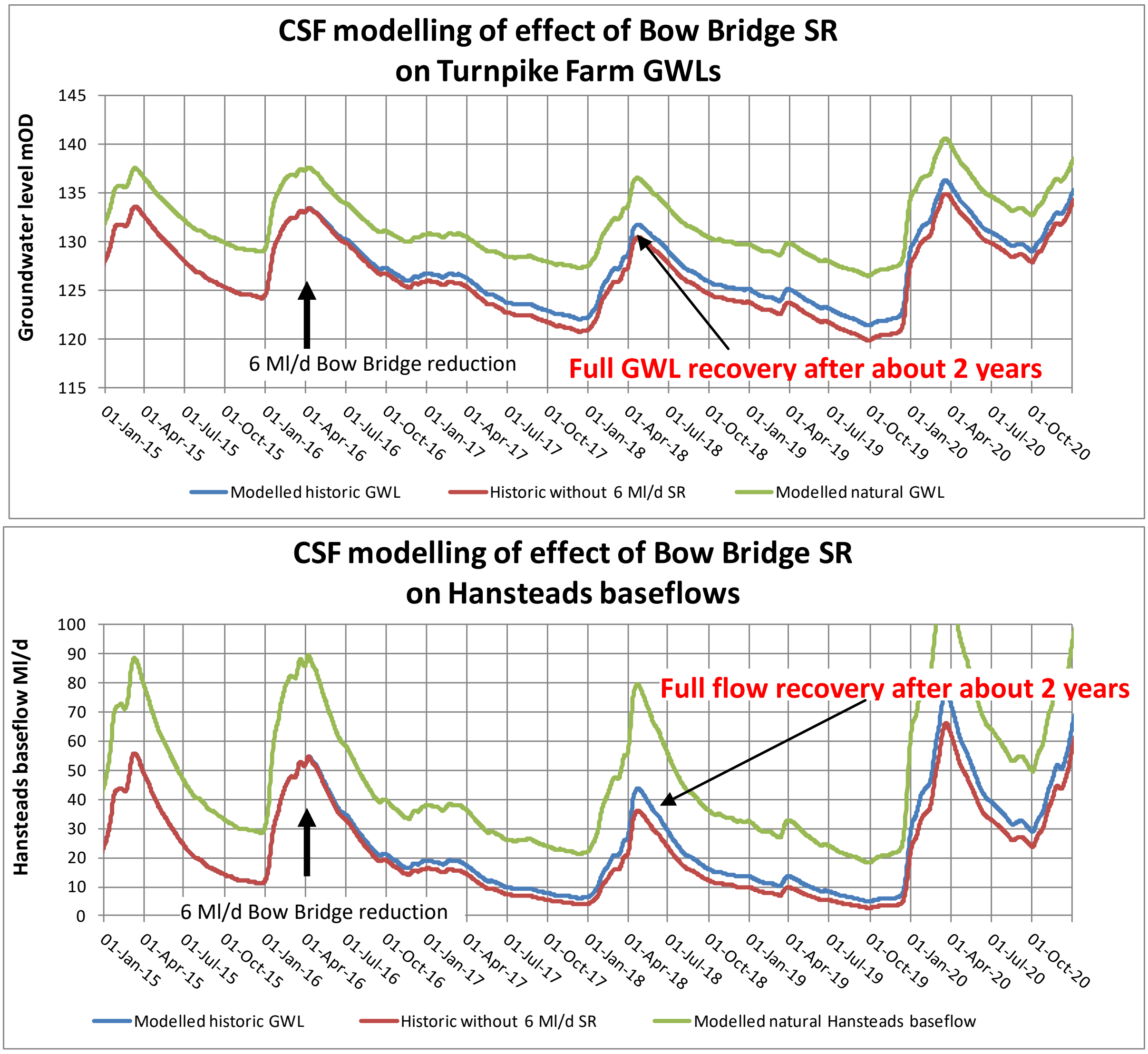


Figure 11 - CSF modelling of effect of Bow Bridge sustainability reduction

The CSF modelling assumes that flow recovery depends on the accumulated increase in aquifer storage and GWLs following the abstraction reduction. This explains the prolonged flow and GWL recovery shown in Figure 11, with full recovery taking about 2 years. The plots show that, even if the Ver catchment abstraction reduction had been 6 Ml/d rather than 2-3 Ml/d, the scale of flow and GWL recovery would have been too small to be realistically measured or distinguishable from natural variations. Flows would still have been far lower than natural flows, so it would have been unrealistic to expect any significant ecological improvement.

The lack of flow recovery or ecological improvements since the Bow Bridge sustainability reduction cannot be used as evidence that the sustainability reductions provide minimal benefits.

3.3 Abstraction induced changes in relative Chess-Ver flows

Comparison of flows and abstractions in the Ver and Chess catchments shows substantial relative flow changes arising from the relative abstraction changes as shown in Figure 11:

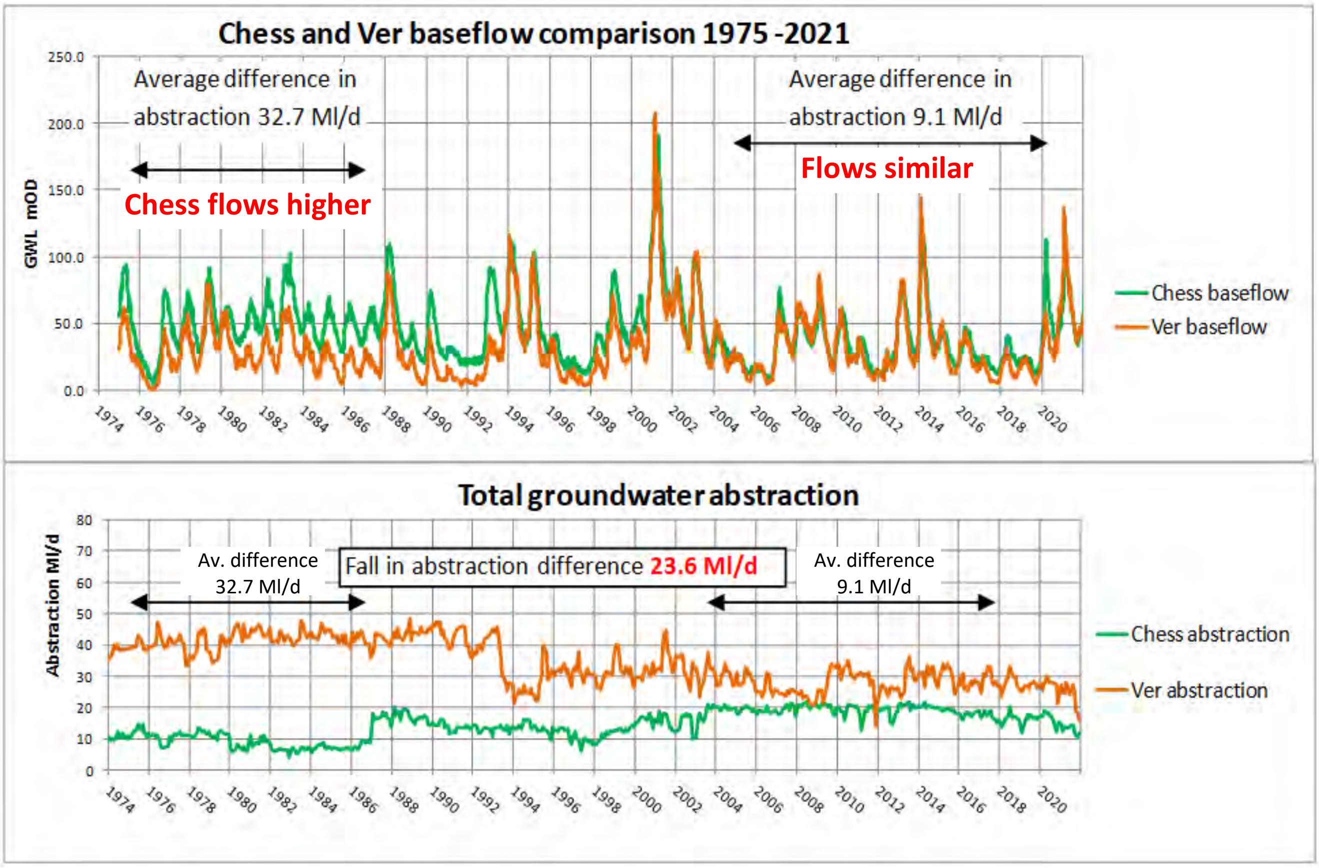
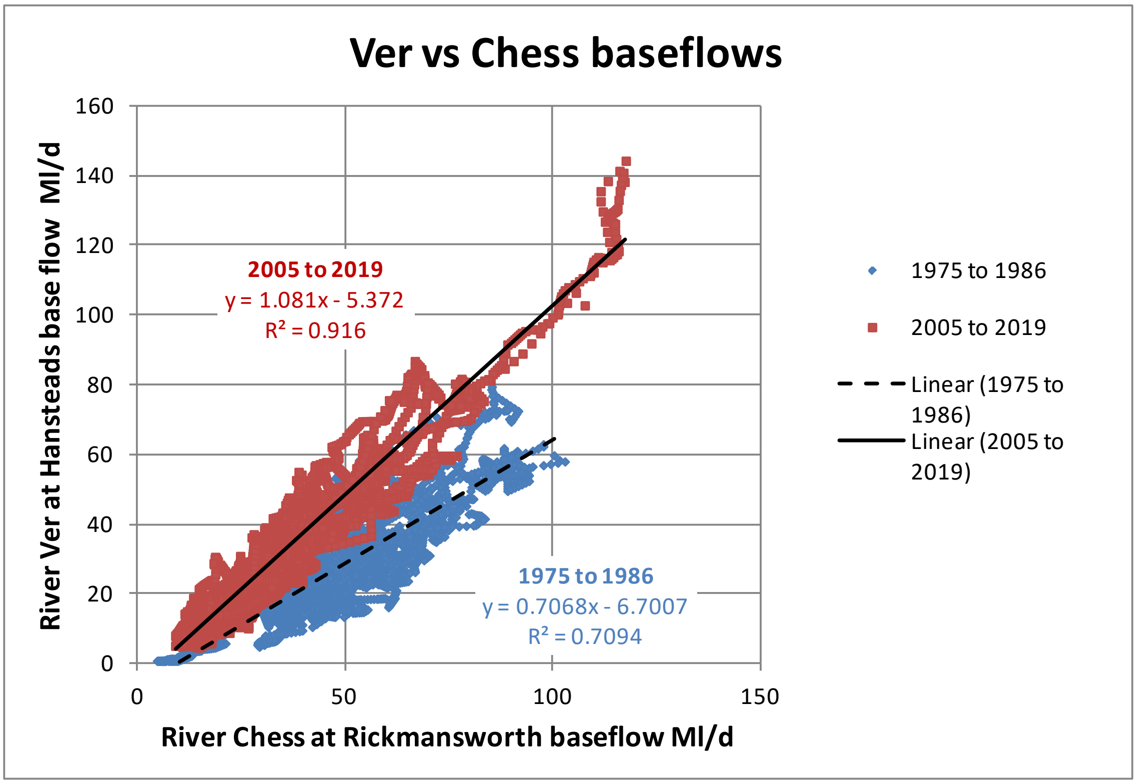


Figure 12 - Relative changes in Chess vs Ver abstractions and flows

This shows that flows in the Chess at Rickmansworth were clearly more than Ver flows at Hanstead before the start of the Chorleywood abstraction in 1987. The magnitude of the relative flow impacts from the relative abstraction changes are shown by plotting Ver vs Chess baseflows in Figure 13, comparing the relationship prior to the start of the Chorleywood abstraction (1975-86) with the relationship after various abstraction reductions (2005-2019):



	Chess flow Ml/d	Relative Ver flow gain 1975-86 vs 2005-18 Ml/d	Gain as % of 23.7 Ml/d relative change in abstraction
Q99	10.3	5.2	22%
Q95	14.0	6.6	28%
Q50	39.7	16.2	69%
Q20	61.8	24.4	104%
Q5	89.9	34.9	148%

Figure 13 - Magnitude of relative Chess-Ver flow changes after abstraction changes

This shows that the 23.7 Ml/d relative change in abstraction generated relative flow changes of 5.2 Ml/d (22%) at Chess Q99 flows, rising to 16.2 Ml/d (69%) change at median flows and 34.9 Ml/d (148%) at Q5 flows. The magnitude and pattern of the abstraction-driven flow changes are similar to those derived using the flow duration comparisons before and after the Friars Wash reduction, as described in Section 3.2.

3.4 Abstraction induced changes in relative Beane-Rib flows

There has been a substantial and sustained reduction in the Whitehall abstraction on the River Beane since 2017, as shown in Figure 14:

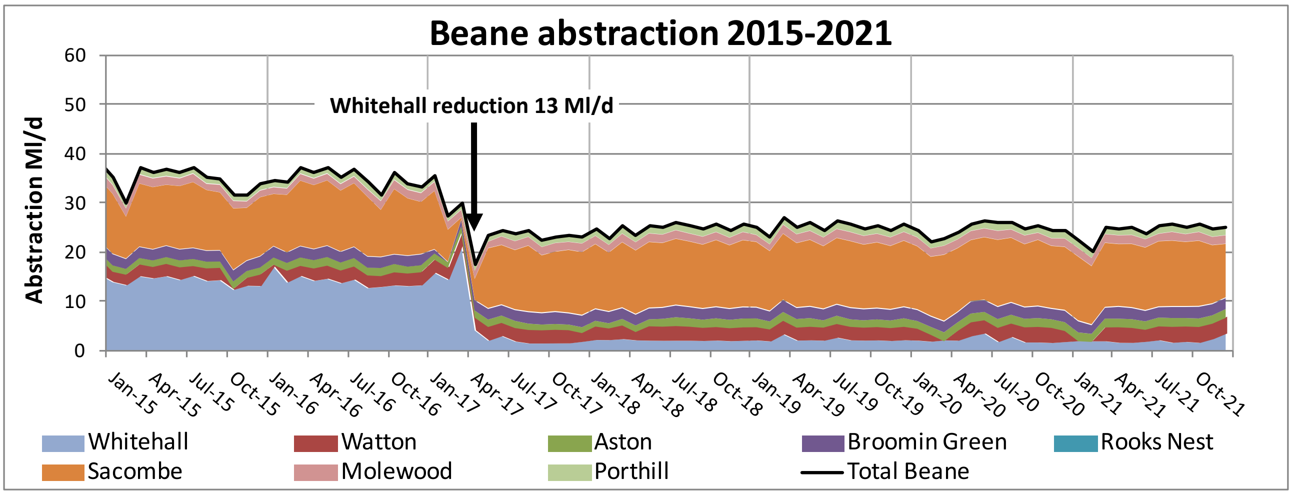


Figure 14 - Recent changes in River Beane abstraction

There are only 5 years of flow and abstraction records available since the 2017 Whitehall reduction, so the effects of the reduction cannot at the moment be reliably separated from seasonal and climatic flow variations, especially bearing in mind the droughts since 2017. However, comparison of relative flows and abstractions in the Beane and Rib catchments shows substantial relative flow changes arising from the abstraction changes as shown in Figure 15:

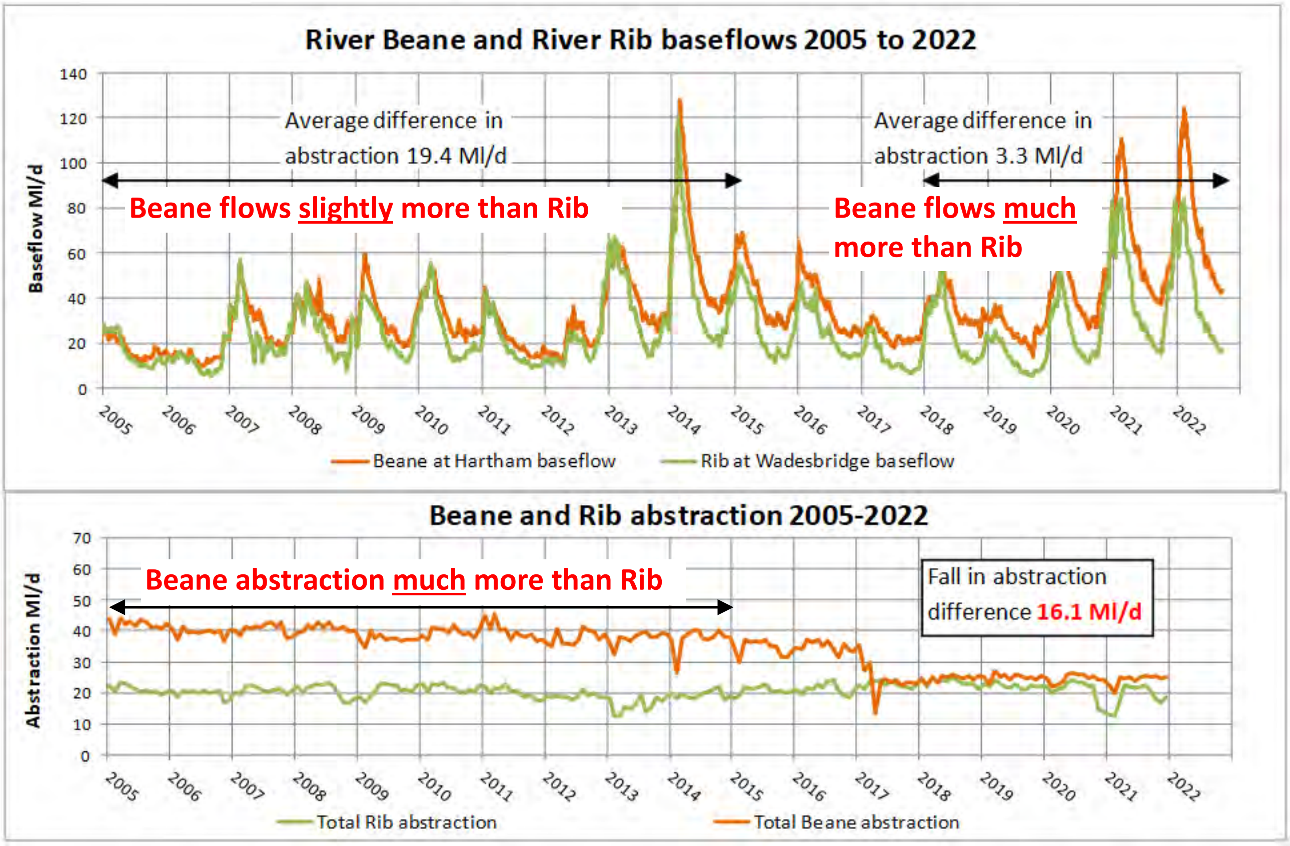
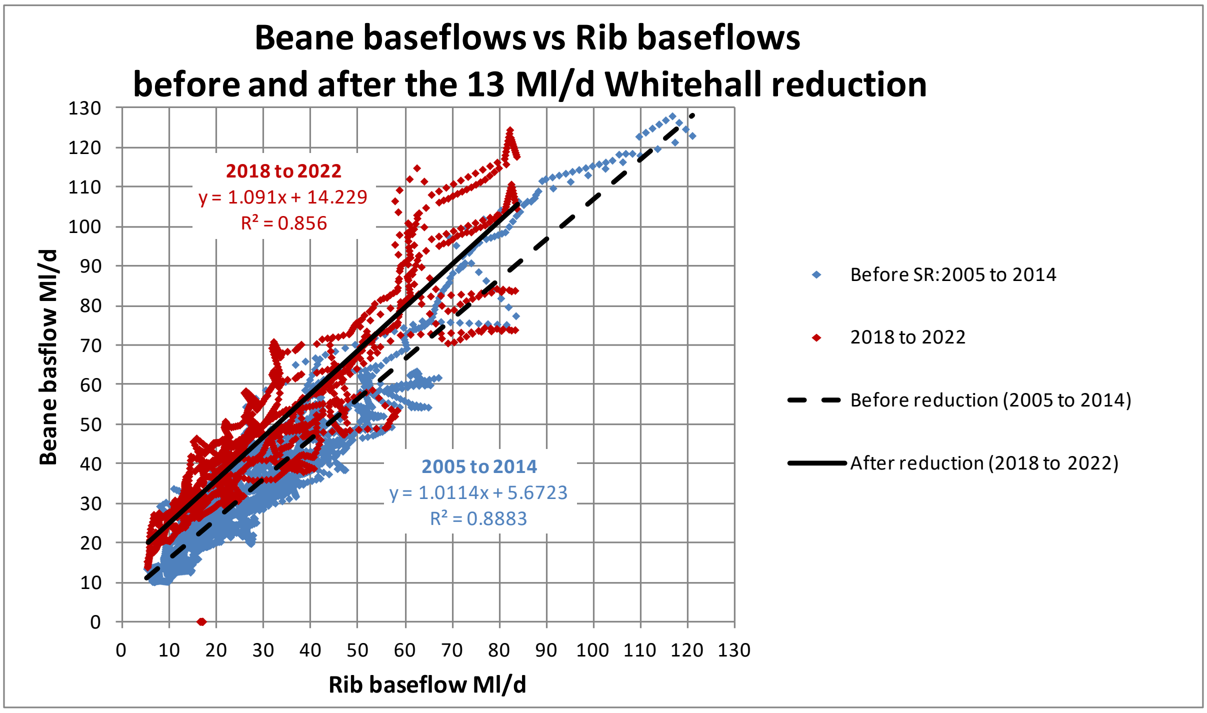


Figure 15 - Relative changes in Beane vs Rib abstractions and flows

This shows that since the 13 Ml/d Whitehall abstraction reduction in 2017, flows in the

Beane at Hartham have clearly risen relative to Rib flows. The magnitude of the relative flow impacts from the relative abstraction changes are shown by plotting Beane vs Rib baseflows in Figure 16. This compares the relationship since the Whitehall reduction in 2017 with the relationship from 2005 to 2014, with a 16.1 Ml/d relative change in abstractions between the two periods:



	Relative Beane-Rib abstractions Ml/d		
	Beane	Rib	Diff
2005 to 2014	39.3	20.0	19.3
2018 to 2021	24.7	21.4	3.3
		Relative change	**16.1**

	Beane flow Ml/d	**Relative Beane flow gain 2018-22 vs 2005-14 Ml/d**	**Gain as % of 16.1 Ml/d relative change in abstraction**
Q99	12.4	9.6	59%
Q95	15.0	9.8	61%
Q50	33.6	11.2	70%
Q20	50.0	12.5	78%
Q5	76.0	14.6	91%

Figure 16 - Magnitude of relative Beane-Rib flow changes after abstraction changes

This shows that the 16.1 Ml/d relative change in abstraction generated relative flow changes of 9.6 Ml/d (59% recovery) to 14.6 Ml/d (91% recovery across the range of flows). The magnitude of the abstraction driven flow changes are similar to those measured following the Friar’s Wash abstraction as described in Sections 3.2 and 3.3, but the range of recovery variation is less across the flow spectrum.

3.5 The Fulling Mill reduction in the Mimram catchment

The Fulling Mill sustainability reduction in 2017 was a deployable output loss of 9.09 Ml/d. The lack of measured flow improvements from the reduction has been cited as evidence that the sustainability reduction has led to only minimal flow improvements[12]:

> *Analysis suggests that flows in the lower catchment (Panshanger gauging station) have not increased as a result of the sustainability reduction. This suggests that recharge (or lack thereof) is the primary driver of river flow in the Mimram and that the potential for the river to gain baseflow from this abstraction reduction under low flows may be limited.*

However, the actual catchment reduction in abstraction since 2015 has been much less than 9.09 Ml/d, as shown for total abstraction and non-consumptive abstraction in Figure 17:

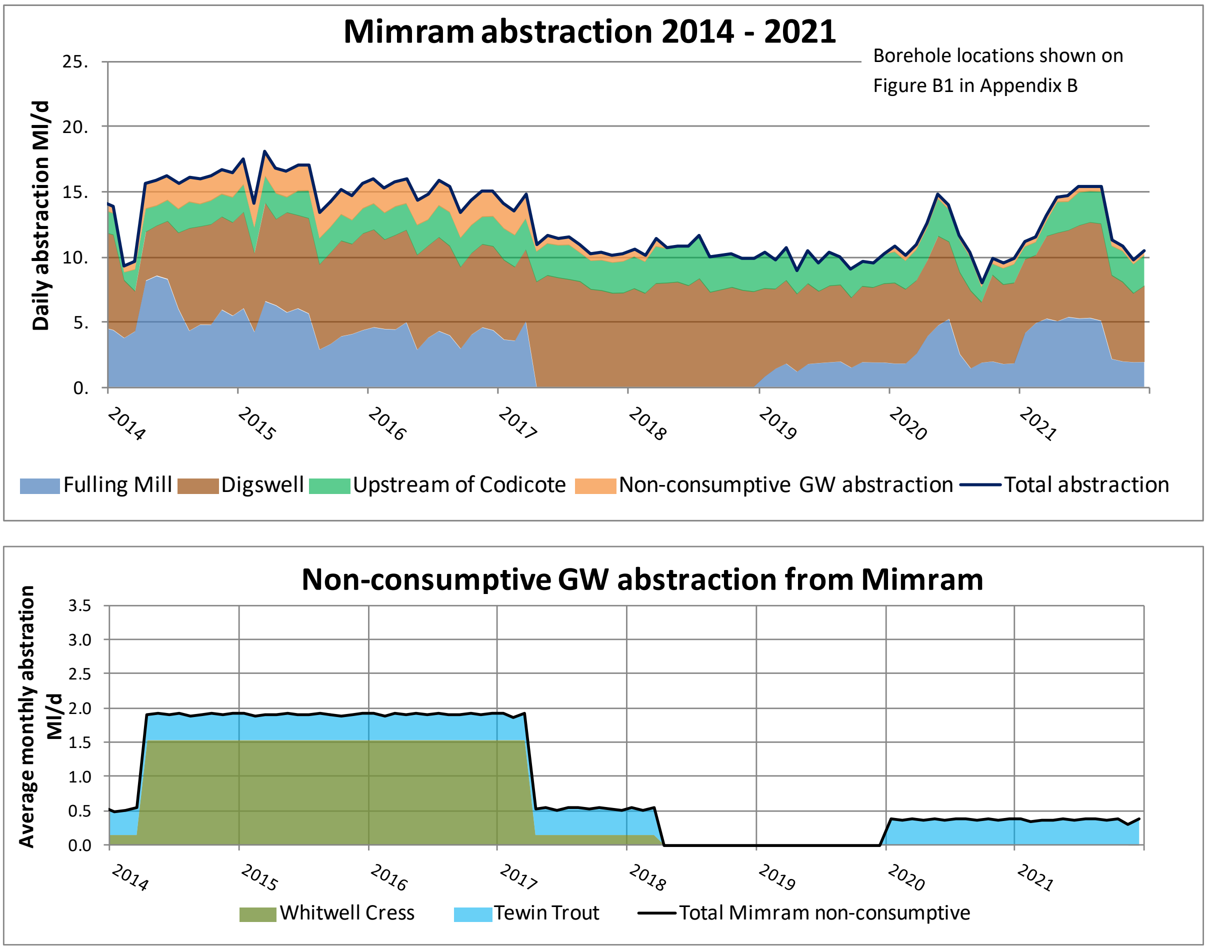


Figure 17 - Mimram groundwater abstraction changes 2014 to 2021

The water cress and fish farm abstractions are non-consumptive, so are returned to the river to augment flows in the lower Mimram at Panshanger gauging station. This augmentation was reduced by about 1.5 Ml/d in April 2017, off-setting flow gains from Affinity Water's 3.8 Ml/d abstraction reduction, especially in the first few months after April 2017, before the

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[12] Affinity Water, Mimram AMP6 NEP report, page 14

GWLs have had time to rise and generate more river flow. The effectiveness of the Fulling Mill sustainability reduction was further reduced by resumption of Fulling Mill abstraction to about 2 Ml/d in 2019, rising to about 5 Ml/d for several months in both 2020 and 2021.

The combined effect of reduced augmentation from the water cress and trout farms with resumption of some abstraction at Fulling Mill would have reduced the effective amount of the nominal 9.09 Ml/d sustainability reduction to an average of about 2 Ml/d. It would have been unrealistic to expect any measurable flow increase at the Panshanger gauging station.

CSF modelling of the actual Mimram abstraction changes since 2015

The CSF model has been used to simulate the reduced Panshanger flows that would have occurred if the 2015 abstraction levels had been maintained until 2021. The total abstraction in 2015 is assumed to have been 15 Ml/d – 13.1 Ml/d for Affinity Water's abstractions and 1.9 Ml/d of non-consumptive abstraction for water cress and trout farms. The CSF model allows for the non-consumptive abstraction impact on aquifer storage and GWLs, but with all the abstracted water also contributing to flow at Panshanger. The modelled flow changes are shown in Figure 18:

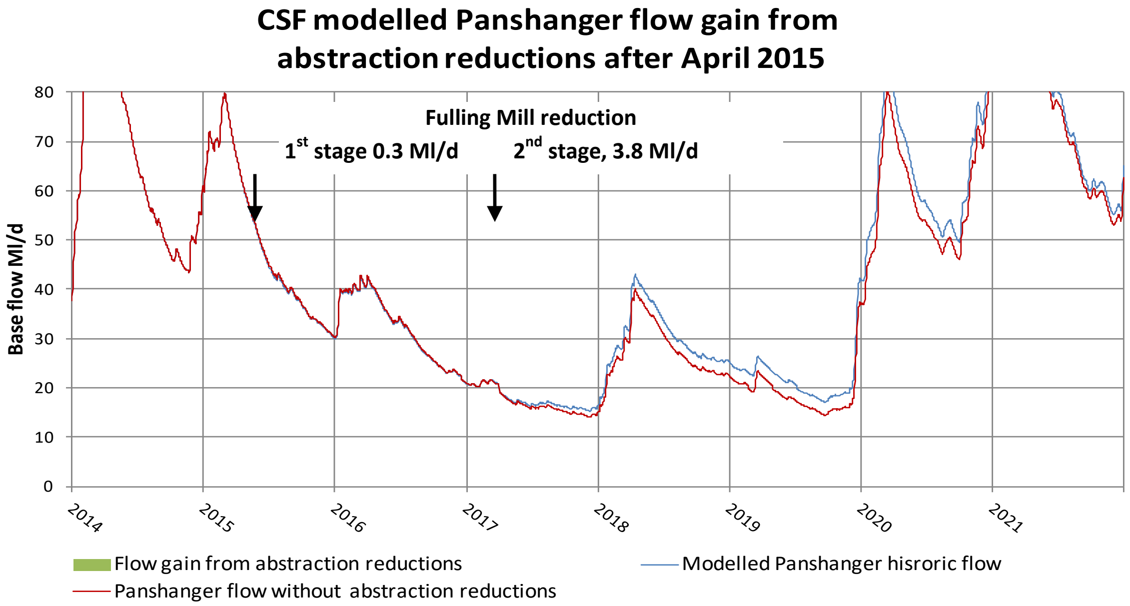

Figure 18 - Modelled flow gain from Fulling Mill abstraction reductions post-April 2015

The modelling shows that the flow gain at Panshanger would have been negligible up to mid-2017. Affinity Water's NEP report on the Mimram only considered data up to the end of 2019, by which time the Panshanger flow gain would have been only about 2 Ml/d and, realistically, would not have been detectable by any of the comparative spot flow measurements attempted in the NEP report.

The lack of detectable flow recovery from the Fulling Mill reduction should not be used as evidence that the sustainability reductions provide minimal flow recovery.

3.6 Flow recoveries measured by signal tests

As discussed in Section 2.3, the effects of abstraction can be considered to be a combination of localised impacts due to the cone of depression (or direct connection to the river) and wider impacts due to effects on the aquifer water balance. 'Signal tests' – short term abstraction switch-offs lasting a few days or weeks – can pick up the cone of depression or direct impacts, but probably won't last long enough to pick up the accumulated effects of reduced abstraction on the aquifer water balance.

If the signal tests show minimal measured flow recovery, it merely shows that the cone of depression impacts are small, so most of the abstraction impacts must be on the aquifer water balance (and eventually on GWLs and flows).

Kensworth Lynch signal tests in the Ver catchment

At Kensworth Lynch in the upper River Ver, there was a planned 10 day outage of the c.6 Ml/d abstraction in 2011, an unplanned two month outage in 2014 and a planned eight week outage in 2015. Affinity Water's NEP report concluded that the lack of significant measured flow increases in these three signal tests demonstrated that any reduction in abstraction from Kensworth Lynch would not benefit river flows in the Upper Ver catchment directly or indirectly[13].

The CSF modelling of the Bow Bridge and Fulling Mill reductions, as plotted on Figures 11 and 18, shows that the maximum two-month duration of the Kensworth Lynch switch-offs would have been far too short to allow the recovery of regional groundwater levels needed to induce any significant flow recovery. Therefore, the NEP report conclusion from the lack of impact of the Kensworth Lynch abstraction is not justified.

Evaluation of Chess signal tests

Signal tests were carried out at two Affinity Water PWS sources in the upper Chess in 2016/17. A recovery test at the Chartridge source was carried out in October 2016 (for 15 days). Prior to the test, abstraction had been continuous and constant at a rate of about 1.2 Ml/d. A recovery test at the Chesham source was carried out in May 2017 (for 13 days). Prior to the test, abstraction had been almost constant at about 3.1 Ml/d.

These tests were, therefore, of short duration and undertaken during times of low river flows (see the hydrographs of spot flow data on Figure D12 in Appendix D). Although the shutdowns would have been expected to have led to local GWL increases within the cones of depression, they are not of sufficient duration to have a material effect on the overall aquifer storage and the regional GWLs, which mainly govern spring and river flows, as per the CSF interpretation of chalk stream behaviour described in Section 2.1-2.3. The low GWLs

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[13] Affinity Water, Ver AMP6 NEP report, page 27

at the times of the tests, with some ephemeral river reaches dry, meant that, even with much longer duration shutdowns, flow increases would probably have been too small to be realistically detectable, for the reasons given in Section 2.6.

The Chess NEP report on page 87 appears to support the view that the signal test shutdowns needed to be of longer duration and at higher GWLs for the river flow increases to be detectable in the Chesham area.

Downstream of the signal test on the Chesham source, some flow increases of up to 1.8 Ml/d were detected – 58% flow recovery from the 3.1 Ml/d abstraction reduction. This was a lot more than the 0.12 Ml/d flow increase predicted by the CSF model at the end of the 16-day shutdown. If the measured 1.8 Ml/d flow increase is correct, it suggests that recovery of GWLs within the cone of depression at the Chesham borehole makes a significant contribution to spring and river flow recovery. If so, the CSF model, which does not account for local impacts due to the cone of depression, would tend to under-estimate the speed of flow recovery, but not the ultimate flow recovery if the reduction is maintained – this would still depend on the eventual gain in aquifer storage and the overall regional GWLs.

3.7 Conclusions from measured flow recoveries after abstraction reductions

Although it is difficult to measure the effects of abstraction changes on flows, there are some clear conclusions that can be drawn from the analysis of abstraction changes in the Ver, Mimram, Beane and Chess catchments:

1. Given sufficient time for flows to recover after genuine and maintained total abstraction reductions in a catchment, the flow gains will average about 80% of the abstraction reduction. The recovery will vary substantially across the range of flows, perhaps from less than 30% recovery in droughts to well over 100% recovery at times of high groundwater levels and flows.

2. This pattern of measured flow recovery is seen consistently in all the examples in the four case study rivers.

3. There are no instances of flow recoveries failing to materialise when they might reasonably be expected after genuine and maintained abstraction reductions.

4. Short term signal tests are not a reliable way of assessing flow gains from abstraction reductions in these rivers.

4. Modelling of abstraction impacts and flow recoveries

4.1 Validation of the HRGM and CSF models

The Environment Agency's HRGM model and the CSF model can both be used to assess abstraction impacts and flow recoveries from abstraction reductions. For the preparation of this report, HRGM model output data is available for the natural, historic, recent actual and full licensed scenarios, covering the period 1970 to 2015, but not for the sustainability reductions since 2015. The CSF model coverage extends to the end of 2021, so includes the recent sustainability reductions.

Both models provide a reasonable fit between observed and modelled historic flows and groundwater levels, as shown below for the Ver catchment modelling:

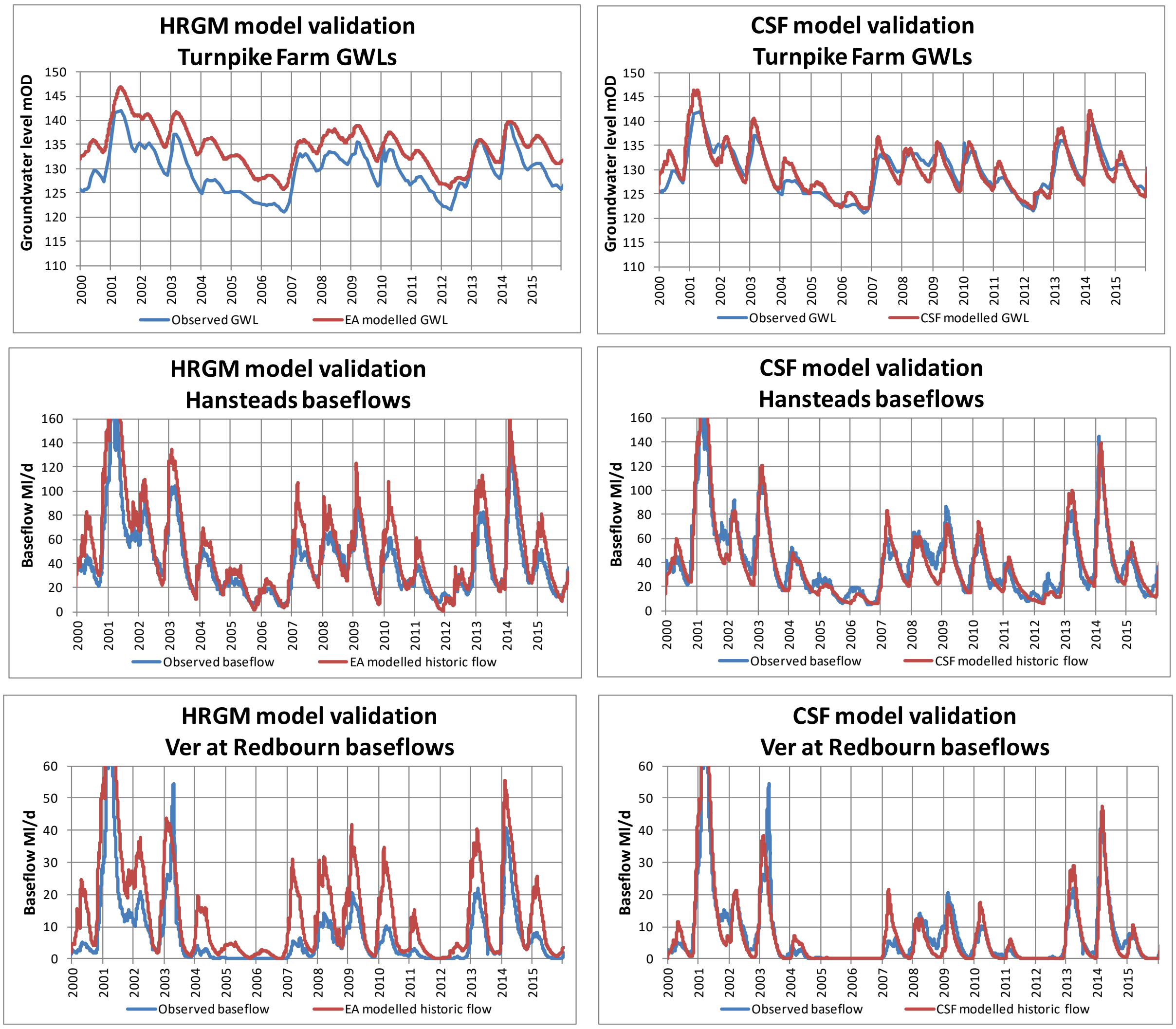


Figure 19 - Comparison of validation data for the HRGM and CSF Ver catchment models

A weakness of the HRGM model simulation of the Ver flows is the generation of false periods of the river drying historically. The river has never dried at Hansteads since the gauging record started in 1956, but the HRGM model shows the river drying in 1973, 1976, 1989, 1991, 1992 (all pre-Friars Wash reduction) and 1997. The periods of river drying cannot be seen in Figure 19, because the plotted data only goes back to 2000.

Comparative validation plots for the Mimram, Beane and Chess models are shown in Figures B13, C15 and D13 in the appendices. In each case, the quality of the validation fits for the two models is similar to the quality shown above for the Ver models.

4.2 Modelling of the Friar's Wash sustainability reduction

CSF modelling of flow duration changes arising from a reduction in total Ver abstraction from 43 Ml/d to 29 Ml/d (average 'before and after' Friars Wash abstractions) is shown on Figure 20 and compared with the measured changes from the Friars Wash reduction shown in Figure 20:

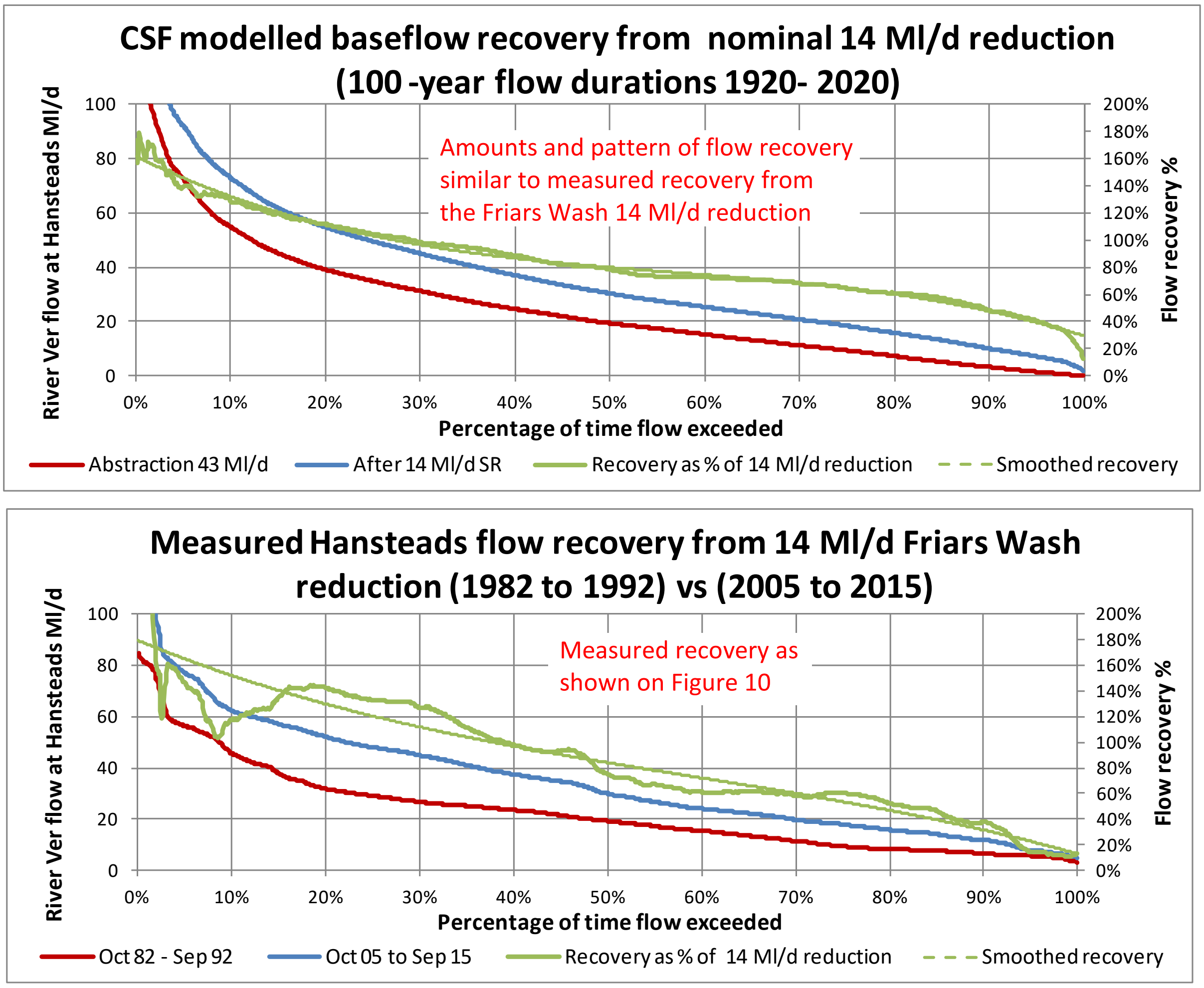
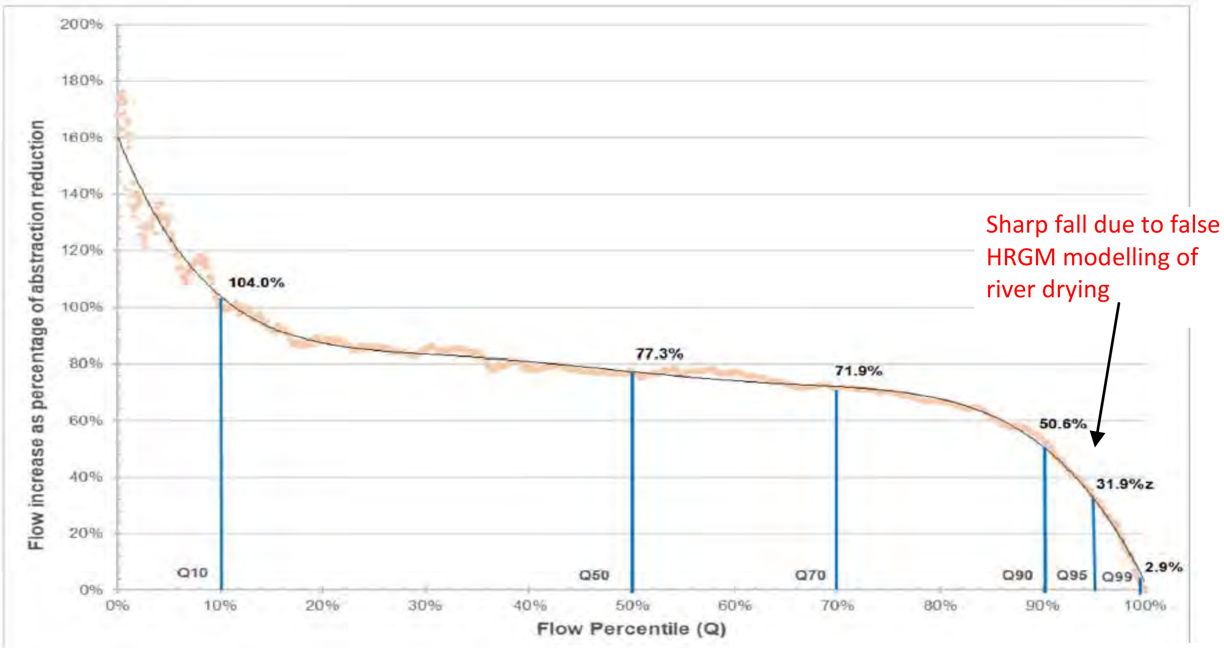


Figure 20 - CSF modelled flow recovery from 14 Ml/d Friars Wash reduction

The CSF modelling of the Friars Wash reduction gives similar amounts and patterns to the measured flow recovery following the Friars Wash reduction – recovery increasing across the flow range from about 20% in extreme droughts to 160% at very high flows, with a modelled median recovery of about 78%, compared to the measured median recovery of 75%.

Modelling of the Friars Wash sustainability reduction was also undertaken by Mott MacDonald for Affinity Water in 2021[14] as part of an exercise to determine "Groundwater Impact Factors (GIFs)", showing how much allowance should be made for flow recovery from abstraction reduction in up-coming Water Resource Management Plans. The modelling was undertaken using the 'Vale of St Albans model (VSA)' component of the HRGM. The modelled % flow recoveries following the Friars Wash reduction are shown in Figure 21:



Copied from Mott MacDonald GIF report Figure 3.2

Figure 21 - HRGM (VSA) modelling of flow recovery from the Friars Wash reduction

This shows a similar amount and pattern of flow recovery as that simulated by the CSF model and the measured recovery at the Hansteads gauging station shown on Figure 20.

The sharp fall in recovery below Q90 is the consequence of the HRGM model showing false river drying at extreme low flows and is not a reliable indicator of recovery at very low flows.

The measured River Ver flow recovery following the Friars Wash sustainability reduction is the only instance in the four river case studies in this report of a substantial and sustained abstraction reduction with good lengths of flow records before and after the reduction. The conclusions that can be drawn from the limited evidence of reliably measured flow recovery are:

1. The CSF and HRGM (VSA) models are both effective in assessing the amount of flow recovery and the pattern of flow recovery across the flow range, aside from the HRGM model's false indication of a sharp drop at extreme low flows.
2. The flow recovery has been around 80% of the abstraction on average, varying between about 20% at extreme low flows and 150% at high flows.

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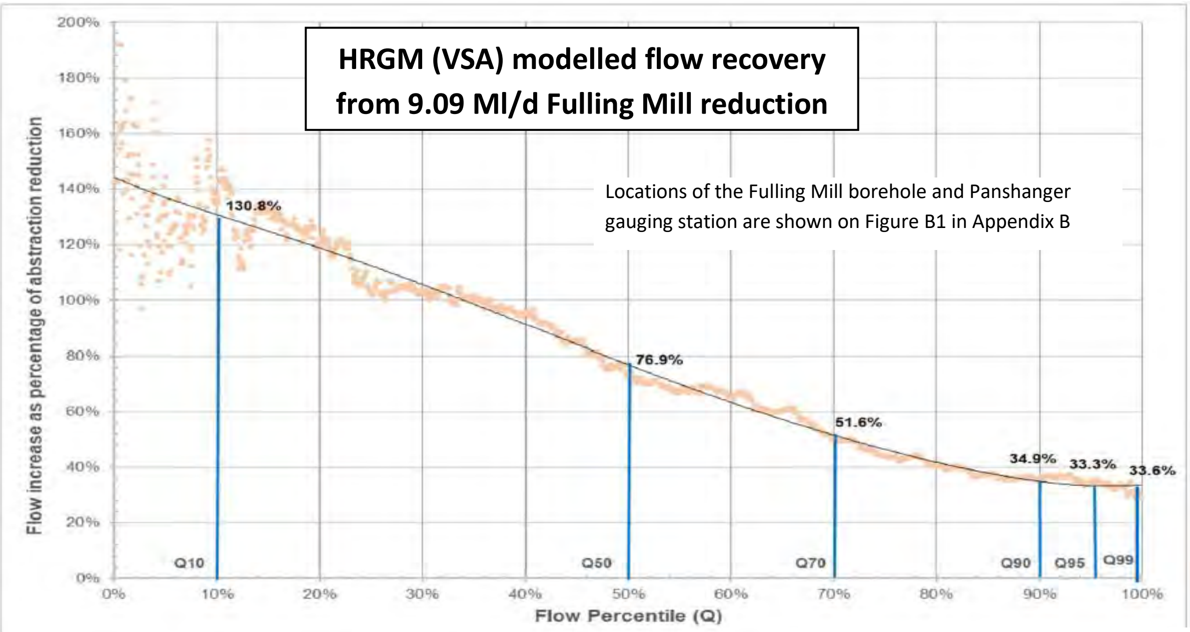
[14] Groundwater abstraction impact factor and impact analysis (GIF), Mott MacDonald, May 2021

4.3 Modelled flow recovery after the Fulling Mill reduction

The Fulling Mill 9.09 Ml/d nominal sustainability reduction has led to only a small flow improvement, because overall actual abstraction reduction in the Mimram catchment has only been about 2 Ml/d, as explained in Section 3.5 and Figure 17. However, the HRGM and CSF modelling of flow recovery from a full and maintained 9.09 Ml/d reduction are compared in Figure 22:



Copied from Mott MacDonald GIF report Figure 3.8

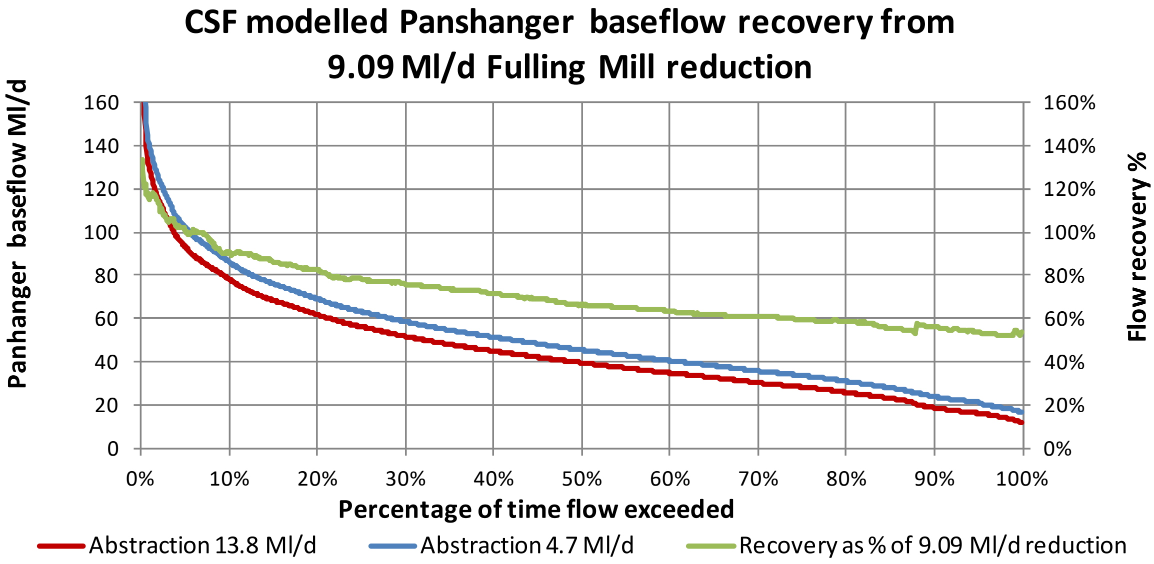
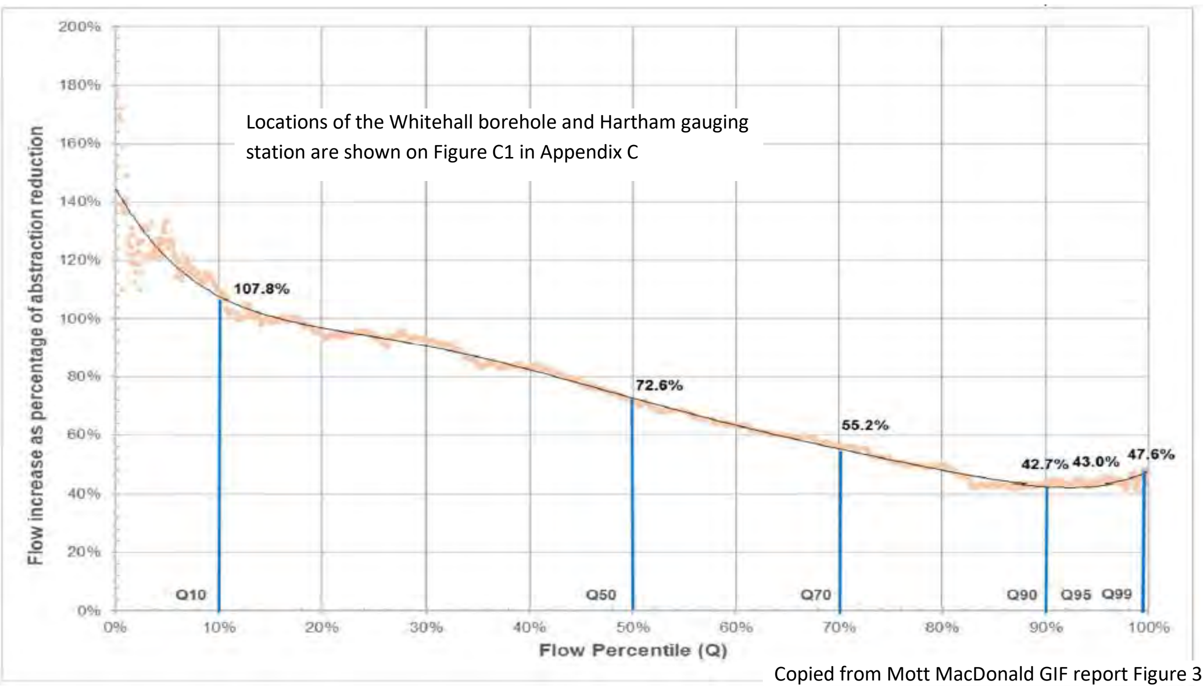


Figure 22 - HRGM and CSF modelled flow recovery from the Fulling Mill reduction

Both models show a similar pattern and amount of flow recovery, with recovery falling as river flows fall. The HRGM model predicts a slightly higher median flow recovery than the CSF model, but a lower recovery at low flows.

4.4 Modelled flow recovery after the Whitehall reduction

The Mott MacDonald GIF report included HRGM modelling of a reduction of the 18.0 Ml/d fully licensed amount of the Whitehall abstraction in the Beane catchment. Figure 23 compares the HRGM and CSF modelling of recovery at Hartham from a full 18 Ml/d reduction:



Locations of the Whitehall borehole and Hartham gauging station are shown on Figure C1 in Appendix C

Copied from Mott MacDonald GIF report Figure 3.6

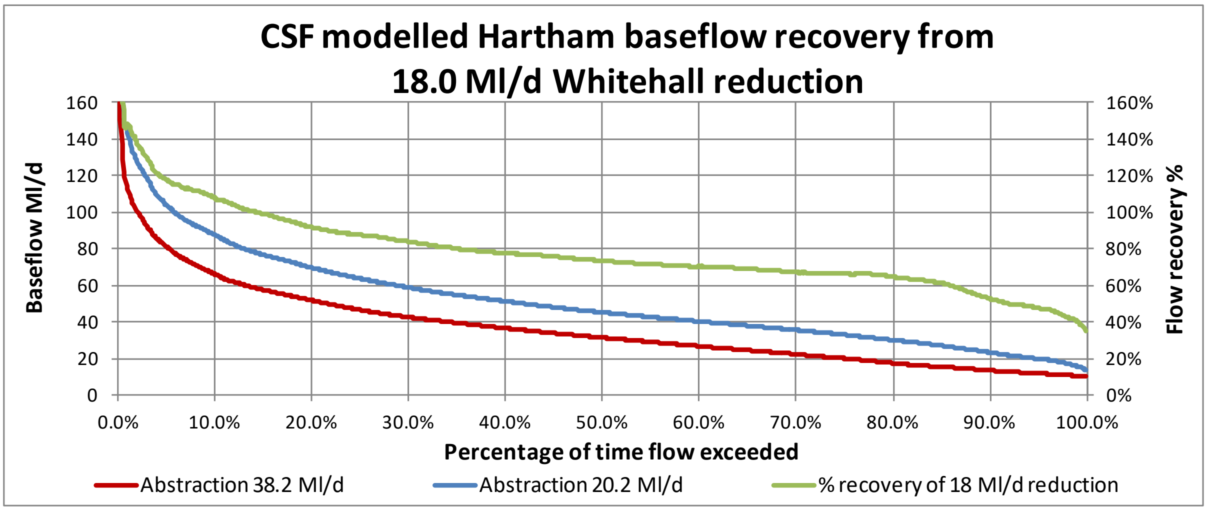
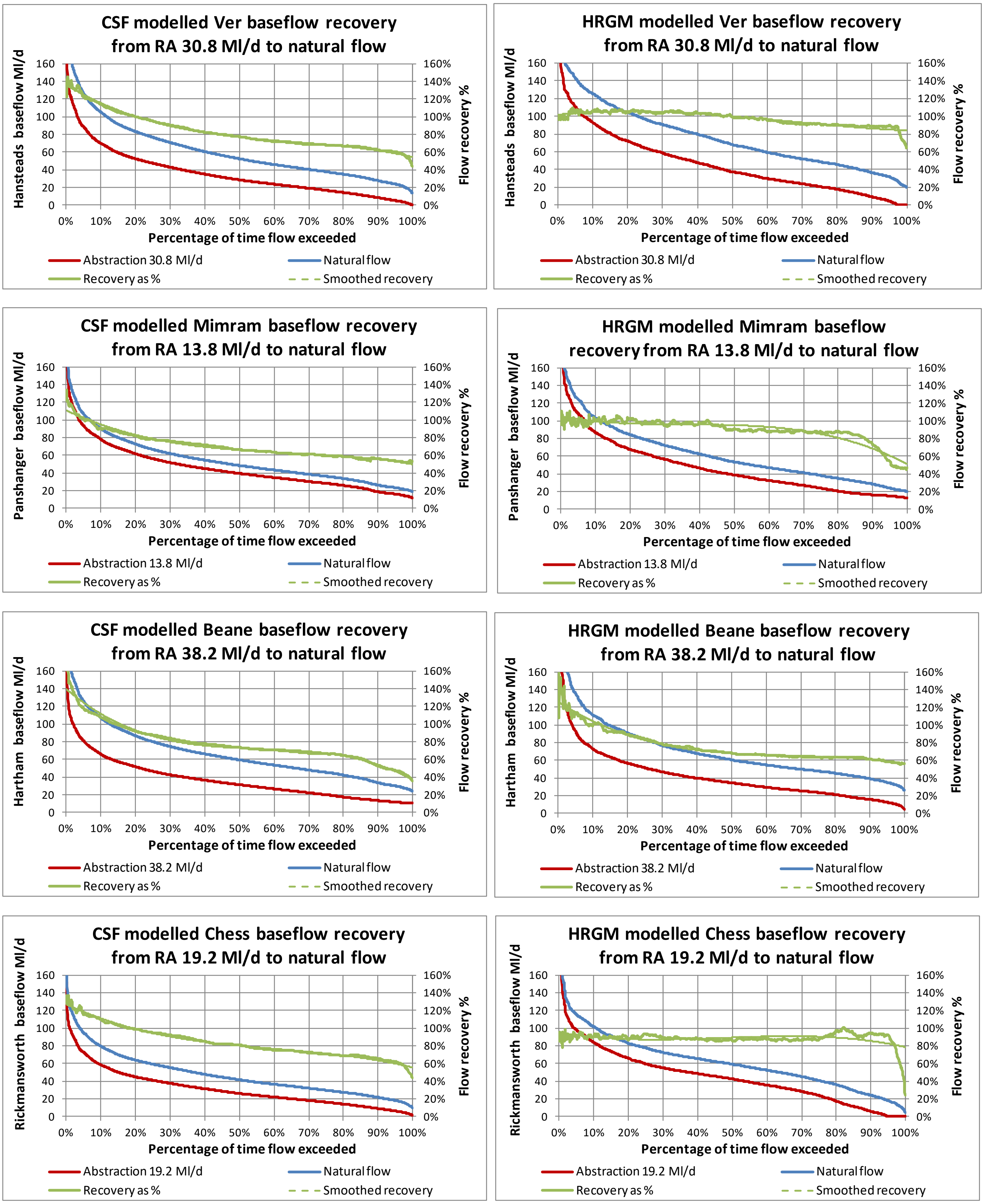


Figure 23 - HRGM and CSF modelled flow recovery from the Whitehall reduction

As for the Ver and Mimram sustainability reductions, both models show a similar pattern and amount of flow recovery, with recovery falling as river flows fall.

4.5 Modelled impacts of recent actual abstraction

Figure 24 compares CSF and HRGM modelling of flow recovery in the lower Rivers Ver, Mimram, Beane and Chess if abstraction is reduced from “recent actual” to zero.



Note: 1. Modelled Chess recent actual flows are net of STW effluents

2. Modelled recent actual abstraction amounts as per EA file *"HERTS Artificial Influences Overview_Red.xlsx"*:

Figure 24 - CSF and HRGM modelled river flow recoveries from recent actual abstraction

The CSF and HRGM models show similar patterns of flow recovery when recent actual abstraction is reduced to zero. Both models show increasing % recovery as flows increase, but the CSF model shows a larger variation across the flow range, in line with the measured recoveries following the Friars Wash reduction. The HRGM model for the Rivers, Ver, Mimram and Chess shows higher flow recoveries at median flows than the CSF model – HRGM recoveries around 90% of abstraction at Q50, compared to CSF modelled recoveries in the range 65-80%.

At very low flows, below Q95, the CSF model shows recoveries in the region of 40% of abstraction. HRGM modelled recoveries vary a lot at very low flows. For the modelling of the Ver and Chess, the HRGM modelling is distorted by the false modelling of the river drying, so the low recoveries at extreme low flows can be disregarded. However, for the HRGM modelling of the Mimram and Beane, HRGM model shows recoveries in the region of 50%, a bit more than the CSF model.

4.6 Conclusions from the modelling of abstraction impacts and flow recovery

The CSF and HRGM models show very similar patterns and amounts of flow recovery from abstraction reductions:

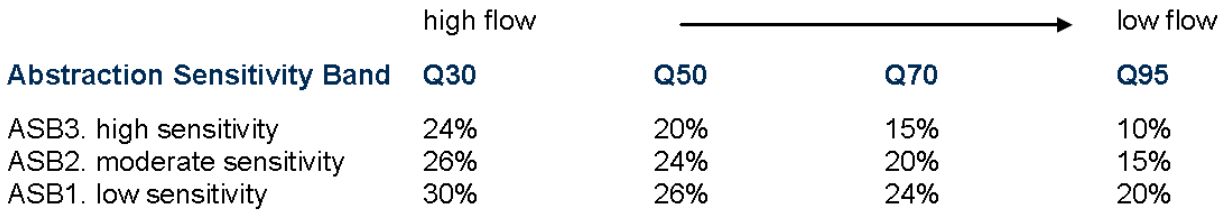
1. The CSF and HRGM models both validate reasonably well against recorded historic data. They can both be used to estimate abstraction impacts and flow recoveries.
2. The patterns and amounts of modelled flow recoveries are similar to the measured flow recoveries described in Section 3.
3. At average river flows, modelled river flow recoveries are in the region of 80% of the abstraction reductions.
4. At extreme low flows, modelled flow recoveries are typically around 30-40% of abstraction reductions.
5. These conclusions are equally true in all four case study rivers.

The modelled and measured flow recoveries are similar. They are far more than the 17% flow recovery assumed in recently published water company draft WRMPs and in the draft regional plan of Water Resources in the South East. The significance of this for the Chalk Streams First proposal is discussed in Section 5.

5. Up-date of the Chalk Streams First proposal

5.1 Objectives for flow improvement

The Environment Agency uses Environmental Flow Indicators to “*indicate where abstraction pressure may start to cause an undesirable effect on river habitats and species*”[15]. The allowable deviations from natural flows for various categories of river are shown in Table 2:



	high flow	→		low flow
Abstraction Sensitivity Band	**Q30**	**Q50**	**Q70**	**Q95**
ASB3. high sensitivity	24%	20%	15%	10%
ASB2. moderate sensitivity	26%	24%	20%	15%
ASB1. low sensitivity	30%	26%	24%	20%

Copied from Reference 18 Table 2

Table 2 - EFIs: % acceptable abstraction from natural flows at different sensitivity bands

At present, the Environment Agency classification of chalk streams ranges through all three ‘sensitivity’ bands. For example the River Mimram and the Candover Brook are ASB3, the Rivers Piddle, Chess and Beane are ASB2, and the River Nar and the Great Eau are ASB1.

The CaBA chalk stream strategy proposes that all chalk streams should be in the most sensitive band, ASB3, unless there is evidence to support a lower band[16]. ASB3 may not be appropriate on the lower reaches of very big chalk catchments or highly modified systems, for example the lower Colne or Lea, the lower Wey, Gade, Stort etc.

An alternative objective would be limiting abstraction to 10% of average recharge, termed A10%R, as described in Section 2.8. The flow deficits using the EA’s methodology are compared with the abstraction reductions using the A%R methodology in Table 3. The Environment Agency’s flow deficits do not equate directly to required abstraction reductions. The abstraction reductions needed to meet the EFI targets will be more than the Q95 EFI deficits, because the flow recovery at Q95 flows is much less than 100% of the abstraction reduction – see measured and modelled flow recoveries in Sections 3 and 4.

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[15] Environmental Flow Indicator, what it is and what it does, Environment Agency, January 2013

[16] CaBA Chalk Stream Strategy, Main Report, page 51. https://catchmentbasedapproach.org/wp-content/uploads/2021/10/CaBA-CSRG-Strategy-MAIN-REPORT-FINAL-12.10.21-Low-Res.pdf

	Environment Agency Assessment								A%R Assessment			
River Assessment Point	**ABS band**	**Calculated Natural Low Flow (Q95)**	**Estimated sustain-able low flow (EFI)**	**Recent Actual Q95 Flow**	**Surface water Abstr-action**	**Cumulative Discharges**	**Flow Deficit to EFI at low flow (Q95)**	**Groundwater Abstraction impact on Flow**	**Effective catchment area**	**Average Recharge**	**Upstream abstraction in 2017-19**	**Over-abstraction in 2017-19 based on A10%R**
Ver to Redbourn	3	5.6 Ml/d	5.1 Ml/d	0.0 Ml/d	0.0	0.7 Ml/d	5.1 Ml/d	7.4 Ml/d	63 km2	49.2 Ml/d	8.8 Ml/d	3.9 Ml/d
Lower Ver	2	39.7 Ml/d	33.8 Ml/d	9.1 Ml/d	0.0	0.7 Ml/d	24.7 Ml/d	31.3 Ml/d	132 km2	103.1 Ml/d	28.1 Ml/d	17.7 Ml/d
Upper Colne (to Watford)	2	96.2 Ml/d	81.8 Ml/d	3.9 Ml/d	0.0 Ml/d	21.2 Ml/d	77.9 Ml/d	113.5 Ml/d	352 km2	275.0 Ml/d	110.8 Ml/d	83.3 Ml/d
Upper Gade	2	17.6 Ml/d	15.0 Ml/d	4.3 Ml/d	0	0.0 Ml/d	10.7 Ml/d	13.3 Ml/d	48 km2	37.5 Ml/d	12.2 Ml/d	8.4 Ml/d
Bulbourne to Gade	3	16.4 Ml/d	14.8 Ml/d	13.8 Ml/d	2.2 Ml/d	7.0 Ml/d	1.0 Ml/d	7.4 Ml/d	66 km2	51.9 Ml/d	9.8 Ml/d	4.6 Ml/d
Lower Gade incl Bulbourne	2	98.0 Ml/d	83.3 Ml/d	37.8 Ml/d	10.4 Ml/d	9.2 Ml/d	45.5 Ml/d	59.0 Ml/d	184 km2	143.8 Ml/d	53.4 Ml/d	39.0 Ml/d
Chess	2	19.6 Ml/d	16.7 Ml/d	11.5 Ml/d	0	6.9 Ml/d	5.2 Ml/d	15.0 Ml/d	105 km2	82.0 Ml/d	16.5 Ml/d	8.3 Ml/d
Misbourne	2	12.6 Ml/d	10.7 Ml/d	0.0 Ml/d	0	0.0 Ml/d	10.7 Ml/d	14.7 Ml/d	95 km2	74.2 Ml/d	17.5 Ml/d	10.0 Ml/d
Lee to Luton Hoo	2	24.4 Ml/d	21.9 Ml/d	0.0 Ml/d	0	0.0 Ml/d	21.9 Ml/d	28.4 Ml/d	65 km2	37.7 Ml/d	32.9 Ml/d	29.1 Ml/d
Lee to Water Hall	2	43.1 Ml/d	36.6 Ml/d	36.0 Ml/d	0	40.0 Ml/d	0.6 Ml/d	47.1 Ml/d	150 km2	87.1 Ml/d	48.4 Ml/d	39.7 Ml/d
Upper Mimram	3	4.0 Ml/d	3.6 Ml/d	0.2 Ml/d	0	0.5 Ml/d	3.4 Ml/d	4.3 Ml/d	49 km2	28.4 Ml/d	2.5 Ml/d	0.0 Ml/d
Lower Mimram	3	46.8 Ml/d	42.1 Ml/d	29.2 Ml/d	0	0.5 Ml/d	12.9 Ml/d	18.1 Ml/d	136 km2	79.0 Ml/d	10.4 Ml/d	2.5 Ml/d
Stevenage Brook	2	1.4 Ml/d	1.2 Ml/d	1.2 Ml/d	0	0.0 Ml/d	0.0 Ml/d	0.2 Ml/d	39 km2	22.6 Ml/d	5.0 Ml/d	2.7 Ml/d
Beane	2	42.7 Ml/d	36.3 Ml/d	25.3 Ml/d	0	0.7 Ml/d	11.0 Ml/d	18.1 Ml/d	175 km2	101.6 Ml/d	24.9 Ml/d	14.8 Ml/d
Upper Rib	3	15.7 Ml/d	14.1 Ml/d	11.0 Ml/d	0	2.2 Ml/d	3.1 Ml/d	6.9 Ml/d	51 km2	29.6 Ml/d	3.0 Ml/d	0.0 Ml/d
Lower Rib	3	14.2 Ml/d	12.7 Ml/d	3.4 Ml/d	0	2.2 Ml/d	9.3 Ml/d	13.0 Ml/d	152 km2	88.2 Ml/d	22.9 Ml/d	14.0 Ml/d
Ash	2	10.4 Ml/d	8.9 Ml/d	3.9 Ml/d	0	0.7 Ml/d	5.0 Ml/d	7.2 Ml/d	89 km2	51.7 Ml/d	1.2 Ml/d	0.0 Ml/d
Upper Stort to Bishop Stortford	2	1.7 Ml/d	1.4 Ml/d	0.6 Ml/d	0	0.5 Ml/d	0.8 Ml/d	1.6 Ml/d	60 km2	34.8 Ml/d	12.2 Ml/d	8.7 Ml/d
Lower Stort	1	17.9 Ml/d	14.3 Ml/d	14.4 Ml/d	0.7 Ml/d	17.5 Ml/d	0.0 Ml/d	20.3 Ml/d	280 km2	162.5 Ml/d	25.0 Ml/d	8.8 Ml/d

Notes:
1. EA figures (in green shade) are as per EA file *‘Chilterns Flow Deficits 2020.xlsx’*
2. Average recharge uses EA daily effective rain for East Chilterns (Colne) and Lee
3. Catchment areas and recharges are for topographic catchments as for A%R analysis

Table 3 - EA and A%R assessments of abstraction reductions for Colne and Lee catchments

The EA deficits are mostly similar to the A10%R abstraction reductions, although there are some significant differences which are discussed in the four case studies in Appendices A-D.

The CSF model was used to model EFI compliance on the four case study rivers and to propose acceptable levels of abstraction for each river as below.

5.2 CSF proposed abstraction reductions in case study rivers

The CSF proposed abstraction reductions in the four case study rivers are shown in Table 4:

Catchment	**Recent abstraction 2019-21**	**Proposed future abstraction**	**Reduction from 2019-21 abstraction**	**Proposed abstraction after reduction as % of topographic recharge in Table 3**
Ver	25.3 Ml/d	4.7 Ml/d	20.6 Ml/d	7.50%
Mimram	11.3 Ml/d	5.2 Ml/d	6.1 Ml/d	7.70%
Beane	24.7 Ml/d	9.8 Ml/d	14.9 Ml/d	9.60%
Chess	15.1 Ml/d	4.1 Ml/d	11.0 Ml/d	5.0%
			Average A%R	**8.3%**

Table 4 - CSF proposed abstraction reductions in case study rivers

The proposed reductions in the case-study rivers have been determined using the CSF model to give acceptable EFI compliance at the gauging station locations on the lower reaches of each river. Table 4 also shows the proposed future abstraction as a % of the catchment recharge shown in Table 3, with recharge calculated from effective rain and the topographic catchment area. Some comments on the proposed future abstraction in each river are as below:

- For the Ver catchment: the catchment area assumed in the CSF model, adjusted to optimise validation fits, was 106 km^2, compared to the topographic catchment of 134 km^2. This gives an adjusted average catchment recharge of 78 Ml/d. The proposed total abstraction of 7.8 Ml/d is 10% of the adjusted average recharge and 7.5% of the topographic catchment recharge. It gives full compliance with the ASB3 EFI at Hansteads at flows up to Q95. At Q95 flows, it complies with ASB2 (the EA's designated sensitivity band), but falls just short of ASB3 EFI compliance – see plot on Figure 25.

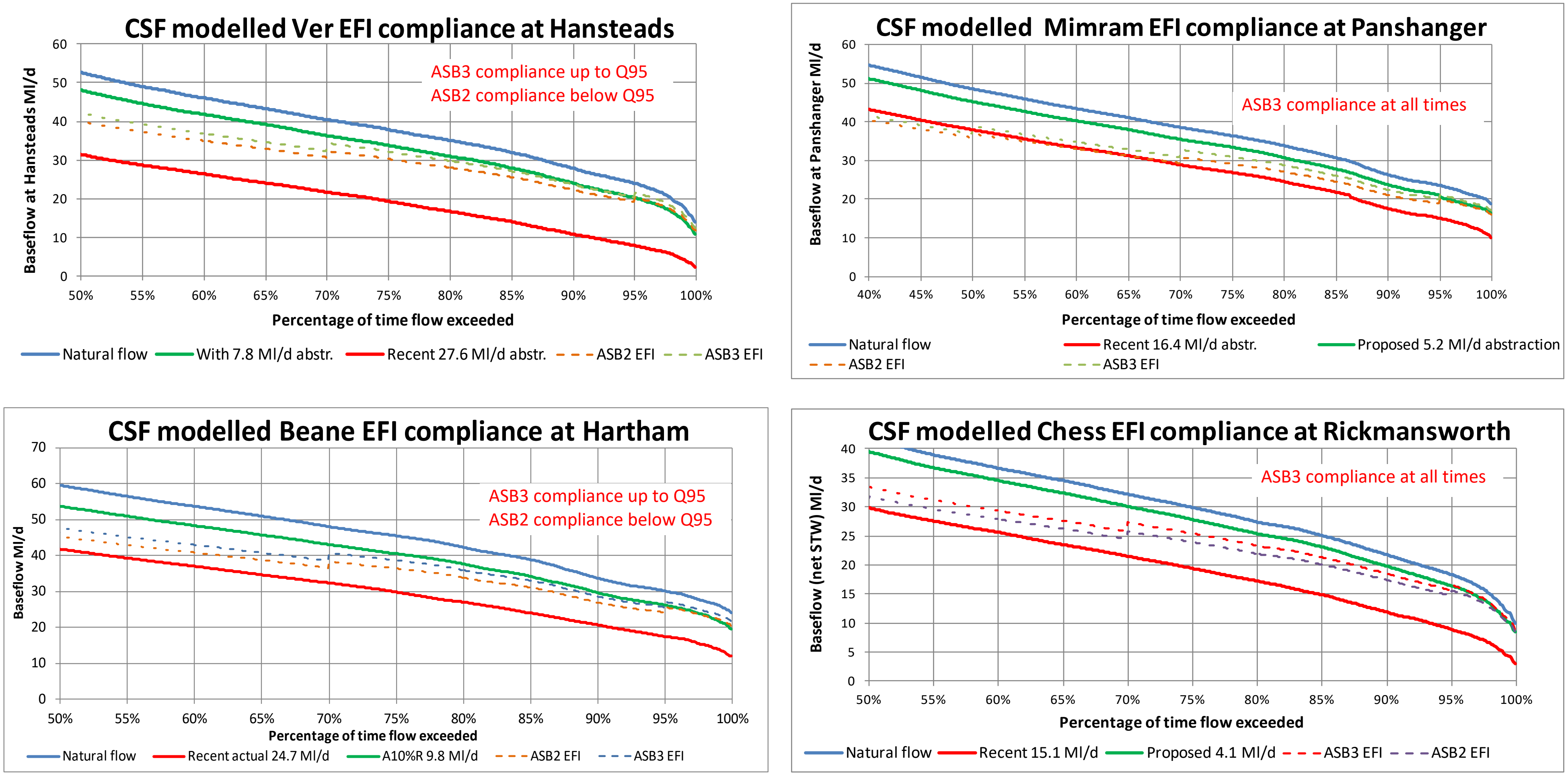
- For the Mimram catchment: the proposed total abstraction of 5.2 Ml/d is 7.7% of the average recharge, based on the topographic catchment. It fully complies with EFIs at Panshanger for ASB3 (as designated by EA for the Mimram) – see plot on Figure 25.

- For the Beane catchment: the proposed total abstraction of 9.8 Ml/d is 9.6% of the average recharge, based on the topographic catchment. It gives full compliance with the ASB3 EFI at Hartham at flows up to Q95. At Q95 flows, it complies with ASB2 (the EA's designated sensitivity band), but falls just short of ASB3 EFI compliance – see plot on Figure 25.

- For the Chess catchment: the catchment area assumed in the CSF model, adjusted to optimise validation fits, was 85 km^2, compared to the topographic catchment of 105 km^2. This gives an adjusted average catchment recharge of 63 Ml/d. The proposed total abstraction of 4.1 Ml/d is 6.5% of the adjusted average recharge and 5% of recharge based on the topographic catchment. It gives full compliance with the ASB3 EFI at Rickmansworth, when flows are assessed net of the STW dry weather flow of c.10 Ml/d – see plot on Figure 25.

Figure 25 shows flow duration curves at the four lower-river gauging stations illustrating the EFI compliance with the CSF proposed abstraction reductions.

Figure 26 shows hydrographs of modelled flow recovery for the Rivers Ver and Mimram, at the lower river and at a winterbourne location, for the period 2015 to 2019, which includes the droughts of 2017 and 2019. Noting that the proposed Ver flow reductions only comply with ASB2 in the lower river (as per EA designation), whereas the Mimram reductions comply with ASB3 (also as per EA), there are very similar flow improvements on the two rivers. The adoption of ASB3 instead of ASB2 makes little material difference to the improvements in river flows.

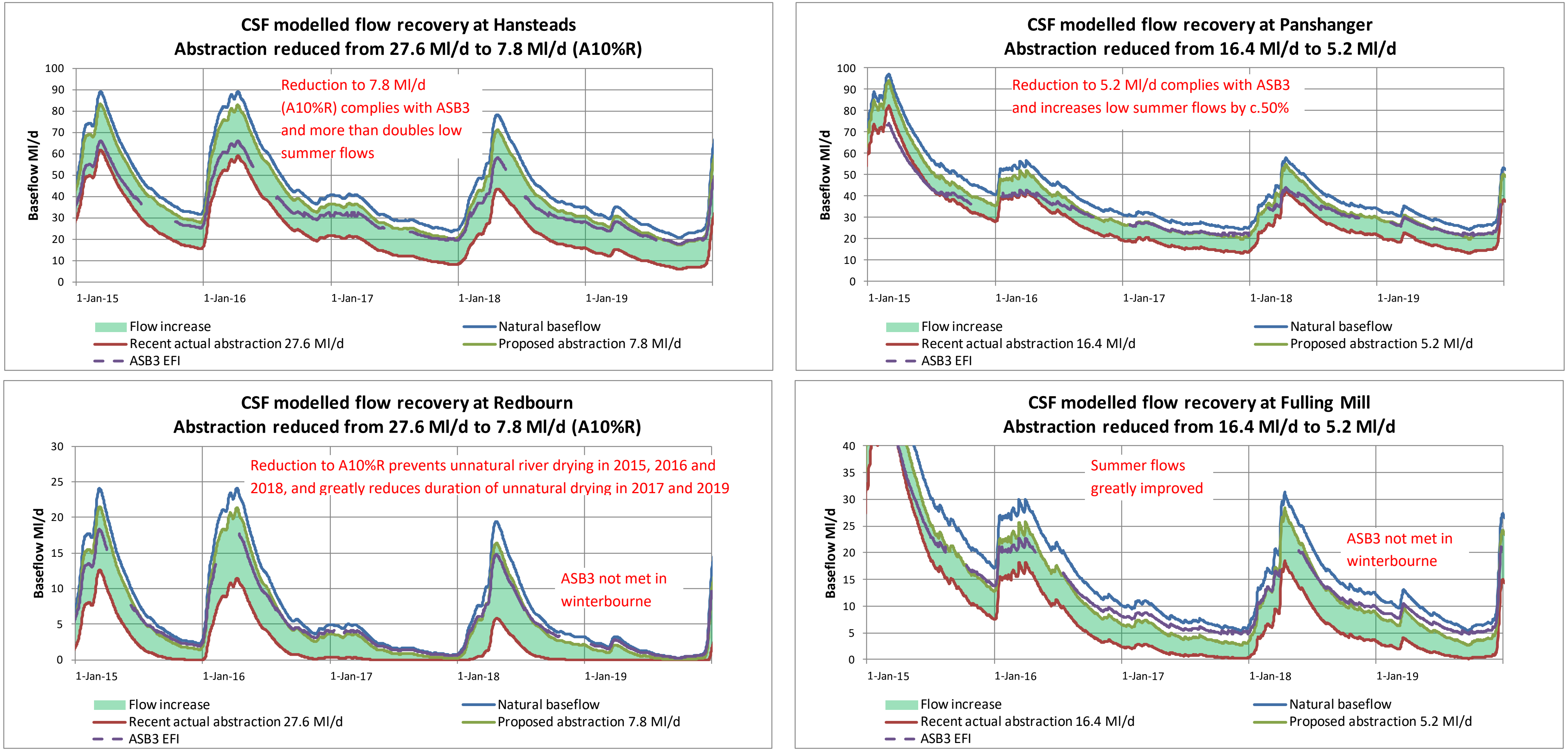

CSF modelled Ver EFI compliance at Hansteads

CSF modelled Mimram EFI compliance at Panshanger

CSF modelled Beane EFI compliance at Hartham

CSF modelled Chess EFI compliance at Rickmansworth

Figure 25 - CSF modelled EFI compliance with the proposed abstraction reductions


CSF modelled flow recovery at Hansteads
Abstraction reduced from 27.6 Ml/d to 7.8 Ml/d (A10%R)

Reduction to 7.8 Ml/d (A10%R) complies with ASB3 and more than doubles low summer flows

CSF modelled flow recovery at Panshanger
Abstraction reduced from 16.4 Ml/d to 5.2 Ml/d

Reduction to 5.2 Ml/d complies with ASB3 and increases low summer flows by c.50%

CSF modelled flow recovery at Redbourn
Abstraction reduced from 27.6 Ml/d to 7.8 Ml/d (A10%R)

Reduction to A10%R prevents unnatural river drying in 2015, 2016 and 2018, and greatly reduces duration of unnatural drying in 2017 and 2019

ASB3 not met in winterbourne

CSF modelled flow recovery at Fulling Mill
Abstraction reduced from 16.4 Ml/d to 5.2 Ml/d

Summer flows greatly improved

ASB3 not met in winterbourne

a) River Ver (note: complies with ASB2 at Q95 on lower river flow durations)

b) River Mimram (note: complies with ASB3 at Q95 on lower river flow durations)

Figure 26 - Ver and Mimram flow improvements with CSF proposed abstraction reductions

5.3 CSF proposed abstraction reductions in Colne and Lea catchments

Table 3 shows that the proposed abstractions after reductions on the four case study rivers are an average of 8.3% of the average recharge based on the topographic catchment. Assuming that abstraction is reduced to 8.3% of recharge based on the topographic catchment in all the other Colne and Lea chalk streams, the overall abstraction reductions are as shown in Table 5:

Colne:	**Topographic catchment**	**Average recharge**	**Recent abstraction 2019-21 average**	**Recent abstraction as % recharge**	**Proposed abstraction as % recharge**	**CSF proposed abstraction**	**Abstraction reduction from 2109-21 average**
Misbourne	95 km^2	74.2 Ml/d	15.8 Ml/d	21%	8.3%	6.2 Ml/d	9.6 Ml/d
Chess	105 km^2	82.0 Ml/d	15.1 Ml/d	18%	5.0%	4.1 Ml/d	11.0 Ml/d
Gade	184 km^2	143.8 Ml/d	36.2 Ml/d	25%	8.3%	11.9 Ml/d	24.3 Ml/d
Ver	132 km^2	103.1 Ml/d	25.8 Ml/d	25%	7.5%	7.7 Ml/d	18.1 Ml/d
					Colne reduction sub-total		**63.0 Ml/d**
Lea:							
Upper Lea to Water Hall	150 km^2	87.1 Ml/d	48.4 Ml/d	56%	8.3%	7.2 Ml/d	41.2 Ml/d
Mimram	136 km^2	79.0 Ml/d	10.4 Ml/d	13%	7.7%	6.1 Ml/d	4.3 Ml/d
Beane	175 km^2	101.6 Ml/d	24.9 Ml/d	25%	9.6%	9.8 Ml/d	15.2 Ml/d
Rib	152 km^2	88.2 Ml/d	22.8 Ml/d	26%	8.3%	7.3 Ml/d	15.5 Ml/d
Ash	89 km^2	51.7 Ml/d	1.2 Ml/d	2%	As present	0 Ml/d	0 Ml/d
Stort	280 km^2	162.5 Ml/d	25.0 Ml/d	15%	8.3%	13.5 Ml/d	11.5 Ml/d
					Lea reduction sub-total		**87.6 Ml/d**
					Total Colne & Lea		**150.6 Ml/d**

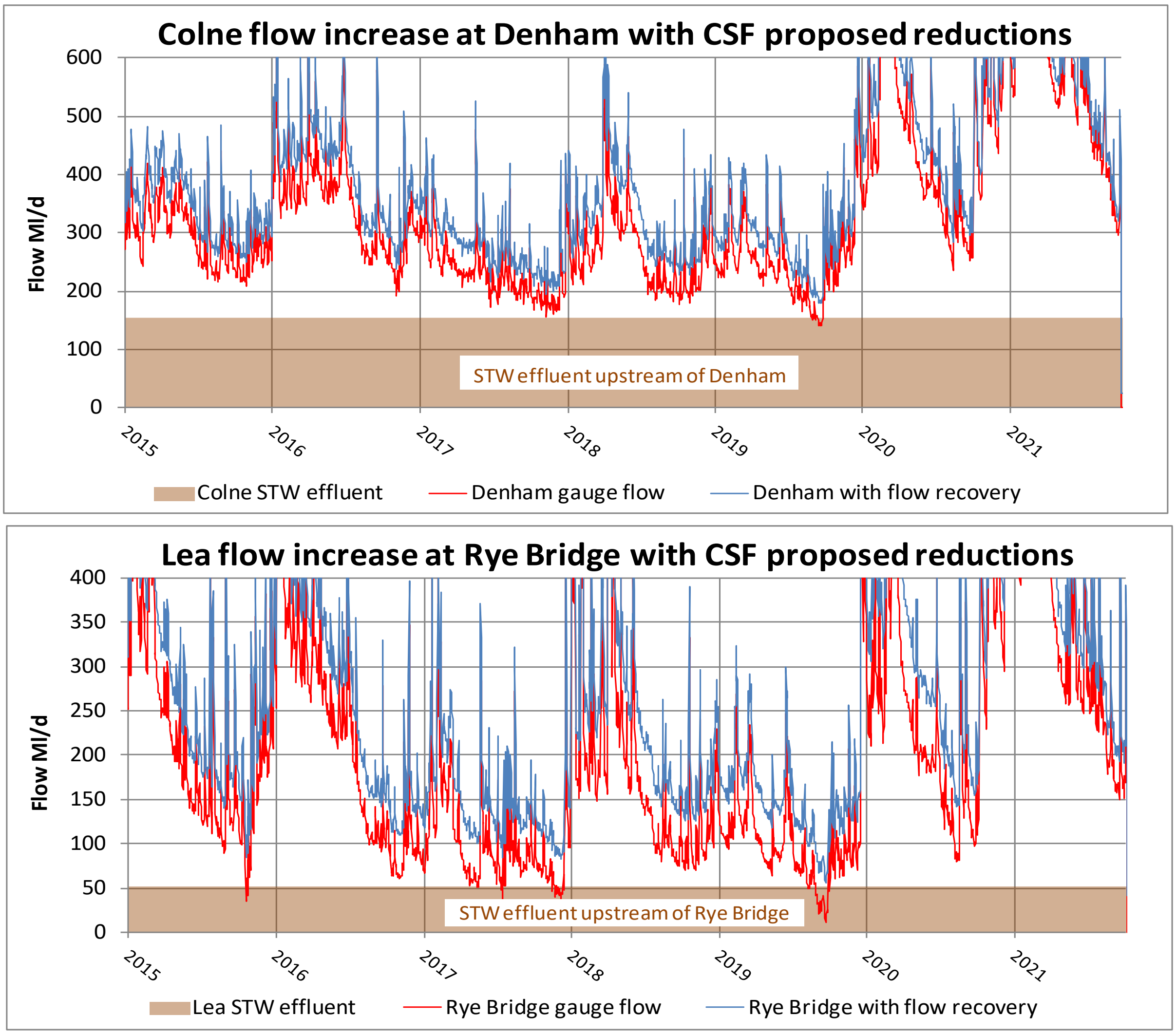
Table 5 - CSF proposed abstraction reductions in the Colne and Lea chalk streams

These reductions would restore flows to EFI compliance in all the Colne and Lea tributary chalk streams and the Upper Lea above Water Hall. The enhanced flows in these chalk streams would also provide substantial flow improvements in the lower reaches of the Rivers Colne and Lea.

5.4 Benefits to lower Colne and Lea flows from CSF proposed reductions

The effect on flows in the River Colne at Denham and the River Lea at Rye Bridge is shown in Figure 27. The Denham gauging station is located downstream of the Misbourne confluence and includes about 150 Ml/d of effluent flows from Maple Cross sewage treatment works and a number of smaller STWs in the upper Colne tributaries. The Rye Bridge gauging station on the River Lea is located downstream of the Ash confluence but upstream of the Stort. Rye Bridge flows include about 50 Ml/d of effluent from a number of STWs in the upper Lea catchment, mainly about 35 Ml/d from Luton STW, but does not include effluent from Rye Meads STW, which discharges downstream of the gauge.

The CSF modelled flow recoveries from the proposed abstraction reductions in the four case study rivers have been extrapolated to simulate the total flow recoveries at Denham and Rye Bridge from all the CSF proposed abstraction reductions shown in Table 5 excluding the Stort, ie total abstraction reductions of 63 Ml/d in the Colne and 76 Ml/d in the Lea. The flow recoveries that would have occurred in 2015 to 2021 are shown in Figure 27:



Note: the plotted STW effluent amounts are 'recent actual' data in 2015 from EA File *'HERTS Artificial Influences overview.xlsx'*

Figure 27 - Lower Colne and Lea flow recoveries from CSF proposed reductions

The CSF proposed abstraction reductions in the upper catchments would substantially increase flows in the lower rivers, which are at present mainly STW effluent flows in droughts. There would be a large increase in STW effluent dilution in droughts. The plotted 2015 'recent actual' effluent amounts in Figure 27 exceed the gauged flows at times, partly because actual effluent discharges may have been lower than 'recent actual', but perhaps mainly because of losses from the river beds at times of drought flows.

At the historic Amwell Magna fishery (about 3 km upstream of Rye Bridge gauge), summer flows would increase by about 30-50% and would no longer be almost entirely STW effluent.

5.5 Benefits to London supplies from CSF proposed reductions

The CSF modelled flow recoveries from the proposed abstraction reductions in the four case study rivers have been extrapolated to simulate the total flow recoveries in the lower Colne and Lea from the total 151 Ml/d of CSF proposed abstraction reductions shown in Table 5.

The modelled daily Colne and Lea flow recoveries since 1920 have been added to the Teddington and Feildes Weir flow records to assess the increase in London deployable output, using the GARD model of the London supply system. Details of GARD’s London supply model are given in Appendix F. In the 100-year period 1920-2019, with the enhanced reservoir inflows, the critical drought which governs London deployable output is July 1933 to November 1934 as shown in Figure 28:

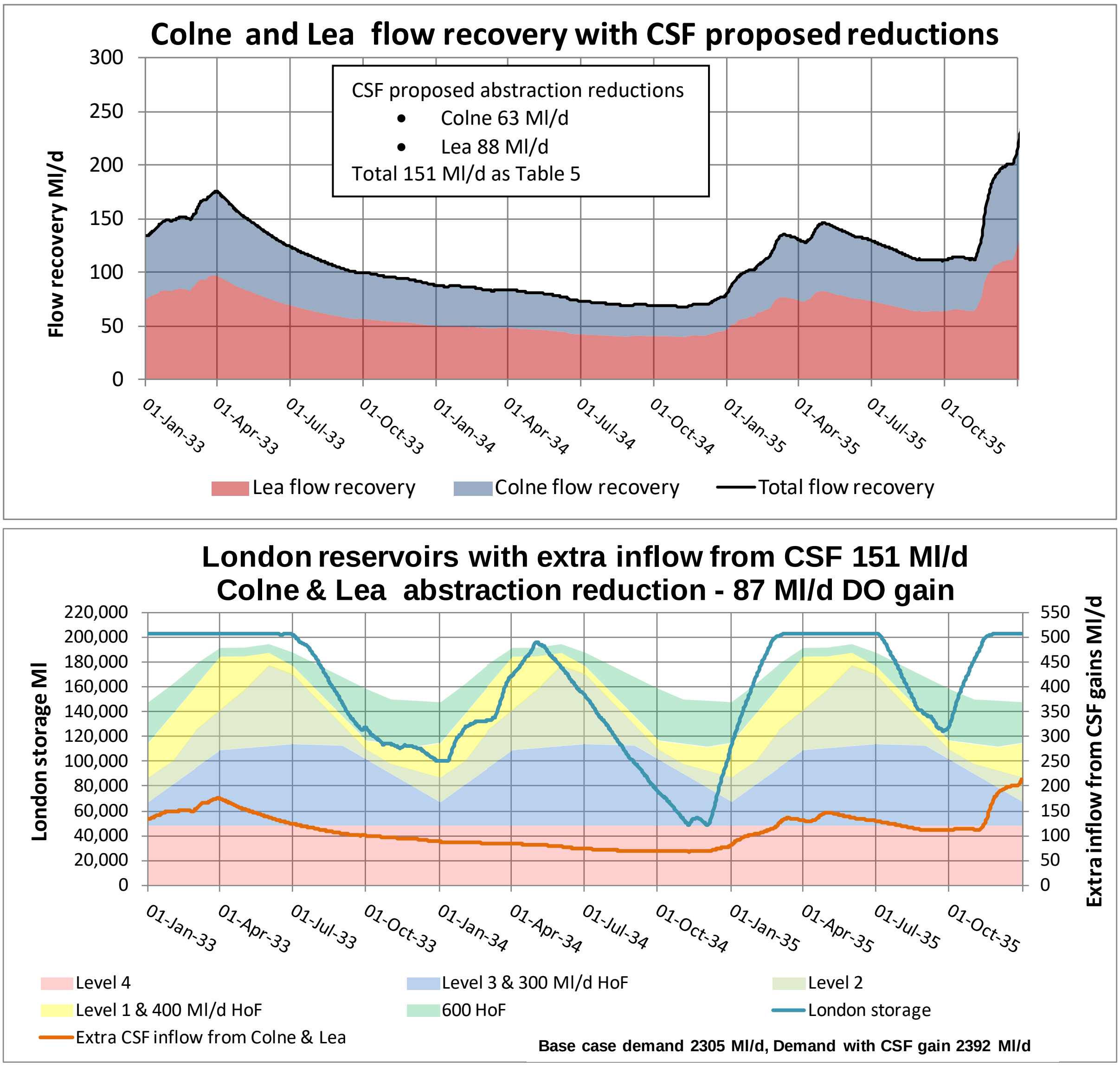


Figure 28 - Modelling of London DO gain from CSF proposed reductions in 1933-34

The modelled 87 Ml/d gain in deployable output is 58% of the 151 Ml/d abstraction reduction – a far higher gain than the 17% assumed in current draft water company WRMPs.

5.6 Conclusions on the up-dating of the CSF proposal

Under the CSF proposal, the proposed abstraction reductions would be a total of 63 Ml/d in the Colne chalkstreams and 89 Ml/d in the Lea chalk streams. The CSF modelling shows that these reductions would achieve flows that comply with the Environment Agency's proposals for Abstraction Sensitivity Bands and Ecological Flow Indicators. The flows in all the upper Colne and Lea chalk streams would be restored to near natural amounts.

In the case of the River Chess and the upper River Lea, where drought flows at present are almost entirely STW effluent, the re-naturalised flows would be in addition to the STW effluent, providing much more dilution.

The CSF proposed abstraction reductions in the upper catchments would substantially increase flows in the lower rivers. There would be a large increase in STW effluent dilution in droughts, particularly for the large STWs at Maple Cross and Rye Meads which at present provide almost all of the drought flows in the lower Rivers Colne and Lea.

At the historic Amwell Magna fishery in the middle River Lea, summer flows would benefit from all the upper catchment abstraction reductions. Flows would increase by about 30-50% and would no longer be almost entirely STW effluent in droughts.

6. Incorporation of CSF in current draft WRMPs and WRSE plan

6.1 Planned abstraction reductions in Chilterns chalk streams

The draft WRMPs for Affinity Water and Thames Water allow for substantial abstraction reductions in the Chilterns chalk streams, but there is an absence of detailed information about the amounts and locations of the planned reductions.

Similarly, WRSE's draft regional plan contains high level figures for planned reductions under several scenarios, but no information on amounts or locations. However, WRSE have responded helpfully to an information request and provided source reduction data under High, Medium and Low scenarios. The WRSE's High scenario deployable output reductions for sources in the upper Colne and Lea valleys are compared with the CSF proposed abstraction reductions in Table 6:

		CSF proposed reduction		**WRSE High scenario DO loss**		
Colne catchment:	**Recent abstraction 2019-21**	**CSF proposed abstraction**	**Abstraction reduction**	**Reduction by 2034-35**	**Reduction by 2039-40**	**Reduction by 2049-50**
Misbourne	15.8 Ml/d	6.2 Ml/d	9.6 Ml/d	2.0 Ml/d	Await more figures from WRSE	2.0 Ml/d
Chess	15.1 Ml/d	4.1 Ml/d	11.0 Ml/d	0.0 Ml/d		2.0 Ml/d
Gade	36.2 Ml/d	11.9 Ml/d	24.3 Ml/d	4.7 Ml/d		36.4 Ml/d
Ver	25.8 Ml/d	7.7 Ml/d	18.1 Ml/d	6.4 Ml/d		11.8 Ml/d
		Colne total	**63.0 Ml/d**	**13.1 Ml/d**		**52.2 Ml/d**
Lea Catchment:						
Upper Lea to Water Hall	48.4 Ml/d	7.2 Ml/d	41.2 Ml/d	4.1 Ml/d	Await more figures from WRSE	36.9 Ml/d
Mimram	10.4 Ml/d	6.1 Ml/d	4.3 Ml/d	4.4 Ml/d		6.9 Ml/d
Beane	24.9 Ml/d	9.8 Ml/d	15.2 Ml/d	14.0 Ml/d		21.6 Ml/d
Rib	22.8 Ml/d	7.3 Ml/d	15.5 Ml/d	2.0 Ml/d		15.8 Ml/d
Ash	1.2 Ml/d	0.0 Ml/d	0.0 Ml/d	0.7 Ml/d		0.7 Ml/d
Stort	25.0 Ml/d	13.5 Ml/d	11.5 Ml/d	12.1 Ml/d		18.0 Ml/d
		Lea total	**87.6 Ml/d**	**37.3 Ml/d**		**100.0 Ml/d**
		Total	**150.6 Ml/d**	**50.4 Ml/d**		**152.2 Ml/d**

Note: WRSE data supplied by WRSE in file *"GARD-03 Source Level Environmental Ambition Data.xlsx"*

Table 6 - CSF and WRSE abstraction reduction proposals in upper Colne/Lea tributaries

The figures in Table 6 show that the CSF proposed reductions align quite well with the losses of deployable output that would ultimately occur under WRSE's High demand scenario, which is understood to be the central planning assumption in Thames Water and Affinity Water's WRMPs. The CSF and WRSE figures are not directly comparable because the CSF figures are reductions from recent abstraction and WRSE figures are losses in deployable output. This will explain some of the differences in figures for the individual chalk streams, but there may be some significant differences in approach, for example:

1. WRSE allow for a combined loss in deployable output of 4 Ml/d in the Rivers Chess and Misbourne, whereas CSF proposed a 20 Ml/d reduction in abstraction from recent levels. This may be because WRSE's figures allow for effluents from STWs in the Chess and Misbourne catchments when calculating EFIs and assessing flow compliance. The CSF figures do not allow for STW effluents when assessing flow acceptability, because treating effluents as natural flow does not take into account the needs for effluent dilution. It sometimes leads to river flows comprising 100% STW effluent in droughts.

2. The WRSE proposed loss of deployable output in the Rivers Gade and Beane is close to 100% of recent abstraction in these catchments. This suggests that no abstraction is considered acceptable in these rivers. The CSF approach allows for in the region of 5-10% of natural recharge to be abstracted.

However, the main difference between the CSF and WRSE proposals for the upper Colne and Lea chalk streams is in the timing of the abstraction reductions. The WRSE plan delays most of the abstraction reductions until after 2040, because of the supposed need to wait for construction of major new sources like the Severn to Thames transfer or Abingdon reservoir. This is the consequence of the water company assumption that only 17% of the flow recovery from abstraction reductions converts to increased deployable output from the London reservoirs. The CSF proposal is that the reductions can be achieved within 10 years without needing to wait for any major new sources, taking account of much higher deployable output recovery for the London reservoirs. This issue is considered further in Section 6.2.

There is also a big difference in approach to the need for abstraction reductions in the lower parts of the Rivers Colne and Lea. WRSE's proposals for the lower rivers are shown in Table 7:

		WRSE DO loss			
	Licensed amount	**2034/35**	**2039/40**	**2049/50**	**2074/75**
Middle Colne groundwater	246 Ml/d		Await data from WRSE	79 Ml/d	79 Ml/d
Middle/Lower Lea groundwater	52 Ml/d	18 Ml/d		22 Ml/d	22 Ml/d
Middle/lower Lea surface water	102 Ml/d*			80 Ml/d	185 Ml/d
	Total DO loss	**18 Ml/d**		**181 Ml/d**	**286 Ml/d**

*Licensed amount is less than the DO loss - WRSE have been asked to clarify

Table 7 - DO losses from WRSE proposed reductions in lower Rivers Colne and Lea

These reductions add up to nearly double the amount of the groundwater abstractions from the upper catchment chalk streams shown in Table 6. However, whereas the abstraction reductions in the upper Colne and Lea catchments are easily justified in terms of restoring near-natural flows in iconic chalk streams, with rheophilic ecologies (suited to fast flow), the benefits of the much larger reductions in the lower Colne and Lea are much less clear, because the river channels are heavily canalised and impounded for current and historic navigational purposes.

It should also be noted that the lower Colne and lower Lea will benefit from substantial flow increases from abstraction reductions in the upper catchment chalk streams, as illustrated in the hydrographs in Figure 27. The flow increases from the upper abstraction reductions alone would give significant improvement to the lower Rivers Colne and Lea.

It is suggested that the abstraction reductions in WRSE's plan and the WRMPs should be transparently prioritised, specifying the benefits and costs of each reduction, with due consideration of the disbenefits of the impacts of constructing the replacement sources.

6.2 The 17% flow recovery assumed in WRMPs and WRSE's plan

WRSE have advised that 17% deployable output recovery for London's supply system has been assumed for all Thames valley abstraction reductions[17]. The basis for this assumption is explained in Technical Appendix 5.6 to Affinity Water's draft WRMP[18]. The justification of the 17% DO recovery appears to have been simply:

1. During the critical historic droughts of 1921 and 1934, the average natural flow percentile in the River Thames at Kingston was said to be around the 98th percentile, ie Qn98 (Appendix 5.6, page 14).
2. Recovery of flows from abstraction reductions in the Colne and Lea catchments was assessed as falling across the flow range, with an average of 17% recovery at the 98th percentile.
3. Therefore, the deployable output gain from abstraction reductions is 17%.

There appear to be several flaws in this assessment. Firstly, the average River Thames at Kingston naturalised flows (NRFA record) during the periods of Thames Water's WARMS2 modelled recession of storage in the London reservoirs during the 1921 and 1934 droughts were more than the 98 %-ile:

- **1921 drought**: recession start 17 April, end 26 December, **average %-ile 95%**
- **1933-34 drought**: recession start 28 June '33, end 9 November '34, **average %-ile 89%**

The average Thames natural flow percentile in the 1921 and 1934 droughts was 92%, not 98%.

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[17] WRSE response to information request in Excel file *"GARD-03 and GARD-04 Environmental Ambition Summary.xlsx"*

[18] Deployable Output Benefits of Abstraction Reduction. Appendix 5.6 to Affinity Water draft WRMP24. https://affinitywater.uk.engagementhq.com/wrmp

Secondly, the average of chalk stream flows during the drought recessions are also at the 92nd percentile rather than the 98th percentile. This is illustrated in Figure 29 for the CSF modelled baseflows at Hansteads on the River Ver in the 1921 and 1934 droughts:

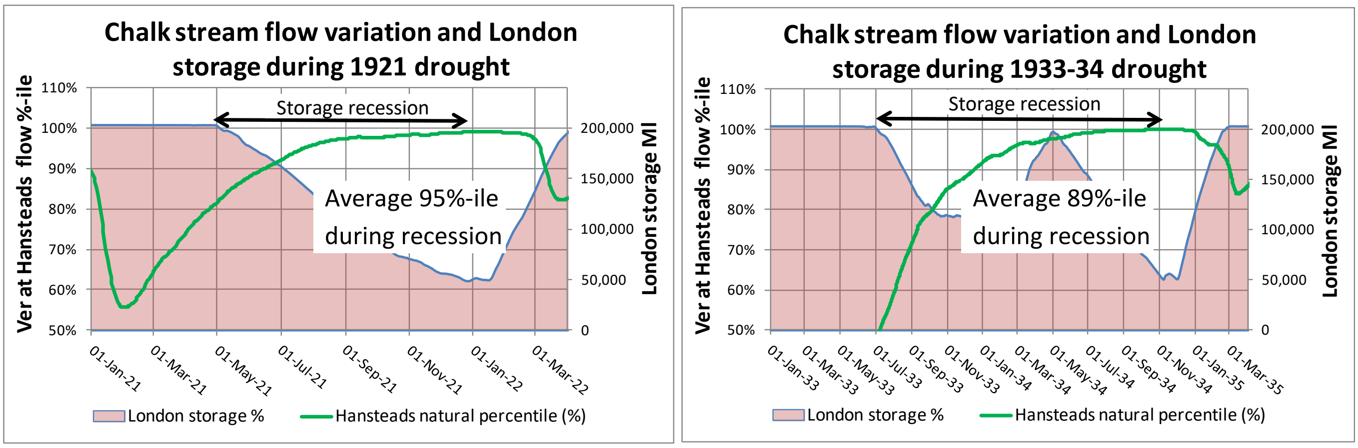


Figure 29 - Chalk stream flow percentiles during 1921 and 1934 droughts

Thirdly, the modelled and measured flow recoveries in droughts at the 92nd percentile described in Chapters 3 and 4 are a lot more than the 17% recovery assumed by Thames Water and Affinity Water. The CSF and HRGM modelled flow recoveries at the 92nd percentile, as illustrated on Figure 16 are compared in Table 8:

	Modelled flow recovery at 92nd percentile flows	
	CSF model	**HRGM model**
Chess at Rickmansworth	62.9%	92.9%
Ver at Hansteads	59.7%	61.7%
Mimram at Panshanger	52.4%	66.5%
Beane at Hartham	51.1%	60.3%
Average modelled recovery at 92nd percentile flows	**56.5%**	**70.4%**

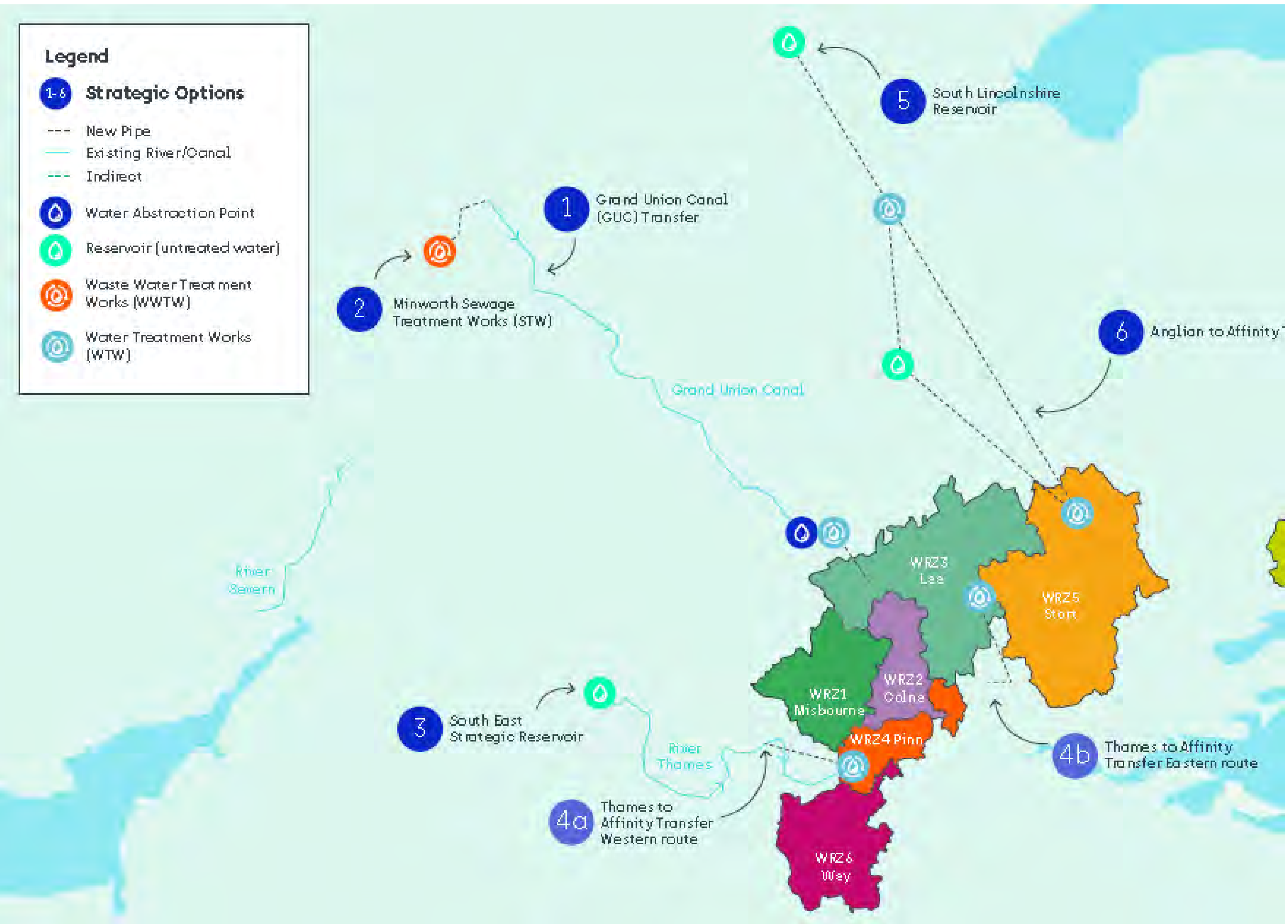
Table 8 - CSF and HRGM modelled flow recoveries at 92nd percentile flows

These flow recoveries are far more than the 17% flow recovery assumed by the water companies in their WRMPs and in WRSE's regional plan. The CSF modelled recovery of 56.5% aligns quite well with the modelled deployable output gain of 58% simulated for all Chilterns chalk streams using the GARD model of the London supply system, as described in Section 5.5 and illustrated in Figure 28.

Due to the difficulty of measuring flow recoveries as described in Chapter 3, it is proposed that groundwater modelling should be the primary means of estimating flow recoveries. This is consistent with use of models to estimate the amounts of required abstraction reductions. It would seem irrational to use models to determine the need for abstraction reductions and then not use the same models to estimate flow and deployable output recovery.

6.3 Infrastructure proposals for CSF in Affinity Water’s draft WRMP

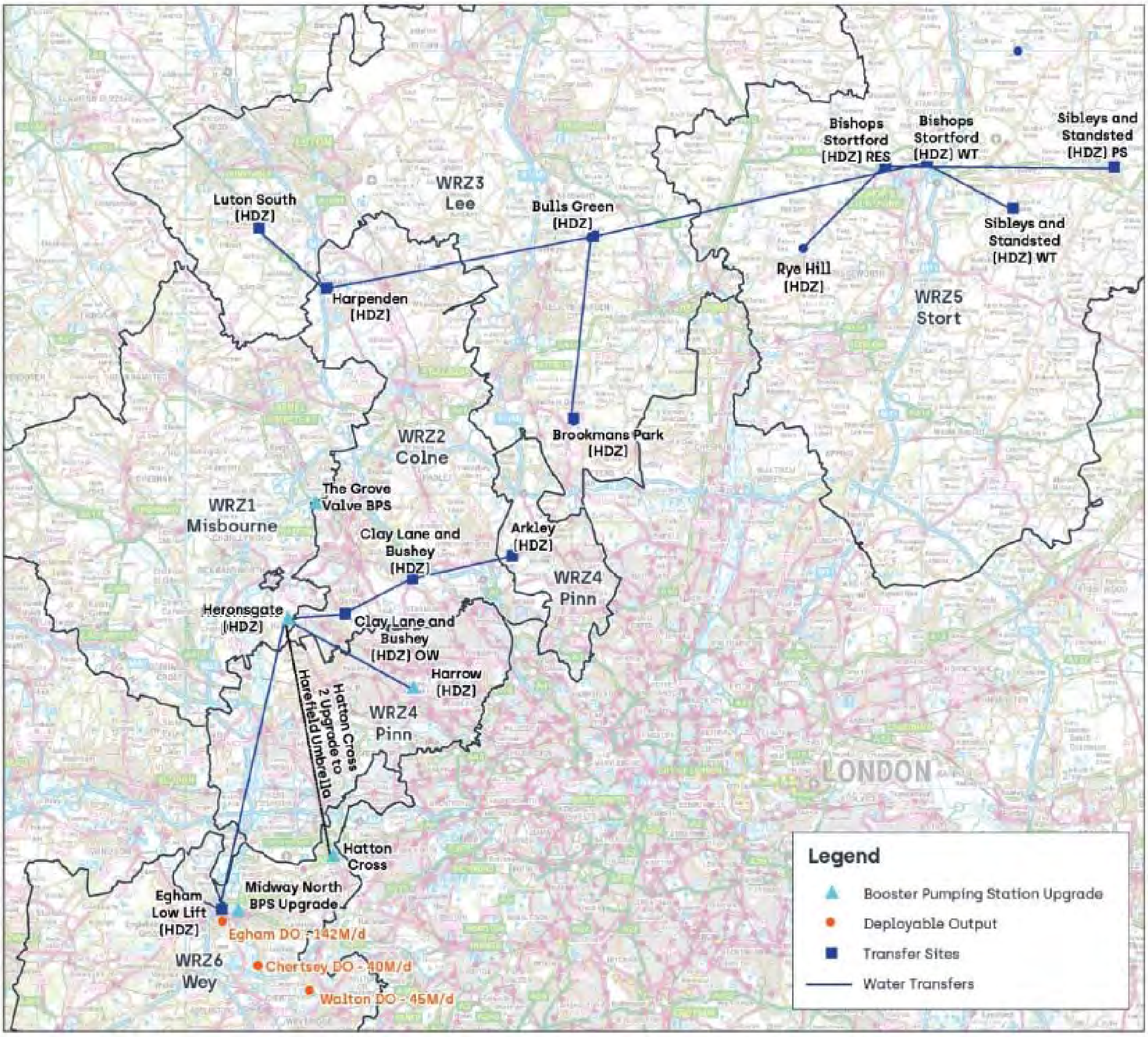
Affinity Water’s draft WRMP includes plans for infrastructure to deliver the replacement supplies needed to enable the CSF proposed abstraction reductions. The planned infrastructure comprises several strategic resource options and a pipe network, termed ‘Connect 2050’, to deliver replacement water to the areas that are scheduled for abstraction reductions. The strategic resource options are shown on Figure 30:



Map copied from Figure 7.3 in draft Affinity Water WRMP24 report

Figure 30 - Strategic Resource Options in Affinity Water's draft WRMP24

From the perspective of Chalk Streams First, any of these strategic options could deliver the required water. However, there would be a strong preference for options that can be delivered quickly to enable the planned reductions in the Chilterns chalk streams to be in operation within the next 10 years, using the planned network system referred to as ‘Connect 2050’ and shown in Figure 31.



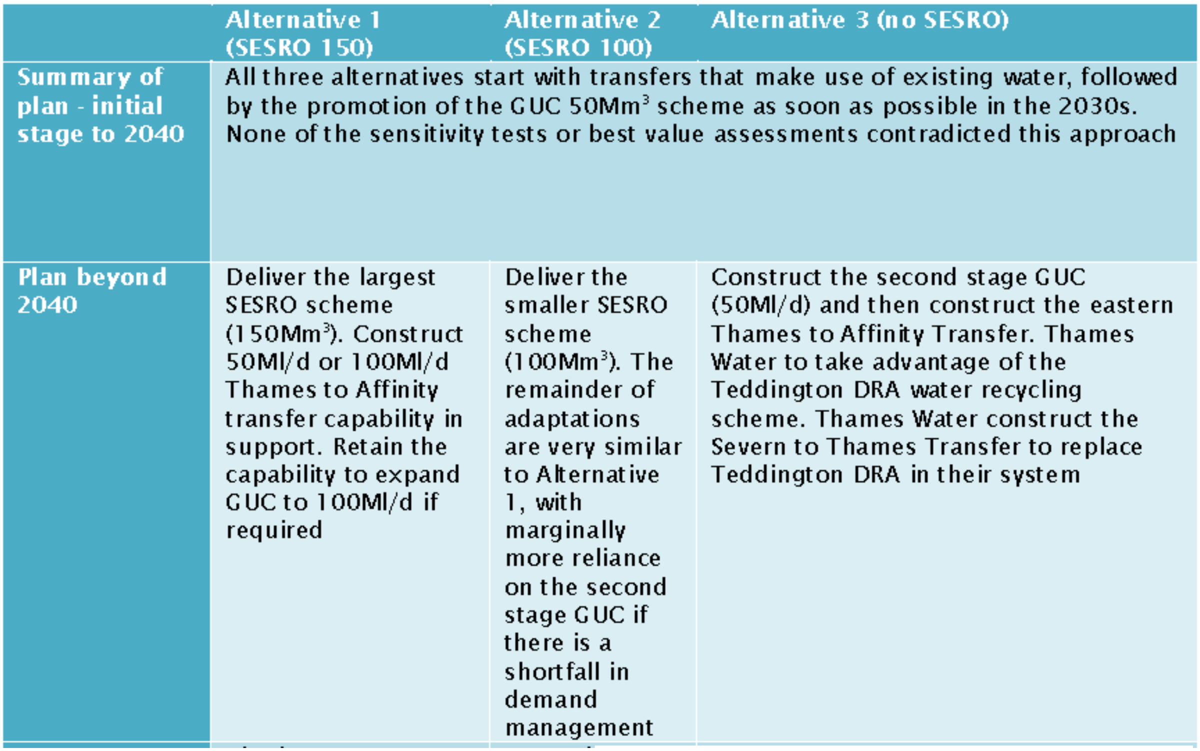
Map copied from Figure 9.18 in draft Affinity Water WRMP24

Figure 31 - Planned 'Connect 2050' pipe network

Affinity Water’s plan proposes that a 50 Ml/d first phase of the Grand Union canal transfer, bringing in treated effluent from Minworth STW, should be in operation by 2031. This has the potential to facilitate a considerable proportion of the planned 150 Ml/d of abstraction reductions in the Chilterns chalk streams, with the potential to replace groundwater supplies in both the Colne and the Lea chalk catchments.

As yet, no decision has been taken on which further strategic resource options will be selected or their timing. However, Affinity Water’s plan says that their ‘best value’ modelling has shown a strong preference for Abingdon reservoir (also termed SESRO) over the Severn to Thames transfer, and a preference for the second phase of the GUC transfer rather than Lea valley link to London’s Eastern supply system (with support from Beckton STW effluent recycling).

Therefore, Affinity Water plan states that they now need to choose between just the three alternatives shown in Table 9:



	Alternative 1 (SESRO 150)	Alternative 2 (SESRO 100)	Alternative 3 (no SESRO)
Summary of plan - initial stage to 2040	All three alternatives start with transfers that make use of existing water, followed by the promotion of the GUC 50Mm^3 scheme as soon as possible in the 2030s. None of the sensitivity tests or best value assessments contradicted this approach		
Plan beyond 2040	Deliver the largest SESRO scheme (150Mm^3). Construct 50Ml/d or 100Ml/d Thames to Affinity transfer capability in support. Retain the capability to expand GUC to 100Ml/d if required	Deliver the smaller SESRO scheme (100Mm^3). The remainder of adaptations are very similar to Alternative 1, with marginally more reliance on the second stage GUC if there is a shortfall in demand management	Construct the second stage GUC (50Ml/d) and then construct the eastern Thames to Affinity Transfer. Thames Water to take advantage of the Teddington DRA water recycling scheme. Thames Water construct the Severn to Thames Transfer to replace Teddington DRA in their system

Table copied from Table 9.11 in draft Affinity Water WRMP24

Table 9 - The three strategic option alternatives in Affinity Water's draft WRMP

It appears that, apart from the 50 Ml/d first phase of the GUC transfer, there will be no other new schemes to provide replacement supplies for abstraction reductions before 2040. This is perhaps why the pipe network shown in Figure 31, named 'Supply 2040' in Affinity Water's 2019 WRMP, has been re-named 'Connect 2050'. It explains why WRSE's plan only allows for about 50 Ml/d of Chilterns chalk stream abstraction reductions by 2035, mostly in the Lea chalk streams, as shown in Table 6.

It seems that the majority of the planned 150 Ml/d of abstraction reductions in the upper Colne and Lea catchments, as shown in Table 6, will have to wait for the construction and filling of Abingdon reservoir and the first phase of the Thames to Affinity transfer, which is not scheduled to be in operation until 2040. From the perspective of the NGOs supporting the Chalk Streams First proposal and the local people and organisations who have been campaigning for improvements for many years, this is all extremely disappointing.

It is particularly disappointing that the first phase of the Thames to Affinity transfer strategic resource option has been put back to 2040, presumably because this is the earliest date that Abingdon reservoir can be built, filled and made available to supply water to Affinity Water's Chilterns supply zones.

The delay in construction of the Thames to Affinity transfer means that there is no opportunity to feed water from London's supplies into the Chilterns before 2040, even though by 2031 London's supplies will benefit from the 50 Ml/d of new water coming into the Chilterns from the GUC transfer – much of this will become available to fill London's reservoirs, either from increased effluent returns or from enhanced chalk stream flows from the abstraction reductions. There will also be additional water coming into the Chilterns and making its way to London from the 25 Ml/d increased supply from Grafham reservoir, scheduled to be in operation by 2025.

Therefore, it is proposed that the first phase of the Thames to Affinity Transfer should be brought forward to its earliest feasible completion date, perhaps the early 2030s. This would facilitate some more of the planned Chilterns chalk abstraction reductions to proceed quickly, particularly in the upper Colne chalk streams. For example, this would enable water from Thames Water's Teddington DRA scheme (using recycled Mogden STW effluent and scheduled for the early 2030s) to support an early transfer of water into the Chilterns, with much of it returning via the enhanced chalk stream flows.

It is appreciated that there is uncertainty over the amount of flow recovery in critical droughts. One way of removing this uncertainty is to convert some of the Chilterns sources scheduled for abstraction reductions into drought-only supply schemes similar to Thames Water's existing West Berkshire Groundwater Scheme. This could only be done or trialled after construction of at least part of the Thames to Affinity transfer. The feasibility of using the West Berkshire Groundwater Scheme concept in the Chilterns is considered in Chapter 7.

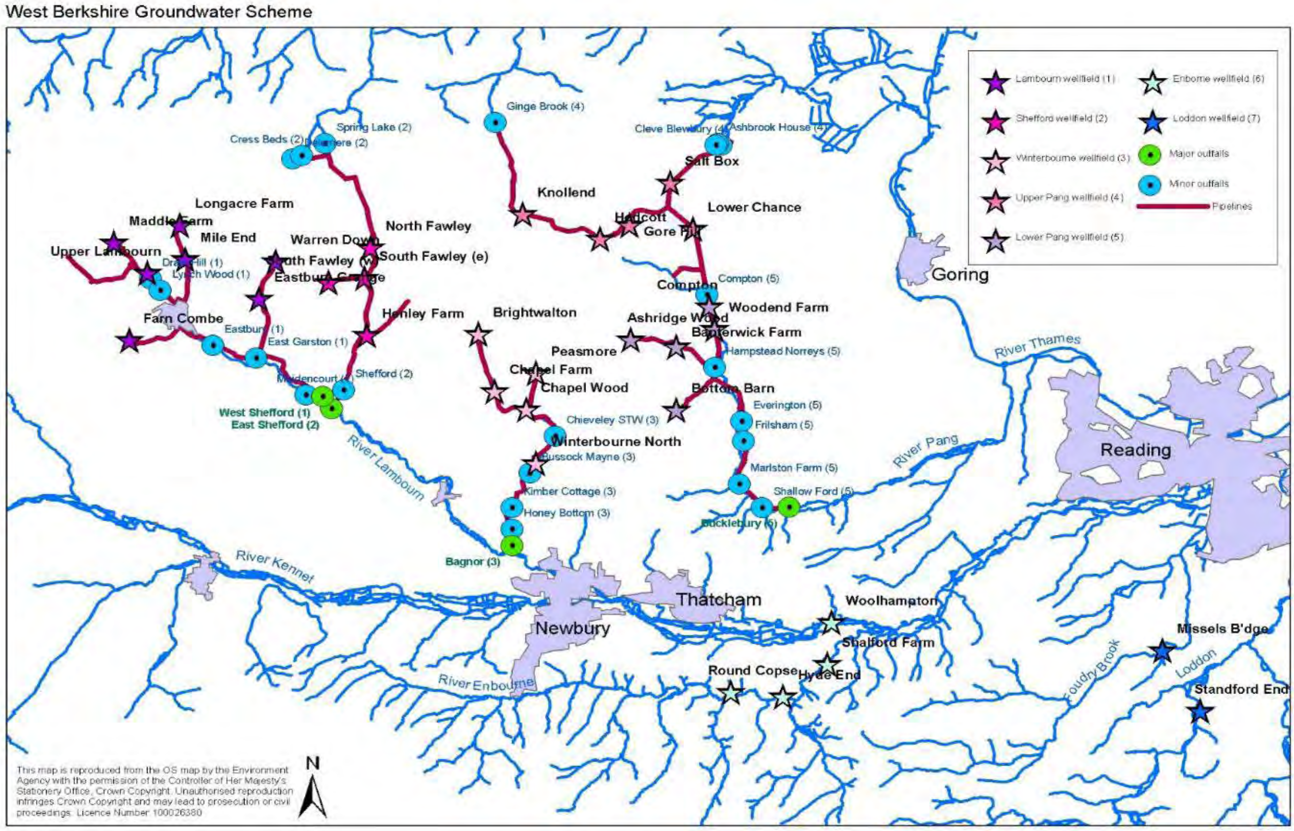
7. Future conversion to WBGWS-type drought support schemes

7.1 The existing West Berkshire Groundwater Scheme

The West Berkshire Groundwater Scheme (WBGWS) was constructed in the 1970s to augment London’s water supplies during severe droughts – its planned use is about once in 25 years. The scheme abstracts water from boreholes in the chalk aquifer in the upper Lambourn, Pang, Enbourne and Loddon valleys, discharging water into those rivers from where it flows down into the River Thames for later abstraction to fill London’s reservoirs. It contributes about 90 Ml/d to London’s deployable output.

The WBGWS concept could be used in the chalk streams of the Colne and Lea valleys, operating in conjunction with the abstraction reductions proposed for the Chalk Streams First scheme. When triggered in droughts, boreholes in the Colne tributaries would augment flows in the River Thames for abstraction into the lower Thames reservoirs. Boreholes in the Lea tributaries would supplement filling of the Lea valley reservoirs.

The layout and components of the existing WBGWS are shown in Figure 32:



Map copied from Environment Agency presentation to Action for the River Kennet in January 2020

Figure 32 - Layout of the West Berkshire Groundwater Scheme

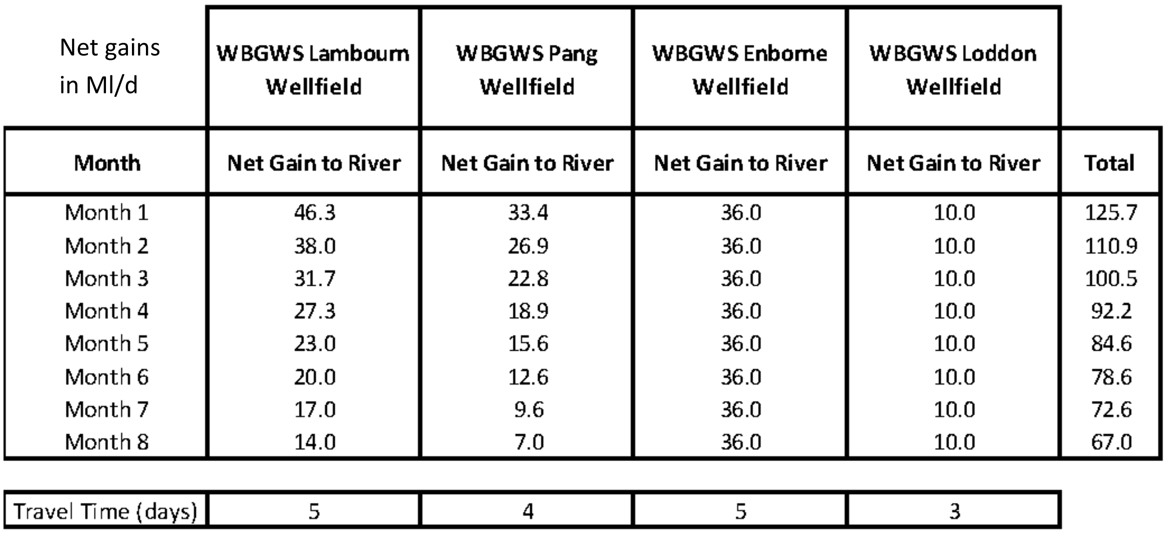
The existing WBGWS scheme has the following components:

- 7 well fields
- 32 abstraction boreholes with pumps

- 100 + observation boreholes
- 4 major outfalls + 24 minor outfalls
- 400+ valves (sluice, air and control) + surge vessels + booster pumps
- 87 km pipelines

In general, the scheme abstracts groundwater in the upper parts of the chalk valleys, where there is little if any perennial river flow, and transfers water via pipelines to discharge into the lower parts of the valleys where there is perennial river flow even in severe droughts. This avoids discharging the water into a dry river bed where it would quickly sink back to the water table. There are some intermediate discharge points to augment drought flows further up the valleys, simulating a natural flow accretion profile.

In a drought, the scheme is allowed to be used for a maximum of 8 months. The maximum daily release in each donor catchment corresponds to roughly 20-30% of average catchment recharge. The total release from the donor catchments gradually reduces from 126 Ml/d to 67 Ml/d, as the drought progresses as shown in Table 10:



Net gains in Ml/d	**WBGWS Lambourn Wellfield**	**WBGWS Pang Wellfield**	**WBGWS Enborne Wellfield**	**WBGWS Loddon Wellfield**	
Month	**Net Gain to River**	**Net Gain to River**	**Net Gain to River**	**Net Gain to River**	**Total**
Month 1	46.3	33.4	36.0	10.0	125.7
Month 2	38.0	26.9	36.0	10.0	110.9
Month 3	31.7	22.8	36.0	10.0	100.5
Month 4	27.3	18.9	36.0	10.0	92.2
Month 5	23.0	15.6	36.0	10.0	84.6
Month 6	20.0	12.6	36.0	10.0	78.6
Month 7	17.0	9.6	36.0	10.0	72.6
Month 8	14.0	7.0	36.0	10.0	67.0
Travel Time (days)	5	4	5	3	

Table from Thames Water response to GARD questions in February 2016

Table 10 - Planned use of WBGWS in droughts

The scheme is triggered in periods of extremely low flows in the River Thames, when the London reservoir storage has been below the Level 2 curve on the Lower Thames Control Diagram for 10 days[19]. The use of the scheme stops when the storage in the London reservoirs has risen above the Level 2 control line for at least 10 days. The scheme cannot be triggered again until 12 months after its last use – this allows groundwater levels to recover before the scheme is used again. The Lower Thames Control Diagram is shown on Figure 33:

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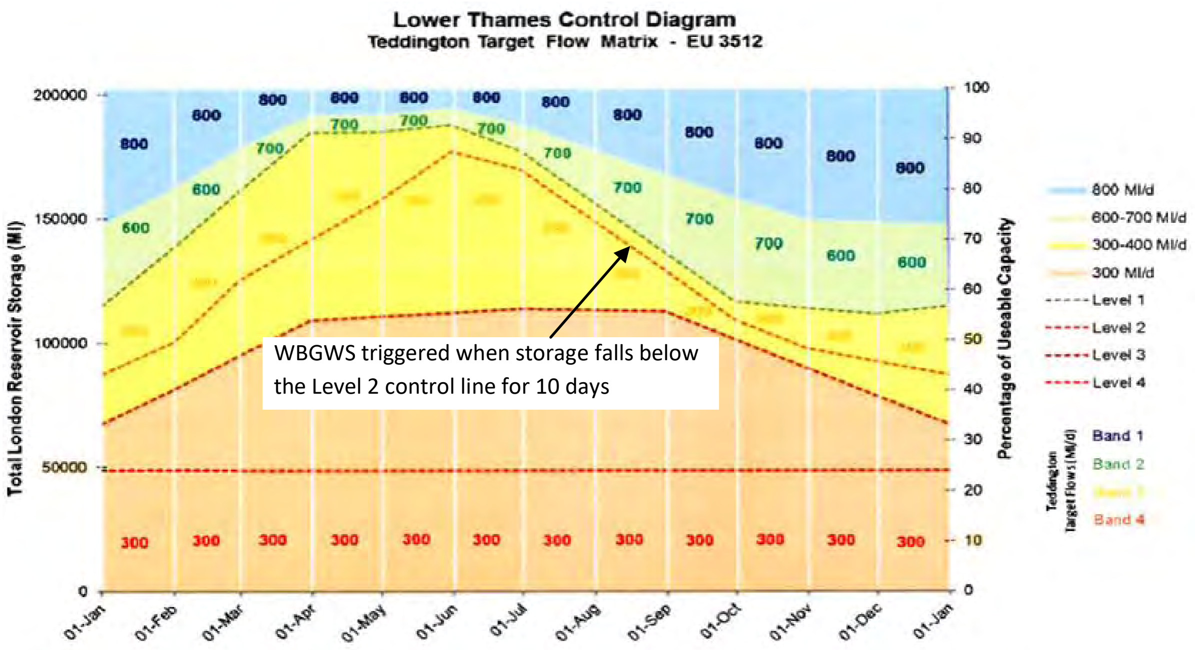
[19] These operating rules are as simulated in Thames Water's WARMS2 modelling for the 2019 Water Resource Management Plan, as provided to GARD in Excel file *"Copy of GARD AR17 London DO 2305 Mld 2017-04.xlsx".*



WBGWS triggered when storage falls below the Level 2 control line for 10 days

Figure 33 - Lower Thames Control Diagram showing trigger for the WBGWS

The London storage only falls below the Level 2 control line in severe droughts. For example, on 12th October 2022, the Environment Agency announced their intention to start using the scheme on 24th October. London reservoir storage was 60% on 30th September[20], but would have been expected to have been below the Level 2 control line for 10 days by 24th October.

Thames Water's WARMS2 modelling of the London supply system for their 2019 Water Resource Management Plan showed that, in the past 100 years, the WBGWS would only have been used significantly in the droughts of 1921/22, 1933/34, 1943/44 and 1975/76. The scheme would also have been triggered briefly in 1949. The WARMS2 model assumes losses of 2% in transferring water from the donor catchments to the London reservoirs.

The GARD model of the London supply system, as described in Appendix F, uses the same WBGWS operating rules as the WARMS2 model and also assumes 2% transfer losses. The GARD modelling exactly matches the WARMS2 model assessment of London's deployable output as 2305 Ml/d.

Using the GARD model of the London supply system, if the WBGWS is switched off, the London deployable output drops by 91 Ml/d from 2305 Ml/d to 2214 Ml/d. In other words, the deployable output of the WBGWS scheme is 91 Ml/d.

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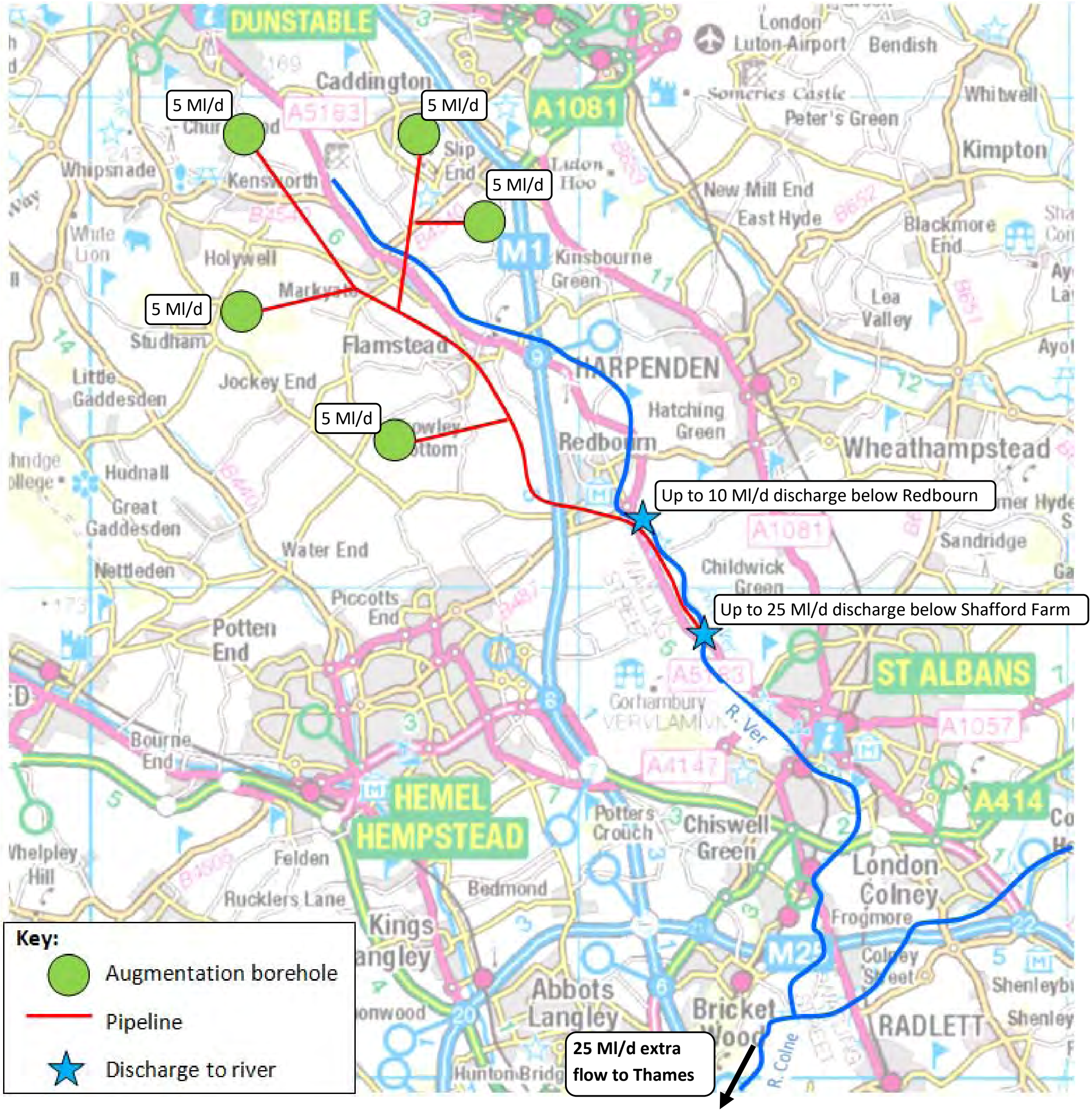
[20] CEH Monthly Hydrological Summary, Sep 22, page 10
https://nrfa.ceh.ac.uk/sites/default/files/HS_202209.pdf

7.2 A potential WBGWS-type scheme for the River Ver

A possible layout of a WBGWS-type scheme for the River Ver is shown on Figure 34:


5 Ml/d

5 Ml/d

5 Ml/d

5 Ml/d

5 Ml/d

Up to 10 Ml/d discharge below Redbourn

Up to 25 Ml/d discharge below Shafford Farm

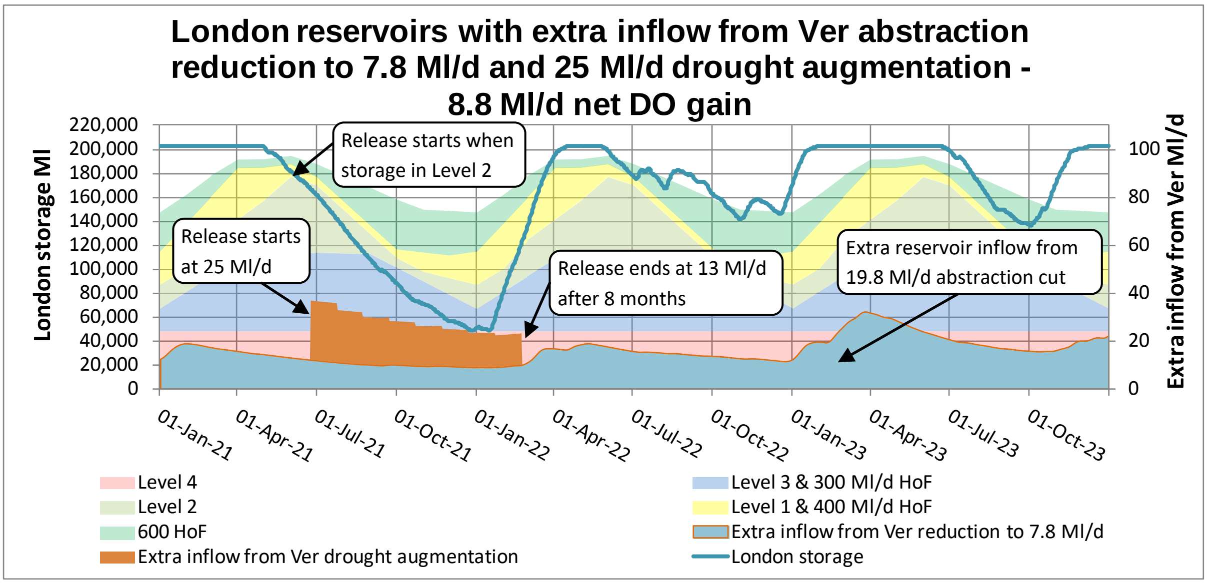
25 Ml/d extra flow to Thames

Figure 34 - Sketch layout of a possible drought augmentation scheme for the River Ver

For example, for the River Ver, new augmentation boreholes in the upper Ver valley could increase river flows in droughts by, say, 25 Ml/d, equivalent to about 30% of average catchment recharge. Abstraction from the public water supply boreholes would continue throughout the droughts at the Chalk Streams First proposed rate of 7.8 Ml/d (A10%R). The main discharge point would need to be at a place where the river would still be flowing at the end of the augmentation period, when total public water supply abstraction is at the CSF proposed rate of 7.8 Ml/d (A10%R). Spot gauging showed that the river always flowed at Shafford Farm in the droughts of 2017 and 2019, when abstraction was about 28 Ml/d, so it would be expected to be flowing throughout severe droughts if abstraction was reduced to the proposed 7.8 Ml/d – Shafford Farm is the 25 Ml/d discharge location shown on Figure 34.

There could also be one or more upstream discharge points, for example below Redbourn at the location shown on Figure 34. At the start of the 8-month augmentation period in early summer, some of the 25 Ml/d augmentation would be discharged at these points, where the river should still be flowing when overall abstraction has been reduced to 7.8 Ml/d. As the drought progresses and groundwater levels fall to beneath river bed levels at the upper discharge points, all the augmentation would be discharged at the lowest discharge point.

If Affinity Water's Ver abstraction is reduced from 27.6 Ml/d to 7.8 Ml/d and replaced by a continuous 19.8 Ml/d transfer from the London reservoirs, the combination with a 25 Ml/d Ver WBGWS-type scheme would <u>give a net London deployable output increase of 8.8 Ml/d</u>. Simulation of the effect of this scheme on the London reservoirs in the critical drought of 1921/22 using GARD's London supply model is shown in Figure 35:



Notes: 1. London simulated demand 2313.8 Ml/d plus 19.6 Ml/d transfer to Affinity Water
2. Extra inflow from Ver reduction to 7.8 Ml/d as per Figure A23 in Appendix A.

Figure 35 - GARD model simulation of Ver 25 Ml/d WBGWS-type scheme in 1921/22

The simulated London demand in Figure 35 is 2313.8 Ml/d, giving a deployable output gain of 8.8 Ml/d over the existing London DO of 2305 Ml/d, as modelled for Thames Water's WRMP in 2019. The 8.8 Ml/d gain arises because the transfer of 19.8 Ml/d from the London reservoirs to Affinity is more than offset by the flow recovery from the 19.8 Ml/d abstraction reduction, combined with the 8 months of drought support releases.

The CSF modelling of the effect of the combined 19.8 Ml/d abstraction reduction and drought support releases on Ver catchment groundwater levels and baseflows is shown on Figure 36:

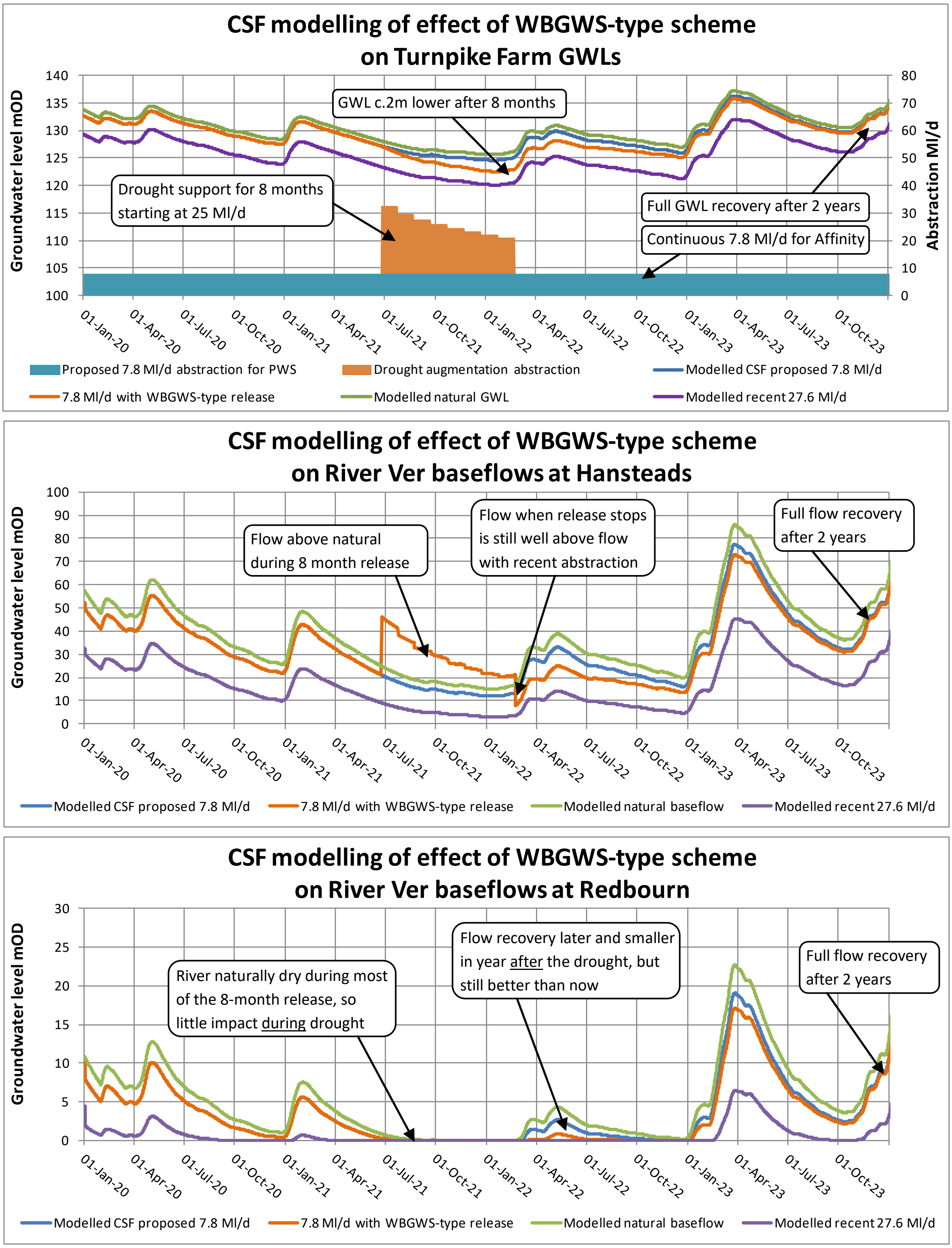


Figure 36 - CSF modelling abstraction reduction with WBGWS-type scheme for River Ver

The upper plot in Figure 36 shows that, at the end of the 8-month drought, support the WBGWS-type release would reduce the GWL at Turnpike Farm by about 2m. GWLs would then take about 2 years to recover fully to the level without the drought support releases.

The middle plot in Figure 36 shows that baseflow in the lower river at Hansteads would be well above natural drought flow while the releases are made, but still less than a ‘normal’ summer flow. After the release stops in February 2022, baseflow would drop from 21 Ml/d to 8 Ml/d, which compares with a flow of only 3.5 Ml/d with abstraction at the present 28 Ml/d and 13.5 Ml/d with abstraction at the proposed 7.8 Ml/d (A10%R). It would take 2 years for full flow recovery, but flows in the first summer after the drought would still be about double the flows without the CSF proposed abstraction reduction.

The lower plot in Figure 36 shows that the WBGWS-type abstraction would have made virtually no difference to the timing of the river drying at Redbourn in July 1921. The arising of flow in the following year, spring 1922 would have been delayed by about 10 days and the flow in summer 1922 would have been be considerably less than it would have been without the WBGWS-type support. However, if abstraction was at the present level of 28 Ml/d, the river would be dry at Redbourn throughout the summer after a drought like 1921/22.

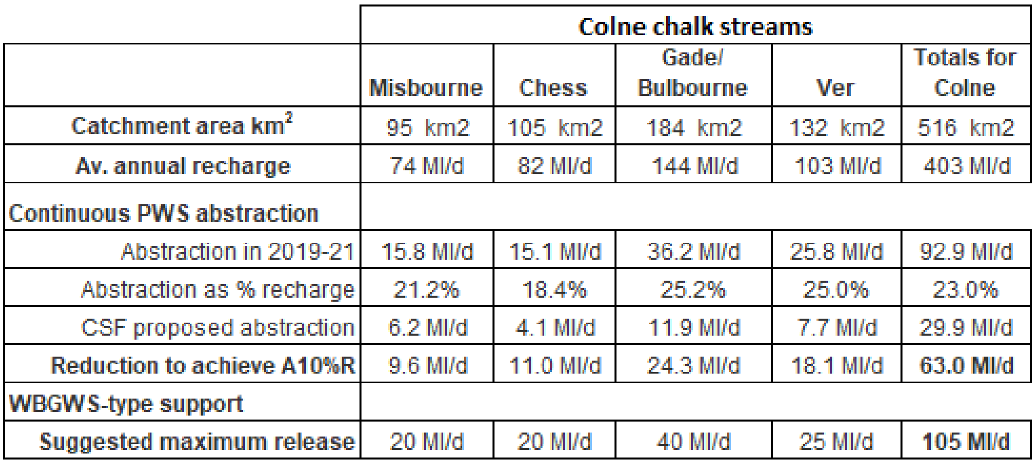
In summary, the effect of the WBGWS-type scheme on flows at Hansteads would be roughly neutral – more flow in the drought year and less flow in the year after the drought. At Redbourn, the WBGWs-type scheme would have little effect on the drying of the river in the main drought year, but would considerably reduce the duration and amount of flows in the following year. However, at both Hansteads and Redbourn, flows in and after the drought would still be much higher than they would be if abstraction remained at its current level of 28 Ml/d.

Overall, the combination of the WBGWS-type scheme with the proposed abstraction reduction from about 28 Ml/d to 8 Ml/d gives a nearly complete re-naturalisation of flows, whilst potentially increasing the combined water resources of Thames Water and Affinity Water by about 9 Ml/d.

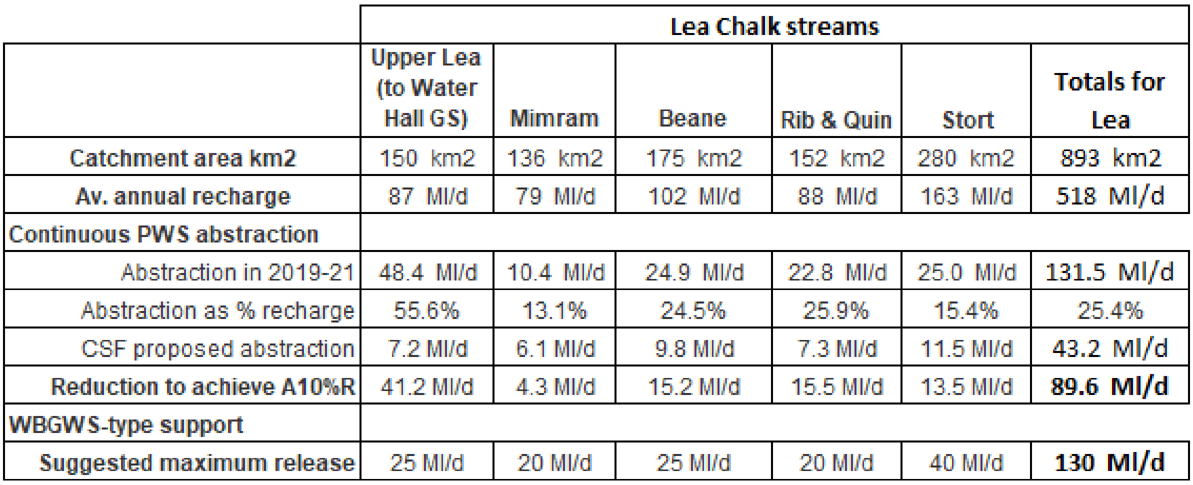
In principle, this conjunctive use of the chalk aquifer with the reservoirs downstream appears to be a much better way of managing the chalk water resource, instead of continuous pumping of water supplies directly from the chalk.

7.3 Use of WBGWS concept in other Colne and Lea chalk streams

The example of the WBGWS concept for the River Ver could be followed in any of the chalk tributaries of the Colne and Lea. Drought support releases from the Colne tributaries could be used for filling the existing lower Thames reservoirs and support from the Lea tributaries would feed into the Lea valley reservoirs. An indication of the potential scale of adopting the WBGWS concept across all the Lea and Colne tributaries is shown in Table 11. The suggested maximum releases for each of the tributaries are in the region of 20-30% of average recharge, as is the case for the Lambourn, Enbourne, Pang and Loddon:



	Colne chalk streams				
	Misbourne	Chess	Gade/ Bulbourne	Ver	Totals for Colne
Catchment area km^2	95 km2	105 km2	184 km2	132 km2	516 km2
Av. annual recharge	74 Ml/d	82 Ml/d	144 Ml/d	103 Ml/d	403 Ml/d
Continuous PWS abstraction					
Abstraction in 2019-21	15.8 Ml/d	15.1 Ml/d	36.2 Ml/d	25.8 Ml/d	92.9 Ml/d
Abstraction as % recharge	21.2%	18.4%	25.2%	25.0%	23.0%
CSF proposed abstraction	6.2 Ml/d	4.1 Ml/d	11.9 Ml/d	7.7 Ml/d	29.9 Ml/d
Reduction to achieve A10%R	9.6 Ml/d	11.0 Ml/d	24.3 Ml/d	18.1 Ml/d	**63.0 Ml/d**
WBGWS-type support					
Suggested maximum release	20 Ml/d	20 Ml/d	40 Ml/d	25 Ml/d	**105 Ml/d**



	Lea Chalk streams					
	Upper Lea (to Water Hall GS)	Mimram	Beane	Rib & Quin	Stort	**Totals for Lea**
Catchment area km2	150 km2	136 km2	175 km2	152 km2	280 km2	893 km2
Av. annual recharge	87 Ml/d	79 Ml/d	102 Ml/d	88 Ml/d	163 Ml/d	518 Ml/d
Continuous PWS abstraction						
Abstraction in 2019-21	48.4 Ml/d	10.4 Ml/d	24.9 Ml/d	22.8 Ml/d	25.0 Ml/d	131.5 Ml/d
Abstraction as % recharge	55.6%	13.1%	24.5%	25.9%	15.4%	25.4%
CSF proposed abstraction	7.2 Ml/d	6.1 Ml/d	9.8 Ml/d	7.3 Ml/d	11.5 Ml/d	43.2 Ml/d
Reduction to achieve A10%R	41.2 Ml/d	4.3 Ml/d	15.2 Ml/d	15.5 Ml/d	13.5 Ml/d	**89.6 Ml/d**
WBGWS-type support						
Suggested maximum release	25 Ml/d	20 Ml/d	25 Ml/d	20 Ml/d	40 Ml/d	**130 Ml/d**

Table 11 - Potential for WBGWS concept in the Colne and Lea catchments

Reduction of abstraction to achieve EFIs across all of the Colne and Lea tributaries would require about 63 Ml/d of replacement supply, potentially from Thames Water's lower Thames reservoirs. The impact on London's supplies could be offset by up to 105 Ml/d of drought support releases from the upper Colne chalk. The equivalent figures for the Lea catchment could be 90 Ml/d of replacement sources and up to 130 Ml/d of drought support releases from the upper Lea chalk.

GARD model simulation of the abstraction reductions and WBGWS-type support releases shown in Table 11 suggests that they could give a net gain to London deployable output of in the region of 55-60 Ml/d after allowing for 87 Ml/d of flow recovery from the total 153 Ml/d of abstraction reductions, as shown on Figure 28.

7.4 Taking forward the WBGWS potential

This Chapter provides a preliminary assessment of the potential for adopting the concept of the West Berkshire Groundwater Scheme in the Colne and Lea chalk tributaries, in combination with reduction of conventional groundwater abstractions to 10% of average catchment recharge (A10%R). Replacement supplies would be transferred from the London supply system using the already planned Thames to Affinity transfer and the 'Connect 2050' pipe network. The conclusions from this assessment of the potential for use of the WBGWS concept in the Chilterns chalk streams are:

1. CSF modelling of the concept for the River Ver shows the reduction of public water supplies from the current 28 Ml/d to about 8 Ml/d, combined with WBGWS-type drought support of up to 25 Ml/d, would almost re-naturalise River Ver flows and give a net <u>increase</u> in London supplies of about 9 Ml/d.
2. The drought support would only be needed about once in 25 years. Flows in the River Ver in drought years would be increased by the WBGWS-type releases and would be slightly less in the following year (but still much more than with abstraction at recent levels).
3. If the concept was adopted in all the Colne and Lea chalk streams, abstraction could be reduced to meet EFIs throughout, with a net gain to London's supplies of possibly 55-60 Ml/d.
4. Although the net gain in London supplies requires much more investigation, the introduction of the WBGWS concept would remove much of the doubt that currently exists over the amount of flow recovery from abstraction reductions.
5. In principle, the conjunctive use of the chalk aquifer and the reservoirs downstream appears a much better way of using the chalk water resource, with far less impact on chalk streams than continuous pumping of water supplies directly from the chalk.
6. The concept should now be investigated as a matter of urgency, with the aim of implementing one or more pilot schemes in AMP8.

A similar proposal for using the WBGWS concept at a pilot scale has been put forward for the River Ivel catchment, an upper catchment chalk tributary of the River Ouse. This would entail much reduced existing abstraction for day-to-day supplies, replacement supplies brought in from Grafham reservoir, enhanced Ivel flows into the River Ouse used to augment Grafham reservoir refilling and use of the existing Ivel groundwater storage as a drought source in a similar fashion to the WBGWS. A pre-feasibility study of this proposal is being undertaken jointly by Affinity Water and Anglian Water, with a report due in summer 2023.

The Ivel investigation can point the way for investigation of the WBGWS concept at a larger scale in the Chilterns chalk streams. If the concept is found to be viable, it removes most of the uncertainty surrounding river flow recovery and maintaining supplies if recovery is found to be less than expected. This would allow the proposed CSF abstraction reductions to proceed quickly with more confidence, without any need for a major new source before 2040.

Appendix A - River Ver case study

Contents

A1 River Ver location, geology and abstraction history

The approximate locations of public water supply abstractions from groundwater in the Ver catchment are shown in Figure A1 **(redacted)**:

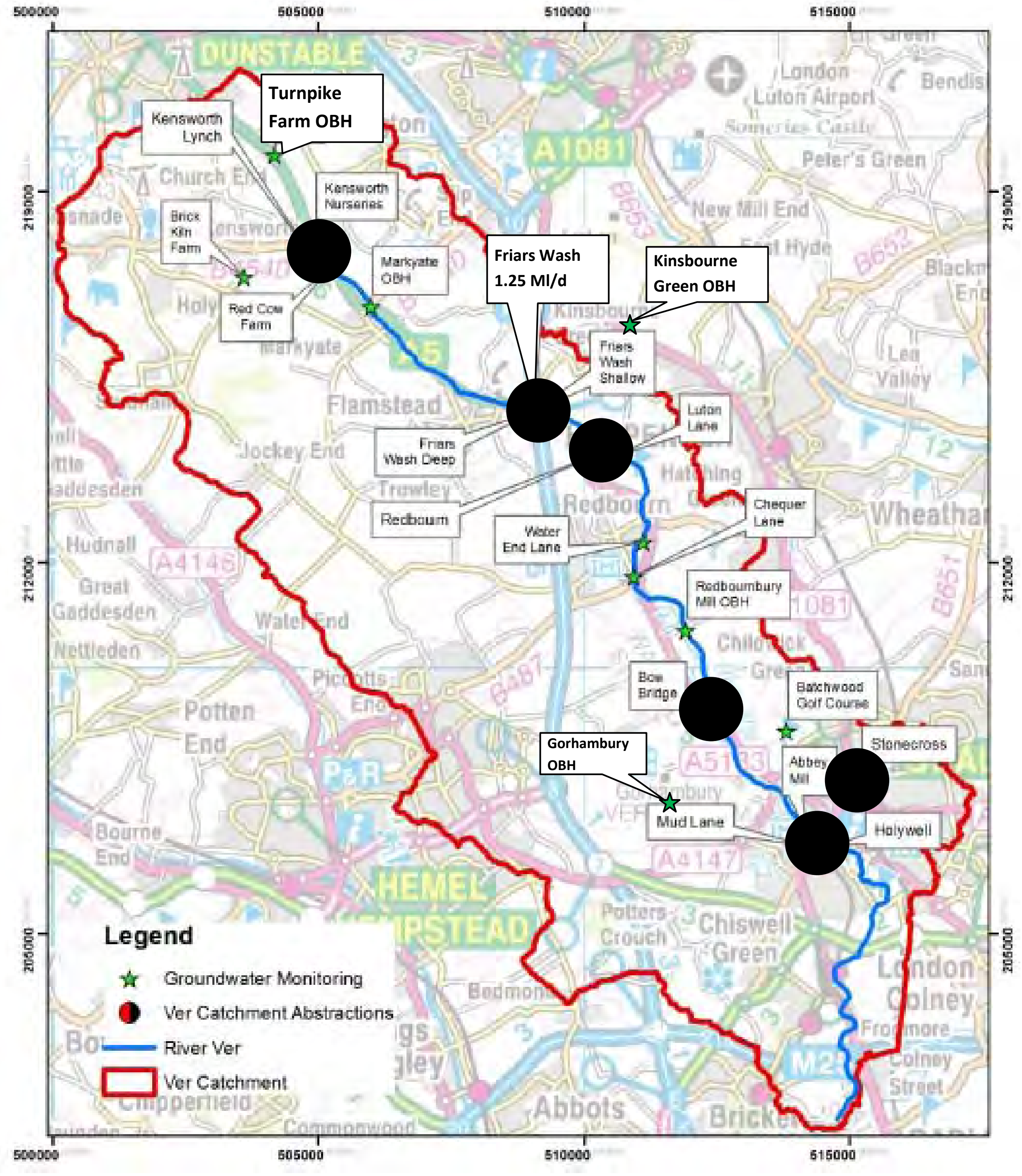
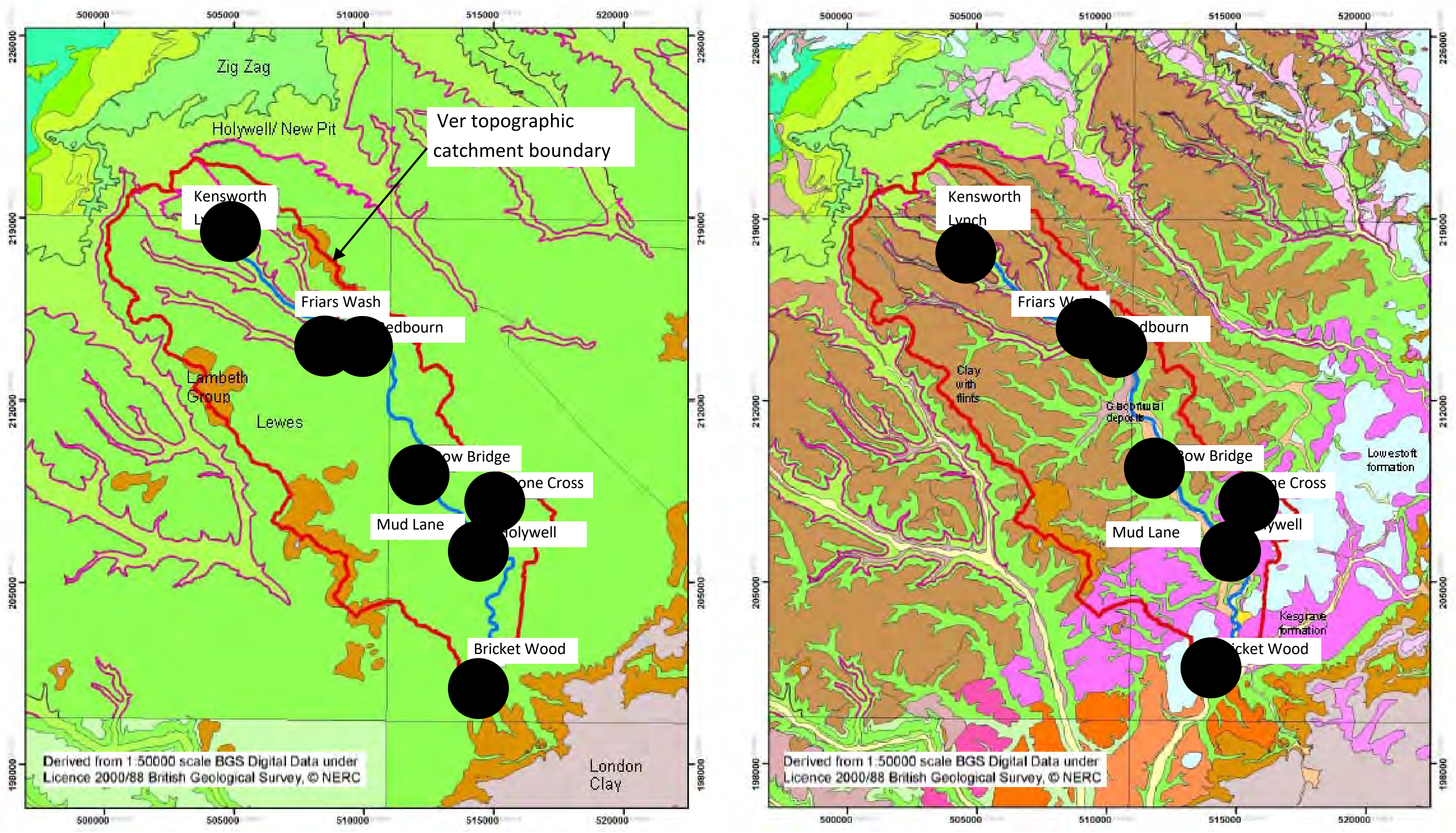


Figure A1 - Locations of groundwater abstractions in the River Ver catchment

The solid geology and superficial deposits of the Ver catchment are shown on Figure A2 and geological sections are shown on Figure A3:

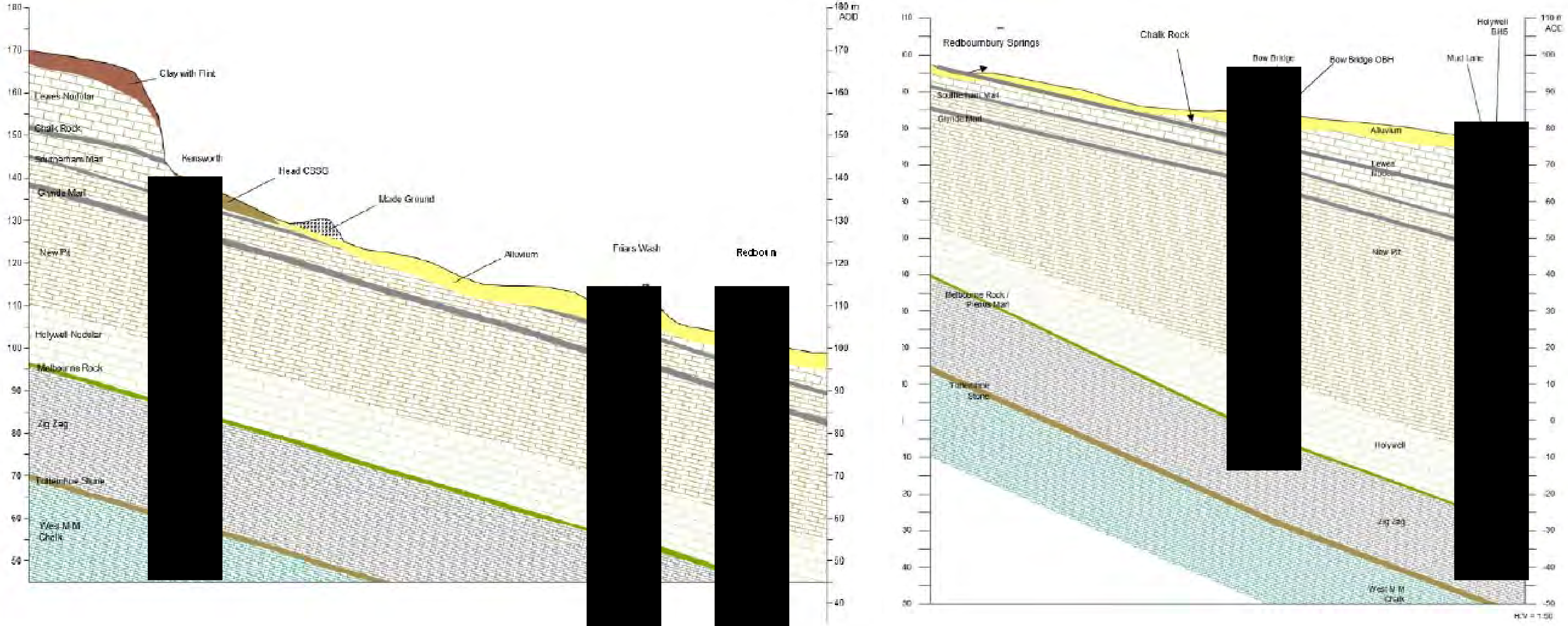


a) Solid geology

b) Superficial deposits

Maps copied from Ver NEP report Figure 7

Figure A2 - Solid and drift geology of River Ver, with PWS borehole locations



[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

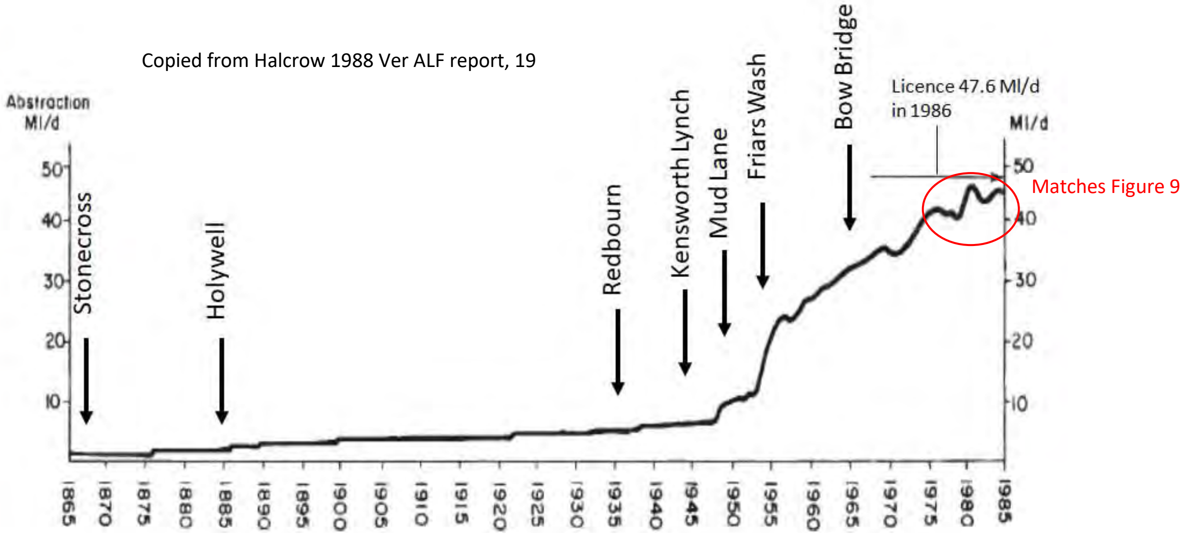
a) Upper Ver

b) Middle Ver

Sections copied from Ver NEP report Figure 5 and 6

Figure A3 - River Ver geological sections

The 1988 Halcrow report on alleviation of low flows in the River Ver[21] showed the history of growth in abstraction up to 1985 as in Figure A4:



Copied from Halcrow 1988 Ver ALF report, 19

Matches Figure 9

Figure A4 - History of Ver abstraction growth 1865 to 1985

Affinity's Ver NEP report[22] gives a breakdown of the abstraction since 1974 as in Figure A5:

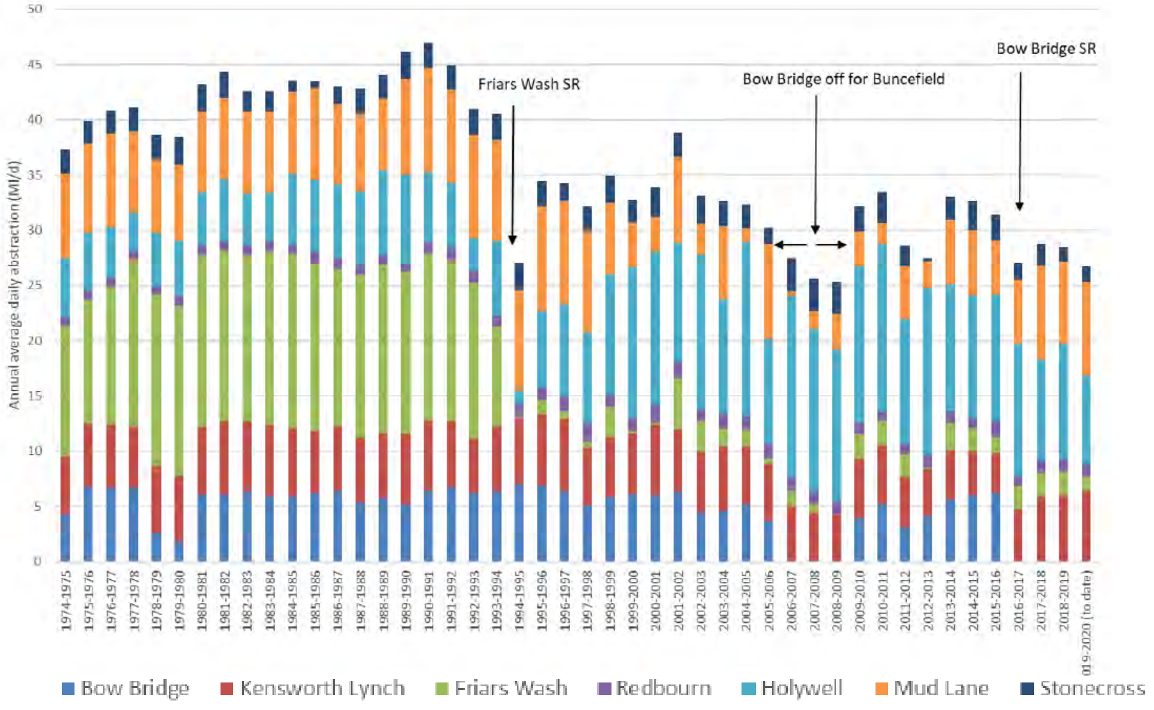


Figure A5 - Changes in Ver catchment abstraction since 1974

Copied from Ver NEP report Figure 3

This shows the timing and relative magnitudes of the Friars Wash and Bow Bridge sustainability reductions. The Bow Bridge abstraction also virtually ceased for about 3 years following the explosion at the Buncefield oil storage facility in December 2005.

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[21] Alleviation of Low Flows (ALF) resulting from groundwater abstraction, Ver Case Study, Halcrow for Thames Water, 1988

[22] River Ver AMP6 National Environment Programme Report, Technical Report 1.6 – Sustainability Reductions and River Restoration, Affinity Water, March 2020

A2 Measured flow and GWL changes after abstraction changes

Changes in average flows at Hansteads on the lower Ver

In the 10 years prior to 1993, the Friars Wash abstraction was typically about 14 Ml/d and the total Ver abstraction average about 43 Ml/d. In the decade after the 1993 sustainability reduction, the Friars Wash abstraction was typically about 1 to 3 Ml/d, but the reduction was offset by increases in the Holywell Abstraction, so the reduction for the whole Ver valley was only about 10 Ml/d, as can be seen in Figure A8. Nevertheless, the Friars Wash reduction was a step change in abstraction which has been sustained for nearly 30 years, so it has provided the opportunity to observe the long term effect on river flows and GWLs.

The long term effect on flows in the lower Ver at the Hansteads gauging station (location on Figure A1) was demonstrated in the Environment Agency's 2018 review of the Friar's Wash reduction[23] by plotting cumulative flows since the late 1950s, as replicated in Figure A6:

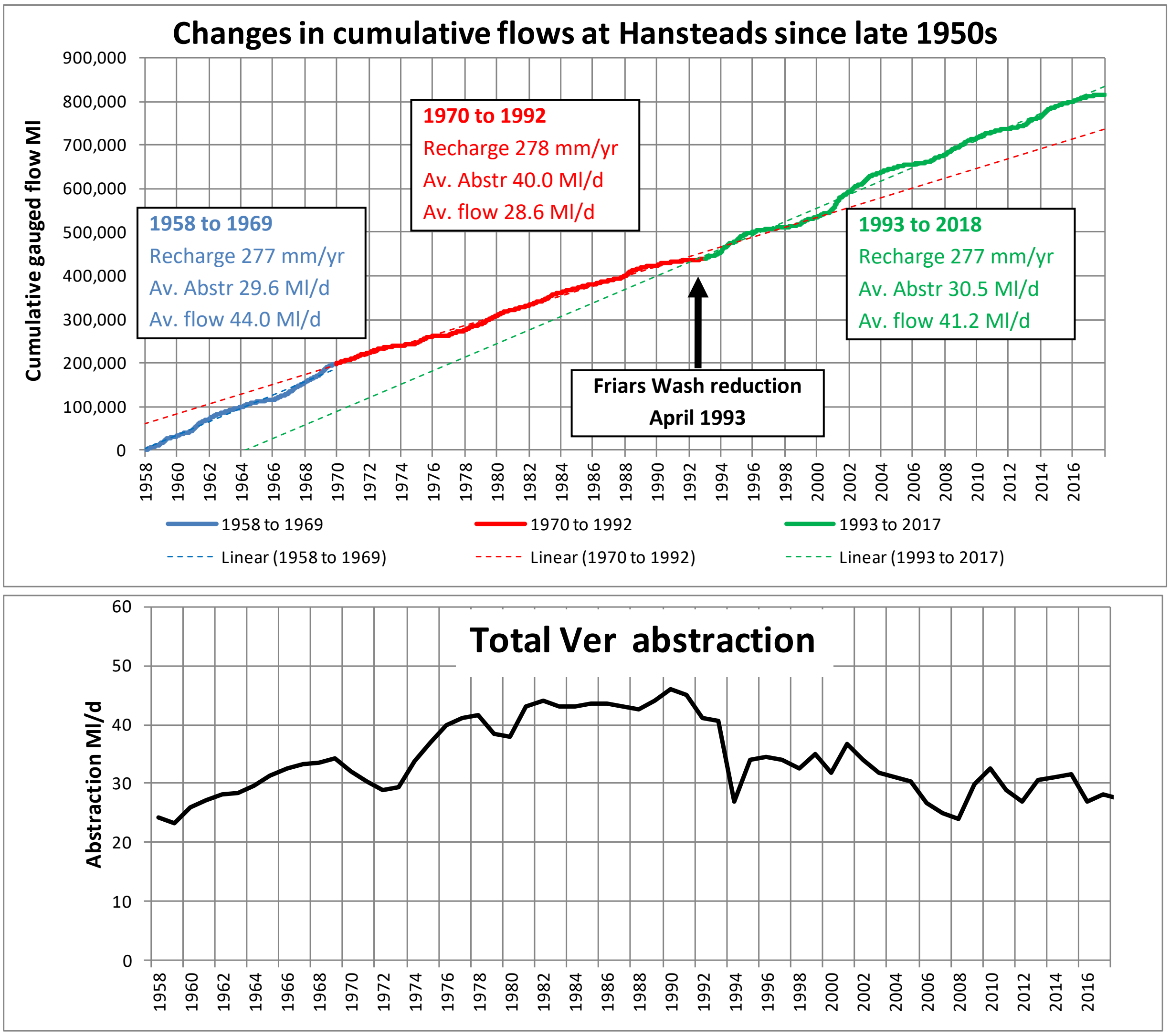

Figure A6 - Changes in Hansteads accumulated flow 1959 to 2018

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[23] Friars Wash Review, PowerPoint slides, Geoff Angell, Environment Agency, 2018

The upper plot in Figure A6 shows a clear and sustained rate of accumulation of flow after the Friars Wash reduction in April 1993. Comparing the period 1970-92 with the period 1993-2018 after the Friars Wash reduction:

- Catchment recharge was virtually identical in the two periods
- Average abstraction reduced by 9.5 Ml/d
- Average flow increased by 12.6 Ml/d

A similar picture is seen for the periods before and after the rapid increase in abstraction in the early 1970s, comparing the period 1958-69 with the period 1970-1992:

- Catchment recharge was virtually identical in the two periods
- Average abstraction increased by 10.4 Ml/d
- Average flow decreased by 15.4 Ml/d

In both cases, the change in gauged river flow was more than the change in abstraction, so the changes in gauged flows, if correct, cannot all be due to the abstraction changes. For example, the drought of 1976 might have distorted both of the comparisons (although the average recharges were virtually identical in the three periods compared).

Nevertheless, this analysis, based on measured flows not modelling, does suggest that a high proportion of the abstraction changes turn into river flow changes. The magnitude of the abstraction changes and the long period over which the flow changes were measured adds confidence to this finding.

However, this analysis of changes in average river flows provides no information on how abstraction reductions would increase flows in droughts.

Analysis of changes in flow duration curves

Comparison of flow duration curves for periods before and after abstraction changes provides an indication of abstraction impacts across the spectrum of river flows. A valid and meaningful comparison of flow duration curves requires the following:

- Similarly lengthy periods, at least 10 years each, containing comparable droughts
- Substantial and sustained differences in abstraction between the two periods
- Continuous gauged flow records in each period
- Similar total effective rain and recharge over each period

The Environment Agency’s paper on the Friars Wash reduction identified a pair of suitable periods: (Oct 1982 - Sep 1992) and (Oct 05 - Sep 15). The same periods were examined in the Mott MacDonald paper on groundwater impact factors[24]. The flow duration curves for these periods have been re-plotted in Figure A7 (with gauged flows converted to baseflows):

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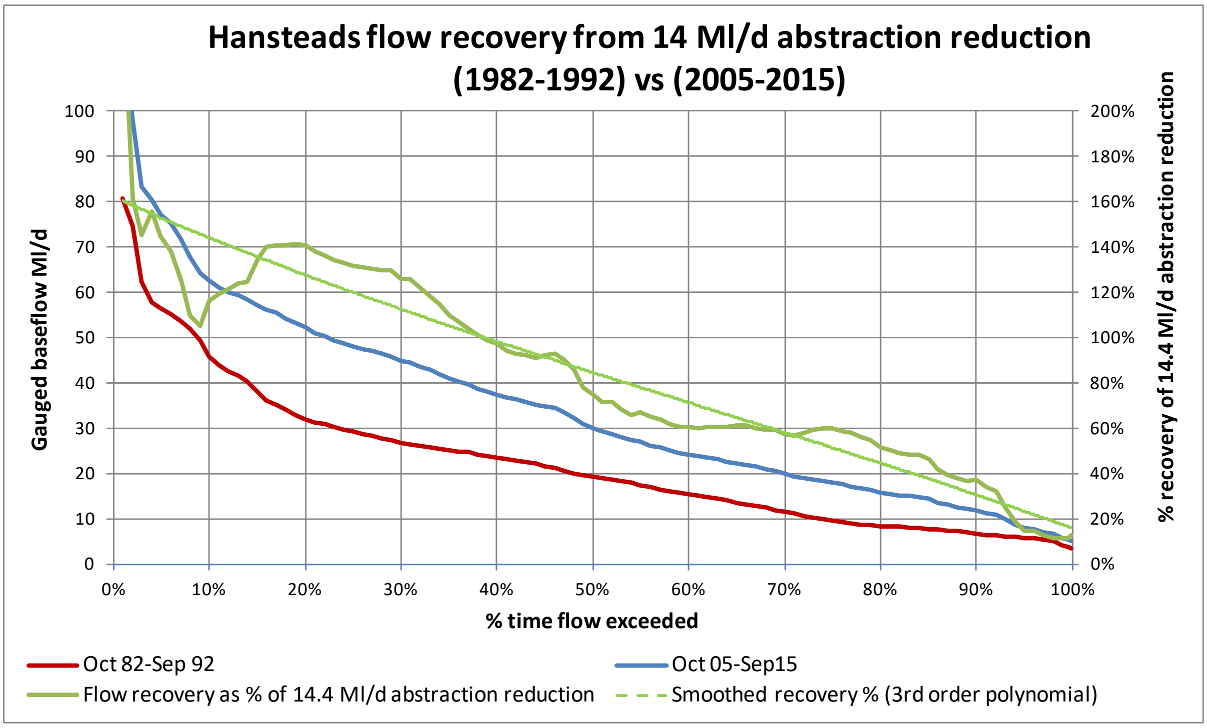
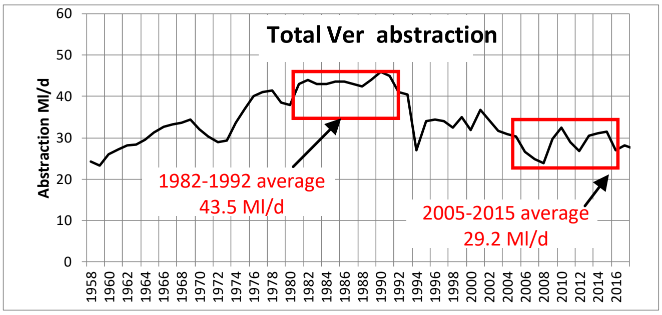
[24] Groundwater abstraction factor impact analysis, Figure 3.10, Mott MacDonald, May 2021



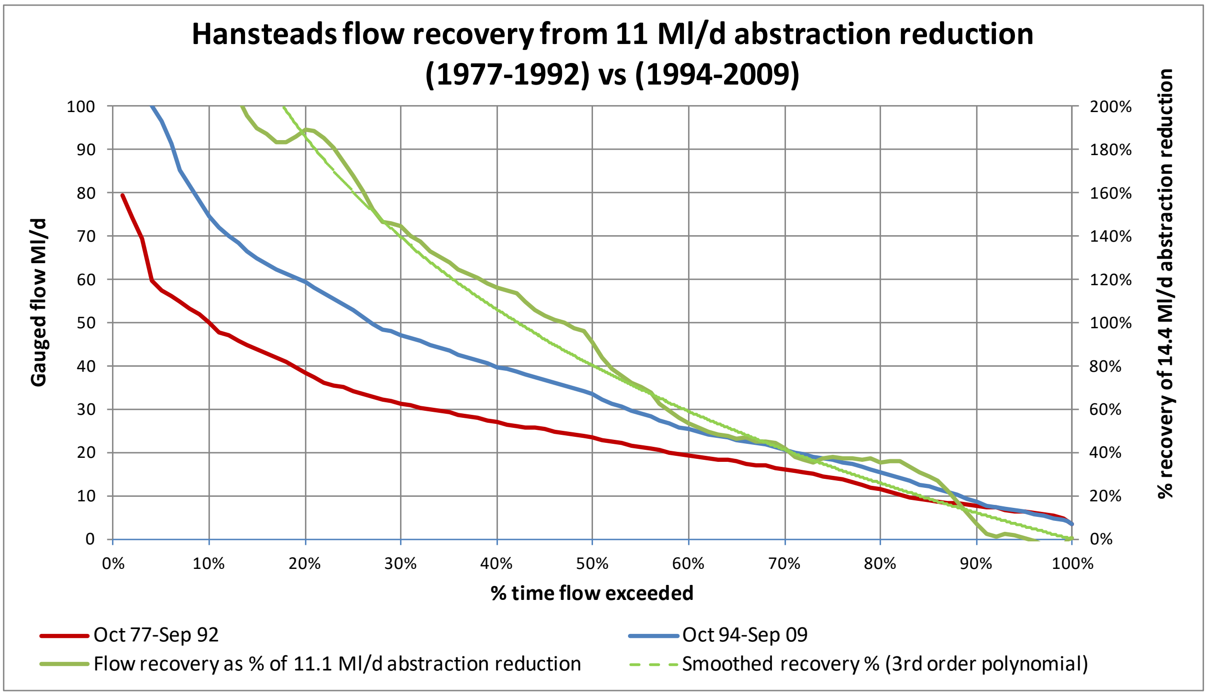


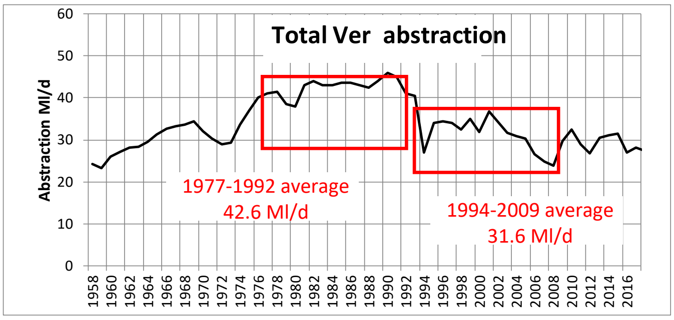
	Oct 82-Sep 92	Oct 05-Sep15	Difference
Average Er mm/year	262	265	3.2
Average abstraction Ml/d	43.5	29.2	-14.4
Average flow Ml/d	22.9	35.4	12.5

Figure A7 - Measured Ver baseflow recovery from Friars Wash SR, (1982-92) vs (2005-15)

This plot shows that the 14.4 Ml/d reduction in average abstraction following the Friars Wash reduction led to a 12.5 Ml/d increase in average flow – an average recovery of 87% of the abstraction reduction. The amount of the recovery varies a lot in percentage terms across the range of flows: about 80% at the median flow Q50, about 30% at Q90 and less than 20% at Q99. At high flows, the flow recovery is considerably more than the abstraction reduction. The average amount of flow recovery to the river is only around 80%, because some of the gained flow in the water balance leaves the catchment as throughflow, either to the lower River Colne or to the adjacent chalk valleys. An explanation for low recovery at low flows and high recovery at high flows is given in Main Report, Section 2.4 and Figure 4.

The amount of flow recovery assessed through this methodology is sensitive to the selection of the periods compared. Figure A8 compares the difference in flow durations for two 15-year periods before and after the Friars Wash reduction, with similar average effective rainfall: (Oct 1977 – Sep 1992) vs (Oct 1994 – Sep 2009):



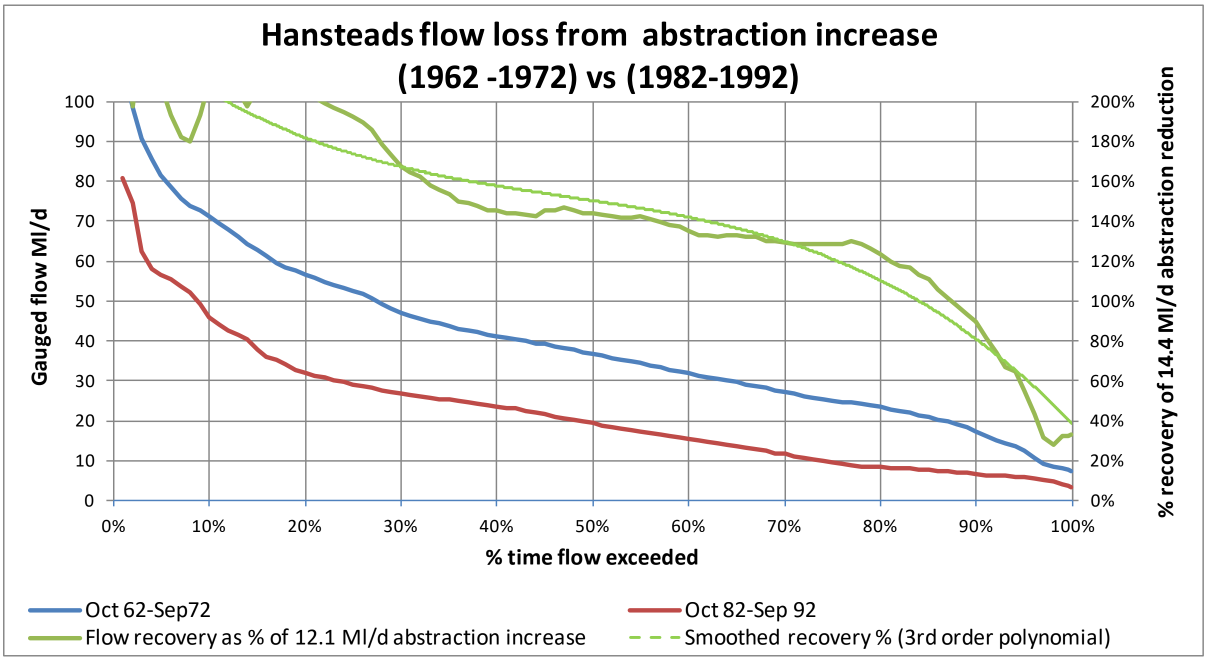


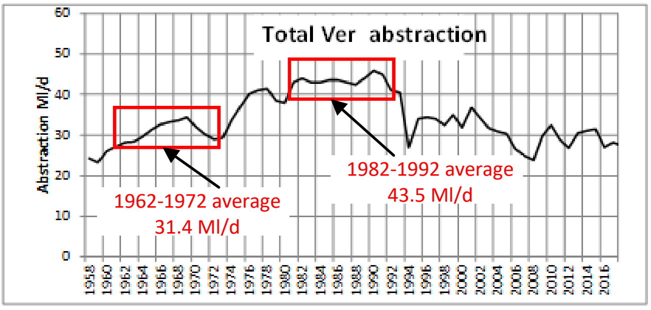
	Oct 77-Sep 92	Oct 94-Sep 09	Difference
Average Er mm/year	280	279	-1
Average abstraction Ml/d	42.6	31.6	-11.1
Average flow Ml/d	26.3	39.2	12.9

Figure A8 - Measured Ver baseflow recovery from Friars Wash SR, (1977-92) vs (1994-09)

This plot shows that the 12.9 Ml/d measured increase in average baseflow following the Friars Wash reduction was more than the 11.1 Ml/d reduction in average abstraction. As for the previous example, the amount of the recovery varies a lot in percentage terms across the range of flows: about 80% at the median flow Q50, about 30% at Q80 and close to zero recovery below Q90. At high flows, the flow recovery is again considerably more than the abstraction reduction. An explanation for the variation in recovery depending on the flow is given in the Main Report, Section 2.4 and Figure 4.

The large growth in abstraction in the 1960s and 70s provides another opportunity to assess the measured impact of abstraction changes across a range of flows, as shown in Figure A9:





	Oct 62-Sep72	Oct 82-Sep 92	Difference
Average Er mm/year	259.6	262.2	2.6
Average abstraction Ml/d	31.4	43.5	12.1
Average flow Ml/d	35.1	22.9	-12.2

Figure A9 - Measured baseflow reduction from 12.1 Ml/d abstraction rise in 1960/70s

This plot shows a clear reduction in baseflows resulting from the rise in abstraction in the 1960/70s, suggesting that the average flow reduction was the full equivalent of the abstraction increase across much of the flow range. However, the flow reduction at flows less than Q90 is a lot less than the abstraction increase, as for the two previous examples and as explained in Main Report Section 2.4.

The examples of abstraction and flow changes shown in Figures A7 to A9 meet the suggested criteria for valid comparisons – large abstraction changes maintained for at least 10 years across periods with similar average effective rain. For all the Colne and Lea chalk streams, these examples probably provide the best opportunity for assessing measured flow changes arising from recorded abstraction changes. Nevertheless, the examples show substantially different patterns and amounts of flow recovery.

This demonstrates the difficulty in making valid before-and-after comparisons of measured flow changes. The climate variability within the assessment periods distorts the differences in measured flows, even though average effective rain and aquifer recharge are in each case very similar for the periods compared. The type and severity of the worst drought in each period has a large effect on the measured flow recovery at low flows, even for these relatively favourable examples of large abstraction changes maintained for many years.

If the abstraction changes are much smaller than the Friars Wash reduction and the periods available for comparing flows are much less than 10 years, the comparison will be meaningless. Unfortunately, this applies to the Bow Bridge abstraction reduction in April 2016. As can be seen on Figure A9, the average Ver abstraction after the sustainability reduction is almost the same as the average abstraction in the previous 10 years, partly due to the abstraction reduction following the Buncefield oil depot explosion.

It is also unfortunate that the only gauged flow record available prior to the Friars Wash reduction is for the Hansteads gauge on the lower Ver. The gauged records for the Rivers Ver and Red at Redbourn started in 1992, so there are no pre-reduction flow data currently available for comparison.

Conclusions from analysis of measured flow and GWL changes

Despite the limitations in the analyses shown in Figure A7 to A9, some general conclusions can be drawn from the measured flow changes arising from abstraction changes on the River Ver:

1. The average flow changes look likely to be about 80% of the abstraction changes.
2. Flow recovery reduces substantially from high to low flows
3. The flow changes at low flows are a lot less than 80% of the abstraction changes, perhaps 20-40% recovery at the peak of extreme droughts (flows below Q99).
4. During periods of higher than median flows, flow recovery is likely to be more than 100% of the abstraction reduction.

A3 Validation of CSF and HRGM models for the River Ver

CSF lumped parameter model for the River Ver

The CSF modelling methodology described in Main Report, Section 2.3 has been used in a lumped parameter model for the River Ver. The model features are:

- Covers 102-year period 1920 to 2021, including droughts of 1921/22, 1933/34 and 1943/44
- Effective rain since 1920 taken from EA daily data for East Colne, Station No 6140TH
- Abstraction data from latest EA records, Ver NEP report and Halcrow 1988 report for data prior to 1975
- Daily GWLs simulated at the Turnpike Farm observation borehole site
- River flows simulated for gauge sites at Hansteads and Redbourn (Ver and River Red)
- Effective catchment area for recharge 106 km^2

The effective catchment area for recharge was reduced by 20% from the topographic catchment of 132 km^2 to allow for drainage of built-up areas via surface sewerage out of the catchment and the large amount of clayey drift in the catchment which reduces recharge, as described in the NEP report on the River Ver[25]:

> *"The Chalk is overlain by glaciofluvial deposits in many areas of the catchment. In interfluve areas, Pliocene Clay-with-flints deposits of 0 – 8 m thickness are present. These deposits are likely to inhibit any direct recharge to the chalk over these regions, however some discrete fractures and pipes have been reported to be present (BGS)."*

The 20% reduction in effective catchment for recharge can be justified as 12% allowance for surface run-off (the Baseflow Index is 0.88[26]) and a nominal 8% for export via sewerage from built-up areas, primarily in St Albans and Hemel Hempstead.

For modelling of the recent actual abstraction scenario of 16.4 Ml/d, starting in 1920 and ending in 2020 on a date when the modelled storage is the same as the modelled starting storage, the water balance over the 100 year period is:

Inputs	Ml/d
• Average aquifer recharge	78.2
• Average STW discharge to aquifer	2.5
Total inputs	80.7
Outputs	
• Average river outflow at Hansteads	37.6
• Average underflow from catchment	15.5
• Average abstraction	27.6
Total outputs	80.7

The current Ver model does not allow for leakage from supplies into the aquifer, as is done for the Mimram model. Leakage will be included in the next version of the model.

The model uses the relationships between river flows and GWLs shown in Figure A10:

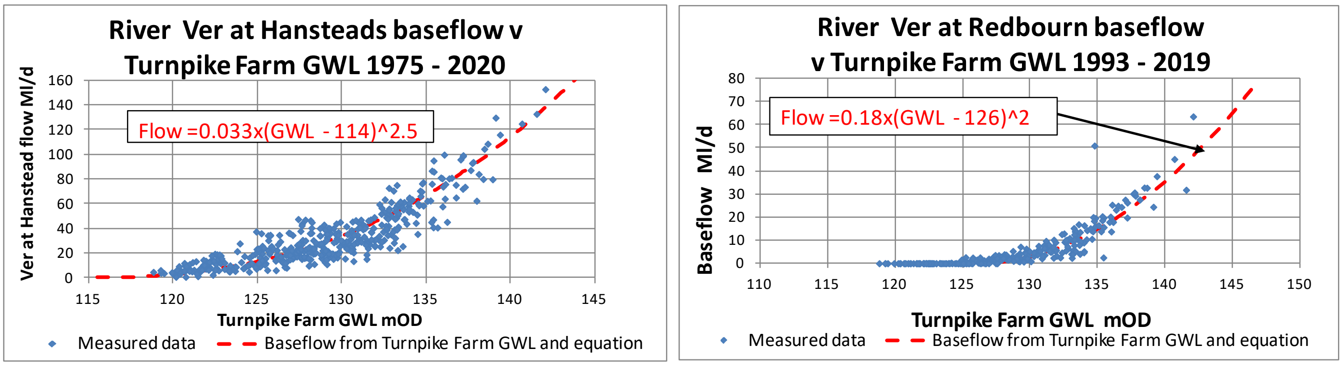


Figure A10 - Measured flows vs GWLs used in CSF Ver model

The CSF model was calibrated to give best fits to recorded groundwater and river flow records in the period 1991 to 2020 (the River Red and Ver at Redbourn records started in the

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[25] Ver NEP report, page 33

[26] National River Flow Archive, Hansteads gauge https://nrfa.ceh.ac.uk/data/station/meanflow/39014

early 1990s). Validation plots are shown in Figure A11:

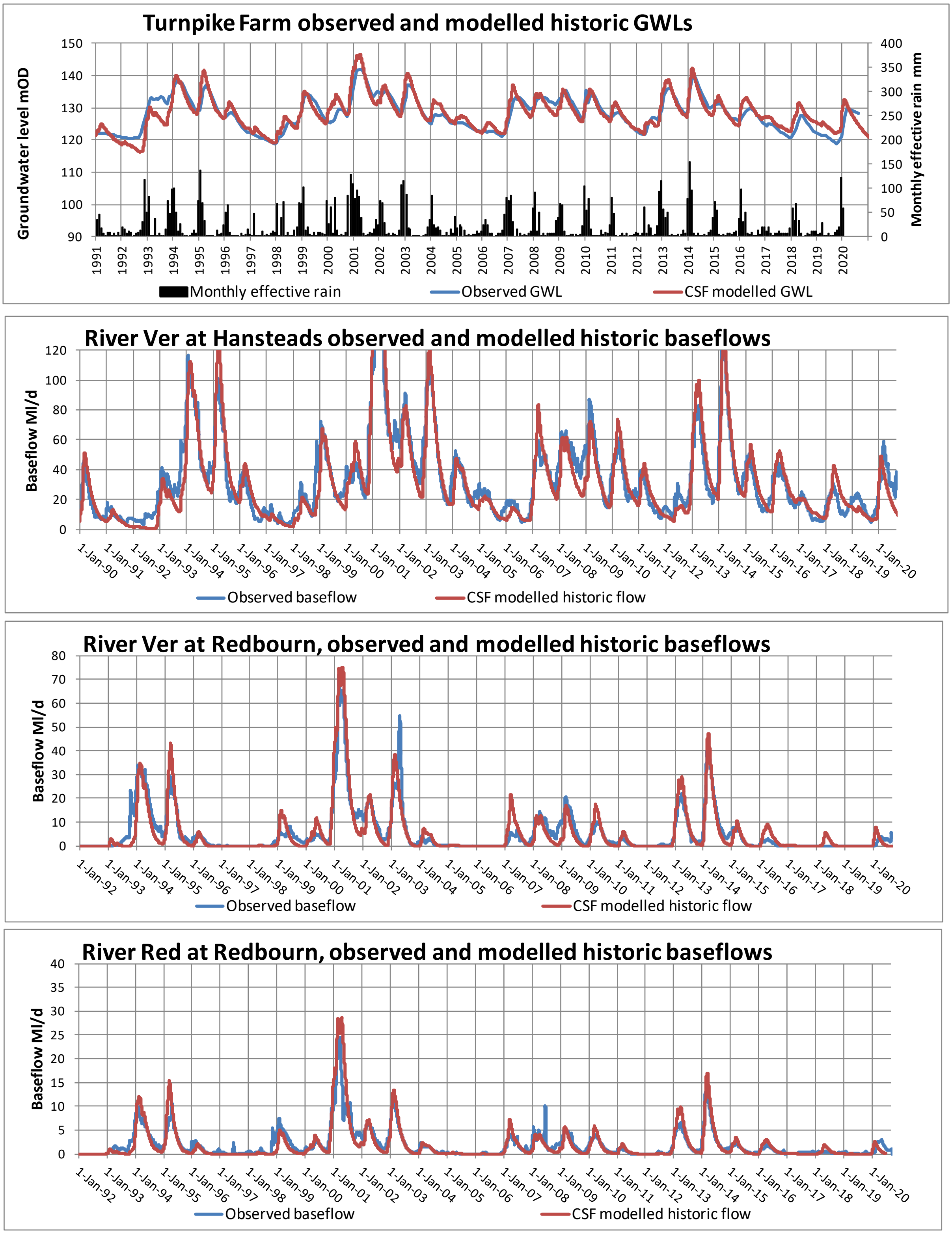


Figure A11 - Validation of CSF River Ver modelled GWLs and flows 1992-2020

The CSF model gives a close fit between modelled and historic measured GWLs and baseflows throughout the 28-year period, 1992 to 2020, for which the model was calibrated.

More validation evidence for the CSF model can be seen by comparing modelled and historic baseflows at Hansteads between 1957 and 1991, ie before the period for which the model was calibrated:

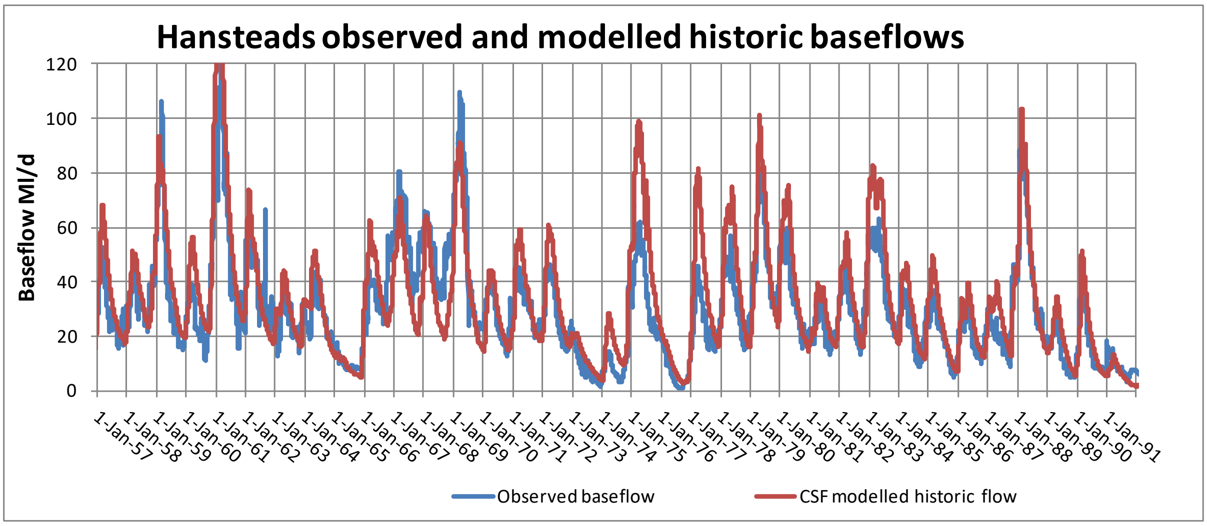


Figure A12 - CSF Ver model validation: Hansteads flow 1957-1991

The CSF model provides a reasonably good fit between observed and modelled flows throughout the 35 year period of available flow data for which the model was not calibrated.

A significant part of the mis-fits is likely to come from the daily effective rain data used in the model: the EA derived daily effective rain time series dating from 1920. If Affinity Water Morecs 151 weekly effective rain (only available since 1975) is used in the re-calibrated model, there is similar overall goodness of fits, with similar amounts of mis-matches, but at different times.

Comparison of validation of the HRGM and CSF models

The Environment Agency's Hertfordshire Regional Groundwater Model (HRGM) and the Chalk Streams First lumped parameter model can both be used for assessing the impacts of historic abstraction changes. A comparison of validation plots for the HRGM and CSF models is shown in Figure A13 (note, there is at present no HRGM data available after 2015). Overall, the CSF lumped parameter model fits the recorded GWL and river flow data rather more convincingly than the HRGM model:

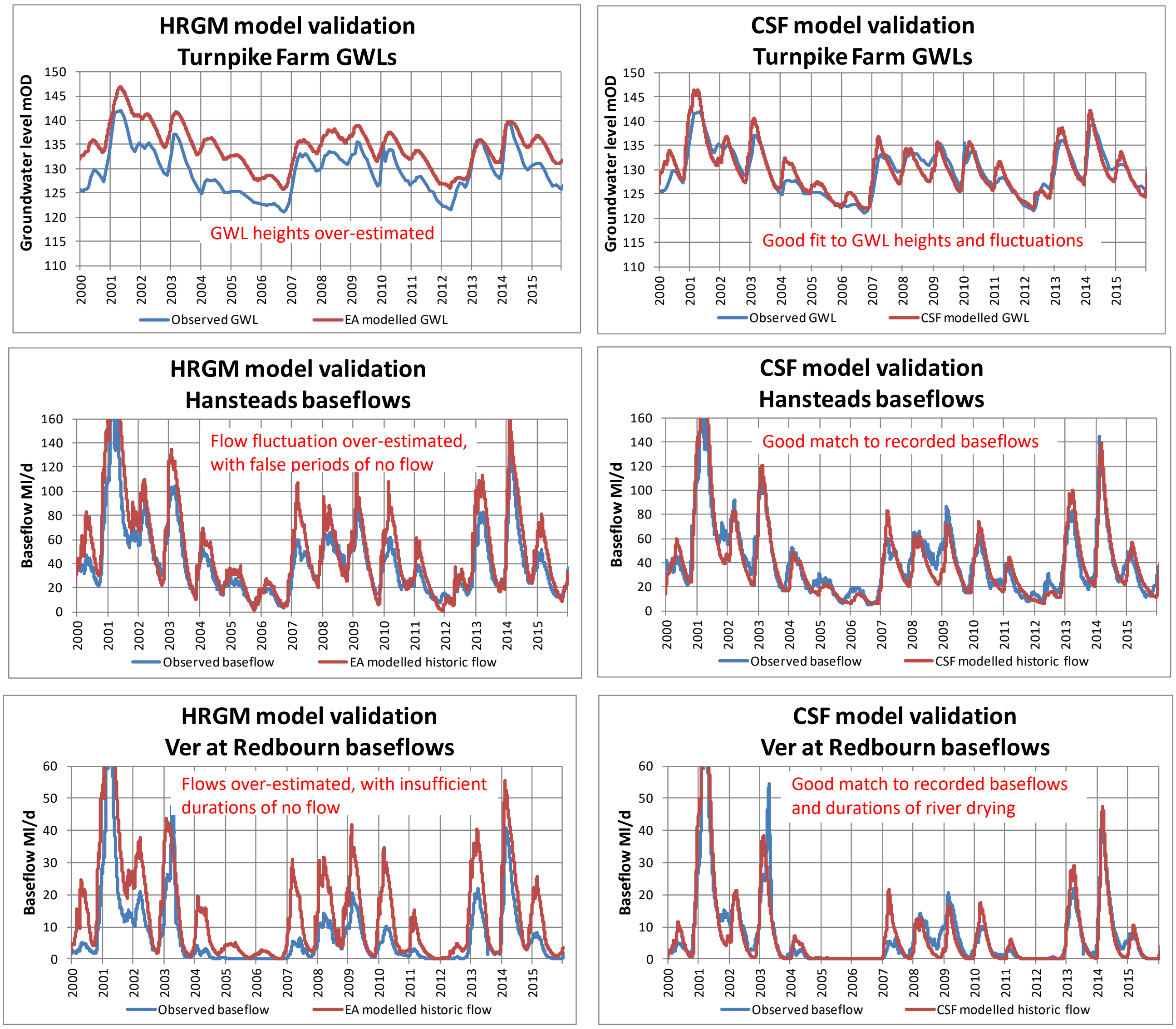
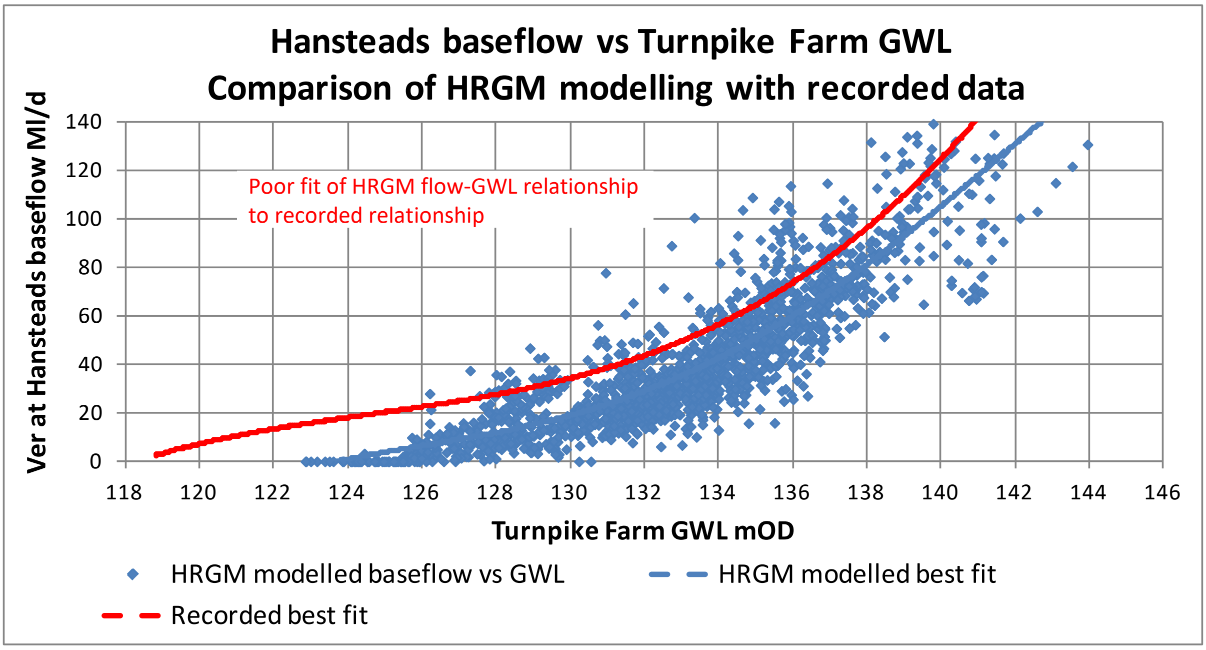


Figure A13 - Comparison of validation of HRGM and CSF Ver models

In particular, the HRGM model tends to over-estimate the magnitude of GWLs and the fluctuations of river flows at both Hansteads and Redbourn. This leads the HRGM model to generate insufficient periods of no flow at Redbourn, and false periods of no flow at Hansteads, for example in 2005 and 2012, as shown in Figure A13. The HRGM model also generates false periods of no flow at Hansteads in 1973, 1990, 1991, 1992 and 1997.

More evidence of the apparently less accurate validation of the HRGM model can be seen in plots of river flows vs GWLs, comparing the modelled relationships with recorded relationships as shown in Figure A14:



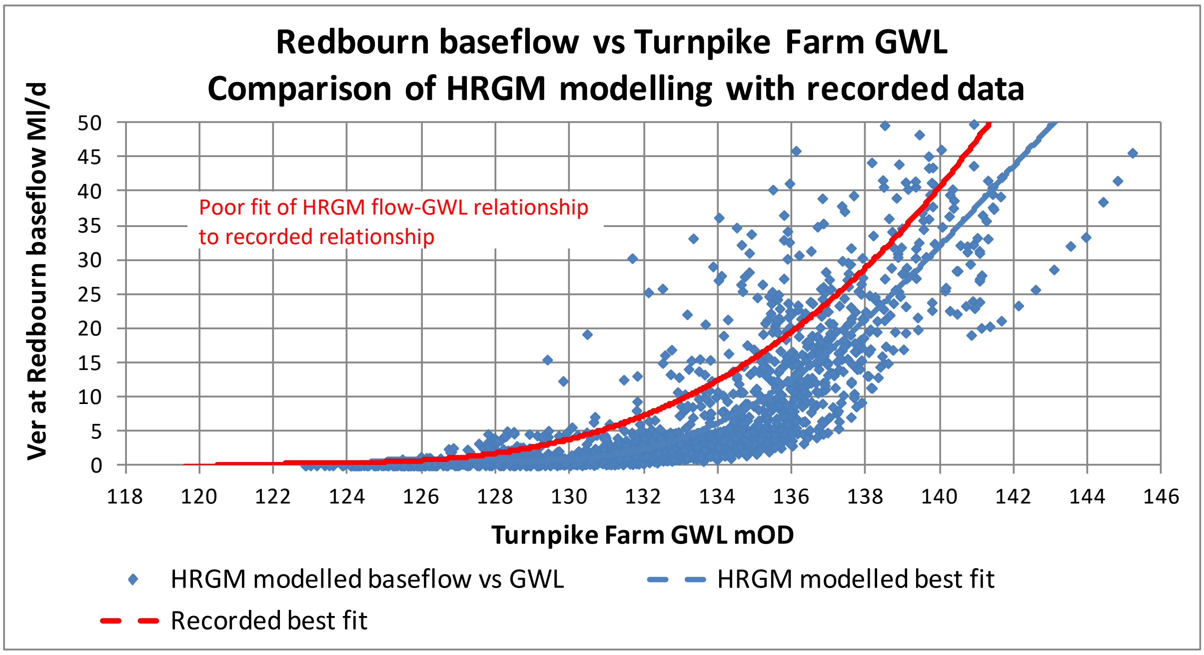


Figure A14 - HRGM Ver model validation comparing Flow vs GWL relationships

Figure A14 shows that the HRGM modelled flow vs GWL relationships are a poor match to the recorded relationships.

A4 Modelling of the Friars Wash reduction

The CSF model has been used to simulate the effect of the Friars Wash reduction, as shown on Figure A15. The upper plot shows the change in modelled flow durations at Hansteads, if the total catchment abstraction is reduced from 43 Ml/d to 29 Ml/d over the duration of the modelled period, 1970 to 2021. The middle plot shows the measured flow recovery, comparing the before-and-after periods (Oct 1982 - Sep 1992) and (Oct 05 - Sep 15), as in Figure A7. The lower plot shows the modelled before-and-after periods.

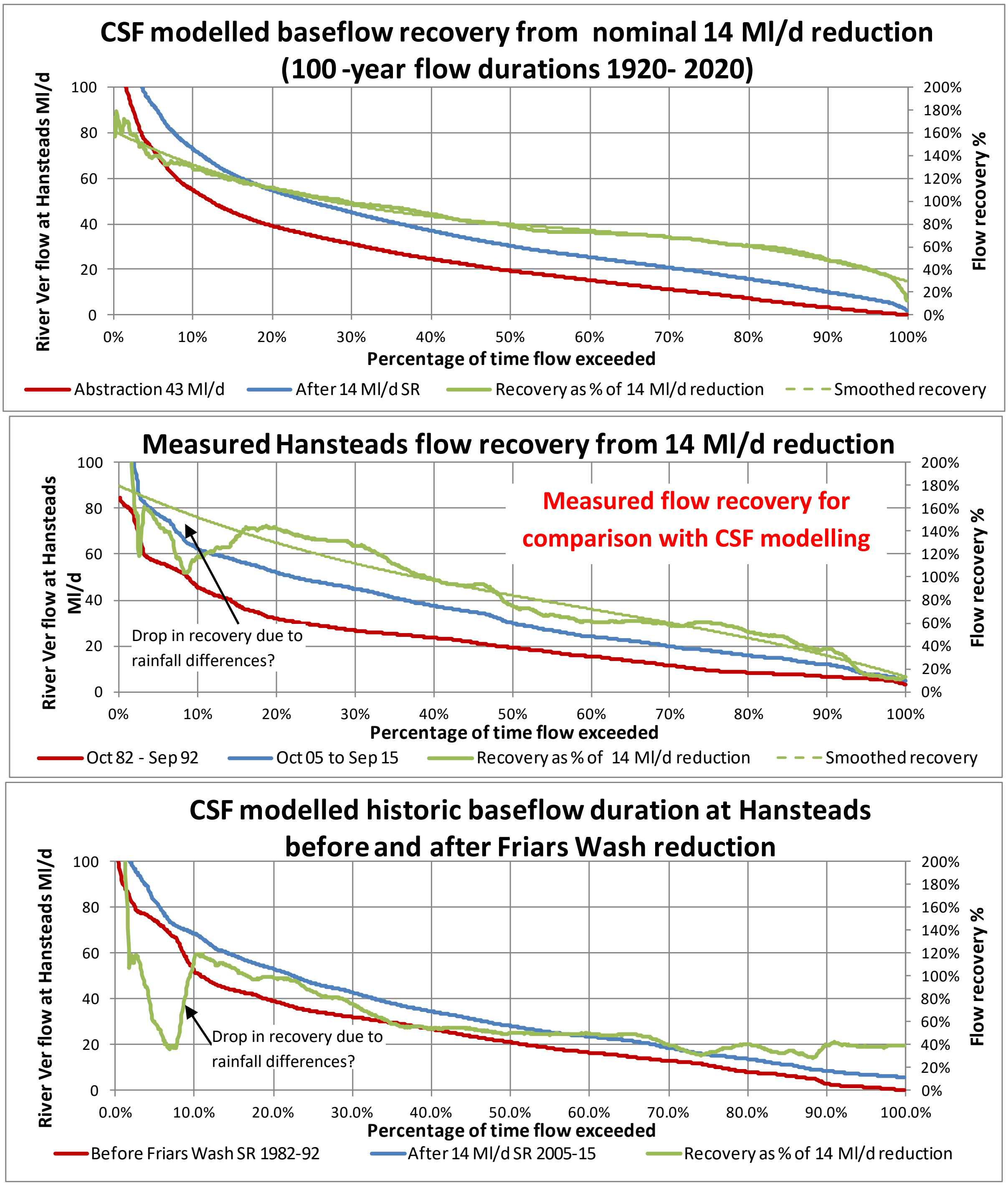


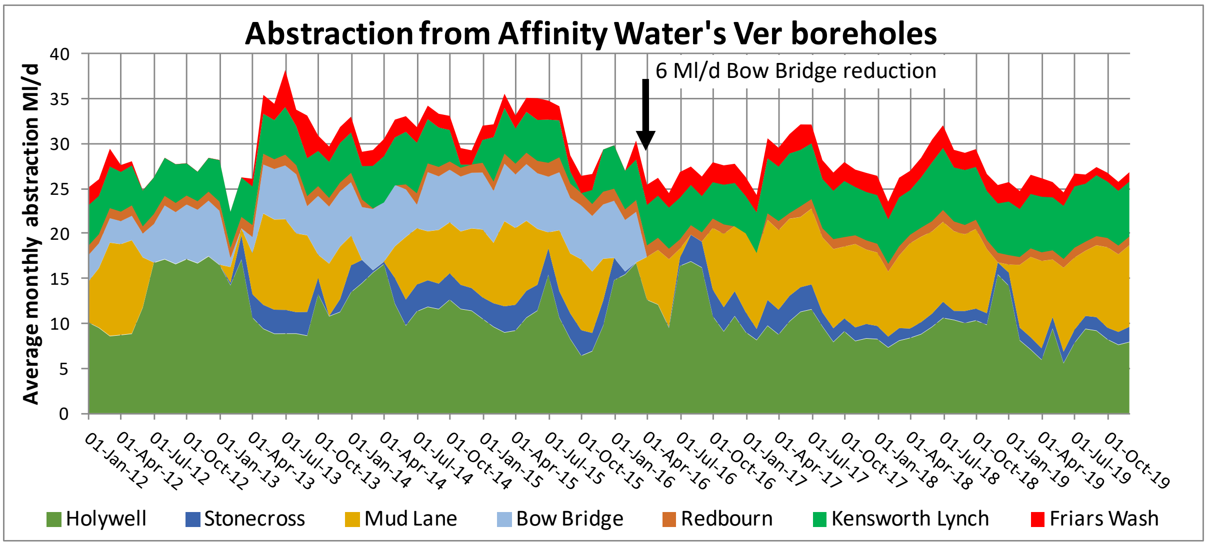
Figure A15 - Modelled and measured low recovery from Friars Wash 14 Ml/d reduction

Comparing the upper and middle plots on Figure A15, it can be seen that the CSF modelling of a total long term abstraction reduction from 43 Ml/d to 29 Ml/d gives similar flow recovery to the measured flow recoveries for the periods (Oct 1982 - Sep 1992) and (Oct 05 - Sep 15), which covered a 14 Ml/d abstraction reduction. The modelling replicates the pattern of steadily reducing recovery as flows reduce, as explained in the Main Report Section 2.4.

The lower plot, showing the modelled periods (Oct 1982 - Sep 1992) and (Oct 05 - Sep 15), shows considerably less recovery than recorded at most times, but more recovery than recorded in droughts. This may be due to the inaccuracies arising from differences in the pattern of effective rainfall between the two modelled periods.

A5 Modelling of the Bow Bridge sustainability reduction

In April 2015 the Bow Bridge abstraction was permanently reduced from around 6 Ml/d to zero. The changes in Ver abstractions since 2012 are shown in Figure 21:

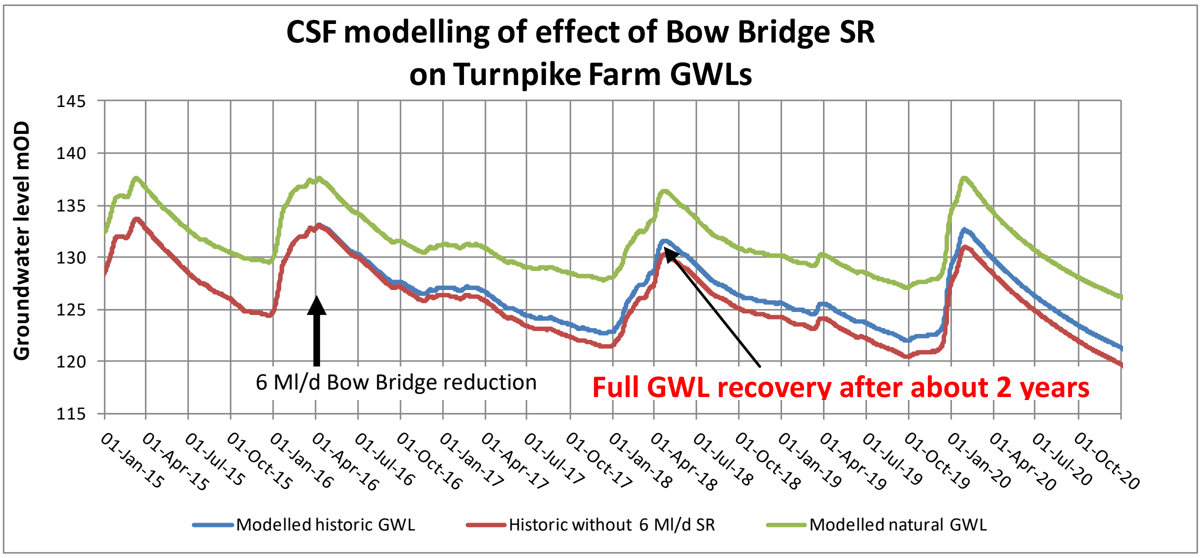


Note: plot will be updated when more recent abstraction data are received from EA.

Figure A16 - Changes in Ver abstraction since 2012

As can be seen from Figure A16, there was no clear change in overall Ver abstraction when Bow Bridge pumping station was switched off in April 2016. The total Ver abstraction had already fallen from about 32 Ml/d to 27 Ml/d in autumn 2015. The Bow Bridge switch-off in April 2016 was largely replaced by an increase in the Mud Lane abstraction, with the total remaining around 27 Ml/d. Therefore, there was no step-change in abstraction which would have allowed comparison of before-and-after flow duration curves as for the Friars Wash reduction in 1993.

Even if there had been a clear 6 Ml/d drop in total abstraction in April 2016, the GWL and river flow changes would have been too small to be distinguishable from natural variations due to climate, especially bearing in mind that groundwater levels and flows were unusually low throughout the Chilterns from 2015 to 2019. This is illustrated by CSF model simulation of what the GWLs and baseflows would have been without the 6 Ml/d Bow Bridge sustainability reduction, as shown in Figure A17:



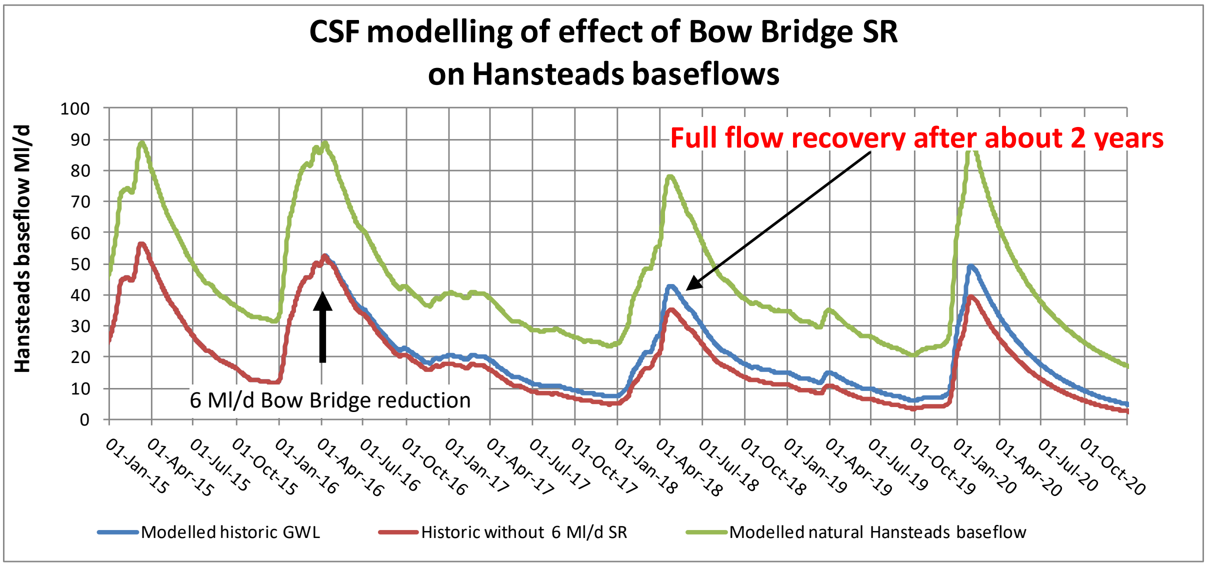


Figure A17 - CSF modelling of effect of Bow Bridge sustainability reduction

The CSF modelling assumes that flow recovery depends on the accumulated increase in aquifer storage and GWLs following the abstraction reduction. This explains the prolonged flow and GWL recovery shown in Figure A17, with full recovery taking about 2 years. The plots show that the scale of flow and GWL recovery was too small to be realistically measured or distinguishable from natural variations. Flows would still have been far lower than natural flows, so it would have been unrealistic to expect any significant ecological improvement.

A6 HRGM model simulation of abstraction reductions

There is no output available for the Environment Agency's HRGM modelling of before-and-after conditions for the Friars Wash or Bow Bridge sustainability reductions. However, comparison of the modelling of the fully licensed abstraction scenario (37.7 Ml/d) with the recent actual scenario (31.0 Ml/d)[27] simulates recovery from a 6.7 Ml/d abstraction reduction as shown in the upper plot in Figure A18. The lower plot in Figure A18 shows measured flow recovery from the 14 Ml/d abstraction reduction at Friars Wash:

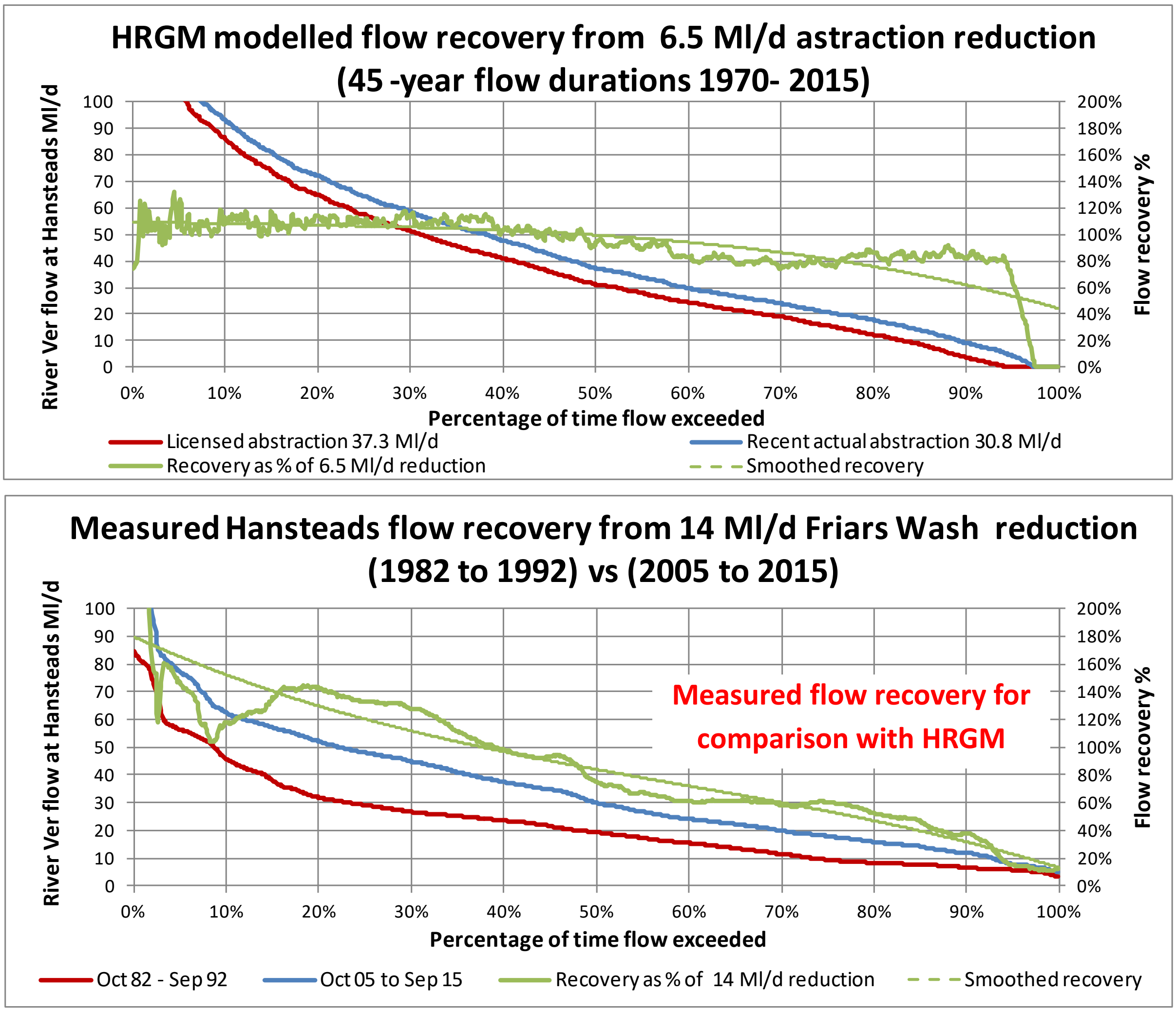


Figure A18 - HRGM modelling of flow recovery from 6.5 Ml/d abstraction reduction

Comparing the HRGM modelled flow recovery in the upper plot with the measured flow recovery in the lower plot, it can be seen that the HRGM modelling appears to over-estimate flow recovery and does not replicate the decline in flow recovery at lower flows. The sharp drop in modelled recovery at flows less than Q95 is due to the HRGM modelled underestimation of low Hansteads flows and the false over-estimation of periods of no flow – see calibration plot on Figures B13 and B14 and the accompanying text. The implication is that the HRGM model is not at present a reliable tool for determining River Ver flow recovery in droughts or the abstraction reduction need to achieve the EA’s EFI flow targets.

A7 Required abstraction reduction in the Ver catchment

As explained in Section 2.5, in addition to the Environmental Agency's environmental flow

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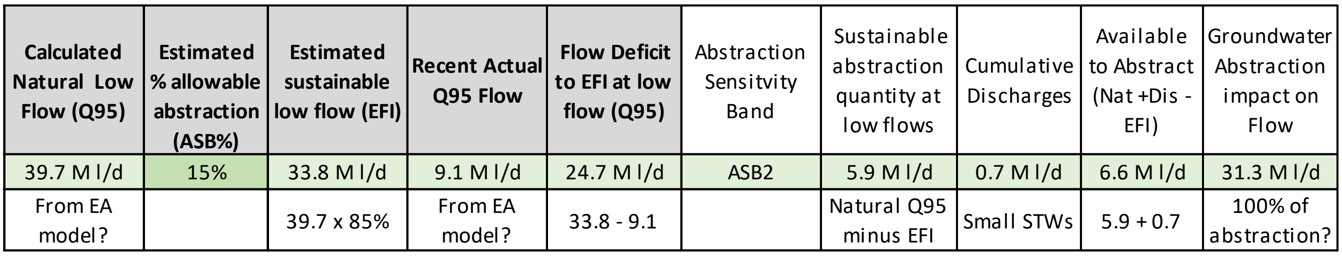
[27] Abstraction amounts from EA file *'HERTS Artifical Influences Overview_Red. Xlsx'*

indicator (EFI) methodology, abstraction as a % of recharge (A%R) is another valid methodology for assessing an acceptable impact of abstraction on flows. Referring to the earlier Table 3, the methodologies give broadly similar results for required abstraction reduction in the Ver catchment, although the reduction using the A%R methodology is somewhat less than when using the EFI methodology:

1. The EFI methodology gives a recent actual EFI low flow deficit of 24.7 Ml/d at Q95, assuming that the Ver is in the medium sensitivity band ASB2. The EA methodology indicates a maximum acceptable Ver abstraction of 6.6 Ml/d.
2. The A%R methodology proposes a maximum acceptable abstraction of 7.8 Ml/d – 10% of the average recharge of 78 Ml/d (A10%R). This assumes that the effective recharge catchment is 100 km^2, as per the CSF modelling (see Section 3.3). The required reduction in recent actual abstraction is 20.3 Ml/d (28.1 Ml/d recent abstraction less 10% of the 78 Ml/d average recharge).

The EA's total Ver flow deficit of 24.7 Ml/d and allowed abstraction of 6.6 Ml/d has been determined as shown on Table A1:



Calculated Natural Low Flow (Q95)	**Estimated % allowable abstraction (ASB%)**	**Estimated sustainable low flow (EFI)**	**Recent Actual Q95 Flow**	**Flow Deficit to EFI at low flow (Q95)**	Abstraction Sensitvity Band	Sustainable abstraction quantity at low flows	Cumulative Discharges	Available to Abstract (Nat +Dis - EFI)	Groundwater Abstraction impact on Flow
39.7 Ml/d	15%	33.8 Ml/d	9.1 Ml/d	24.7 Ml/d	ASB2	5.9 Ml/d	0.7 Ml/d	6.6 Ml/d	31.3 Ml/d
From EA model?		39.7 x 85%	From EA model?	33.8 - 9.1		Natural Q95 minus EFI	Small STWs	5.9 + 0.7	100% of abstraction?

Notes: 1. Copied from EA worksheet 'Chilterns flow deficits 2020.xlxs' provided by EA email dated 9.12.2020

2. John Lawson comments in bottom row

Table A1 - Environment Agency allowable abstraction calculation for the lower River Ver

There are some questionable aspects to the calculation shown in Table A1:

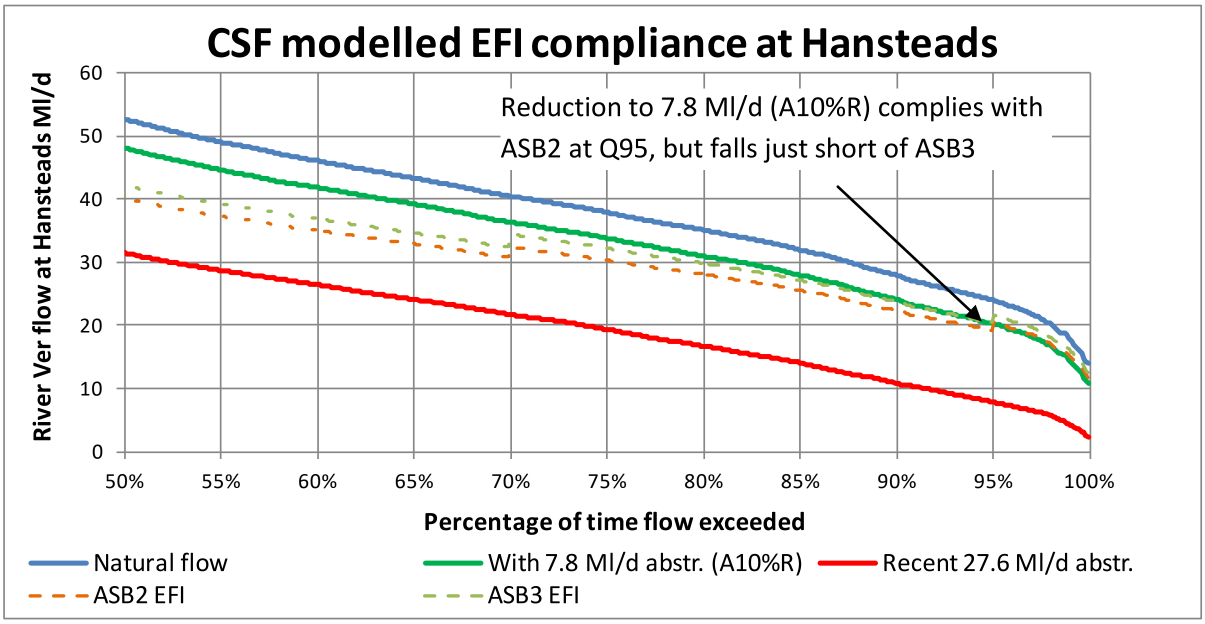
- The natural and recent actual Q95 flows don't match the HRGM model output
- The recent actual abstraction impact of 30.6 Ml/d at Q95 appears to be 100% of the recent actual abstraction, based on the 3 year average 2012-15 (the HRGM modelling runs to end 2015) – this doesn't match the recorded much lower recovery at low flows following the Friars Wash reduction.

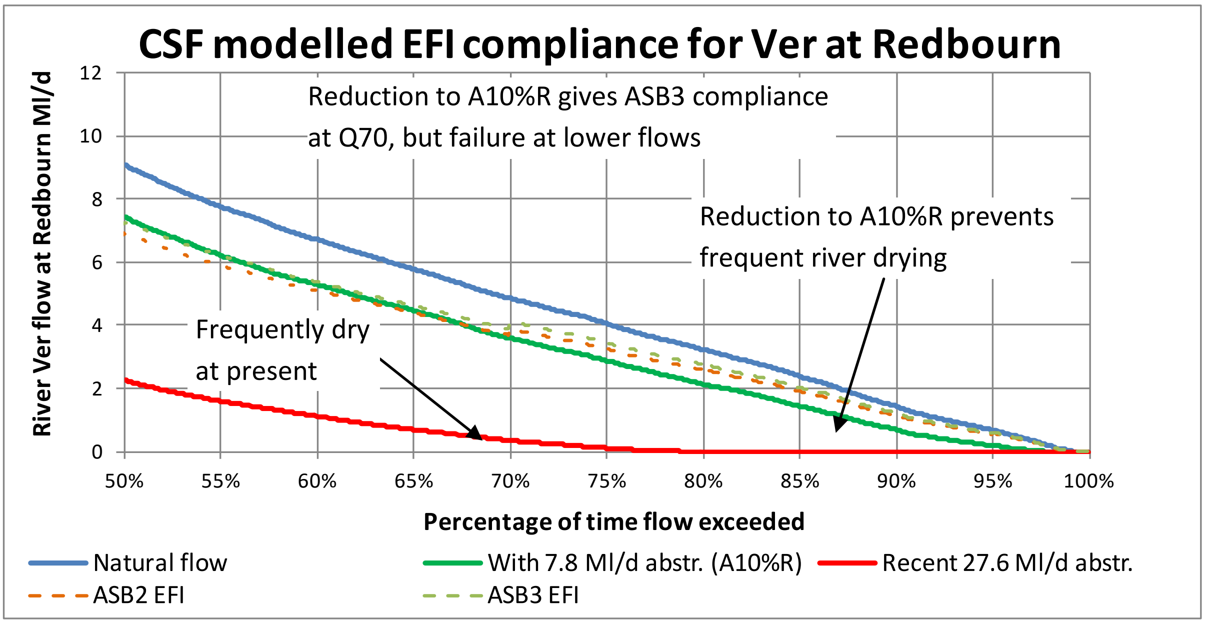
Nevertheless the EA allowable abstraction of 6.6 Ml/d is similar to the A10%R allowable abstraction of 7.8 Ml/d. In view of the poor validation of the HRGM model and the questionable aspects of the EFI assessment, it has been assumed that the required abstraction reduction is determined by the A%R methodology, limiting abstraction to 7.8 Ml/d.

A8 Modelling the benefits of abstraction reduction to A10%R

Compliance with Environmental Flow Indicators

The CSF model has been used to assess the flow benefits from reducing abstraction to 7.8 Ml/d (A10%R) – a 20.3 Ml/d reduction from the recent actual abstraction of 28.1 Ml/d. The modelled flow duration compliance with EFIs at Hansteads and Redbourn is shown on Figure A19:



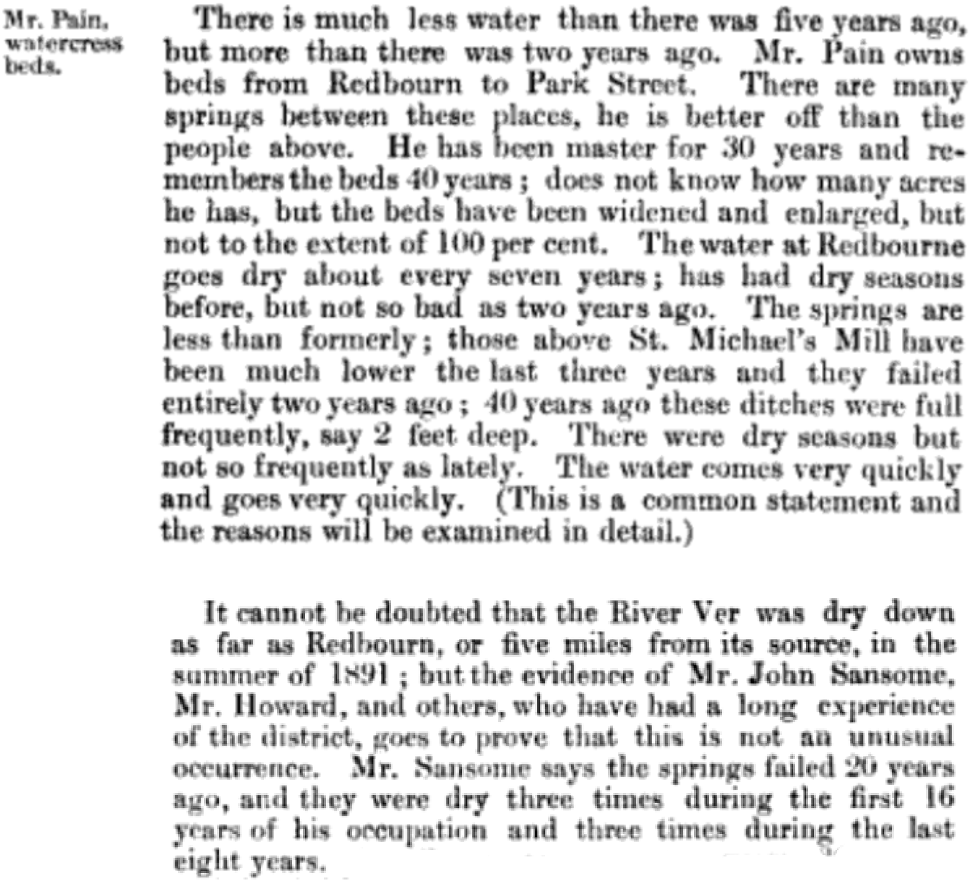


Note: Flow durations are calculated for the full 100 years of modelled flows 1920 to 2019

Figure A19 - CSF modelled Ver flow compliance with abstraction cut to 7.8 Ml/d (A10%R)

As can be seen on Figure A19, reduction of total Ver abstraction to 7.8 Ml/d (A10%R) gives Hansteads flow compliance with the ASB2 EFI target, but not with quite ASB3. Summer flows at Hansteads, typically below Q75, would be about double the flows that have occurred with the recent abstraction of about 28 Ml/d.

For the Ver at Redbourn, reduction of total abstraction to 7.8 Ml/d would greatly reduce the amount of river drying at Redbourn, getting close to the natural frequency of drying. The modelling shows that the river at Redbourn would be naturally dry at Redbourn for more than 5% of the time. This is consistent with the frequency of drying at Redbourn in the late 19th century (before the start of major public water supply pumping), as reported in the Royal Commission Report on Metropolitan Water Supplies in 1893[28], for example:



Mr. Pain, watercress beds.

There is much less water than there was five years ago, but more than there was two years ago. Mr. Pain owns beds from Redbourn to Park Street. There are many springs between these places, he is better off than the people above. He has been master for 30 years and remembers the beds 40 years; does not know how many acres he has, but the beds have been widened and enlarged, but not to the extent of 100 per cent. The water at Redbourne goes dry about every seven years; has had dry seasons before, but not so bad as two years ago. The springs are less than formerly; those above St. Michael's Mill have been much lower the last three years and they failed entirely two years ago; 40 years ago these ditches were full frequently, say 2 feet deep. There were dry seasons but not so frequently as lately. The water comes very quickly and goes very quickly. (This is a common statement and the reasons will be examined in detail.)

It cannot be doubted that the River Ver was dry down as far as Redbourn, or five miles from its source, in the summer of 1891; but the evidence of Mr. John Sansome, Mr. Howard, and others, who have had a long experience of the district, goes to prove that this is not an unusual occurrence. Mr. Sansome says the springs failed 20 years ago, and they were dry three times during the first 16 years of his occupation and three times during the last eight years.

Figure A20 - Reported frequency of Redbourn drying in the late 19th century

These historic records, show that the River Ver has always been a natural winterbourne down to Redbourn, so natural Q95 flow is zero. This shows a weakness in the Q95-EFI as a tool for assessing flow acceptability in the winterbourne reaches of chalk streams. It would be better to have a target based on the frequency of drying of winterbourne reaches.

Improvement of flows in typical years

With total abstraction reduced to 7.8 Ml/d (A10%R), the CSF modelled increases in flows at Hansteads and Redbourn for the 5-year period 2015 to 2019, including the 2019 drought, are shown in Figure A21:

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[28] Royal Commission on Metropolitan Water Supply, 1893, Appendices page 592/3 https://books.google.co.uk/books?id=QlxFAQAAIAAJ&newbks=0&printsec=frontcover&pg=RA2-PA507&dq=%22Hertfordshire+County+Council%22+River+Lea+Enquiry&hl=en&redir_esc=y#v=onepage&q=curb&f=false

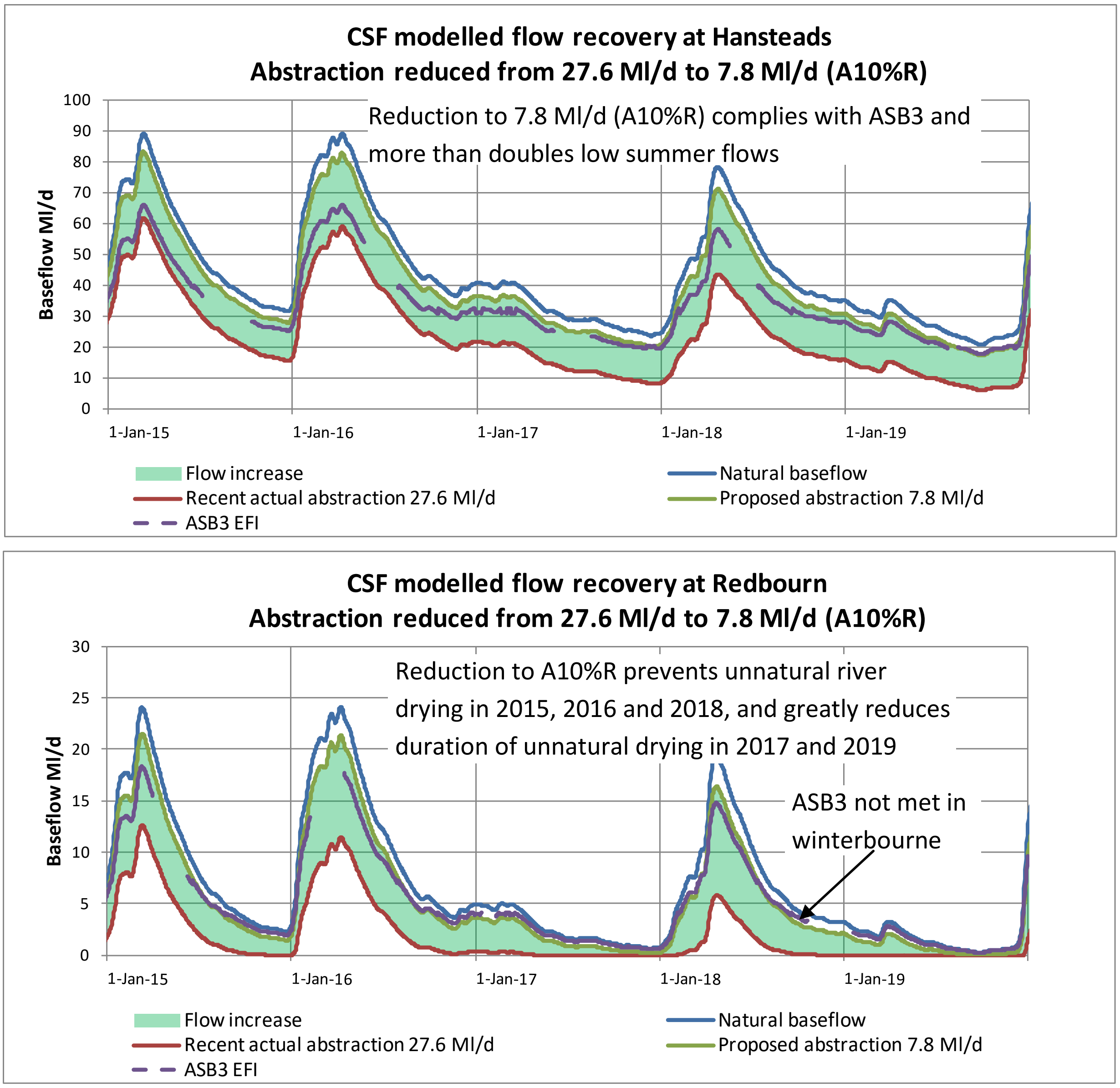


Figure A21 - CSF modelled Ver flow recovery at 7.8 Ml/d abstraction, 2015-2019

The plots shown in Figure A21 cover two ‘average’ years, 2015 and 2016, and the drought of 2018-19. It can be seen that reduction of abstraction to 7.8 Ml/d (A10%R) gives a big improvement in flows, recovering to close to natural flows at both Hansteads and Redbourn. ASB3 EFI flows at Hansteads would be achieved at all times, including the drought of 2019. It is suggested that this degree of compliance with ASB3 EFIs is acceptable, especially when taking account of the almost complete elimination of the unnatural drying of the river at Redbourn as shown in the lower plot in Figure A21.

A9 Benefit of flow recovery for London’s supplies

After using the CSF Ver lumped parameter model to generate 100 years of daily increase in River Ver-Colne-Thames flows from the Ver abstraction reduction, the GARD model of the London supply system has been used to assess the deployable output (DO) gain for London’s supplies. Details of GARD's London supply model are given in Appendix F.

In the 100-year period 1920-2019, the critical drought which governs London deployable output is May to December 1921. The modelling shows a London deployable output gain of 10.4 Ml/d in this drought when the Ver abstraction is reduced from 27.6 Ml/d to 7.8 Ml/d. The London DO gain of 11.4 Ml/d is 58% of the 19.8 Ml/d abstraction reduction:

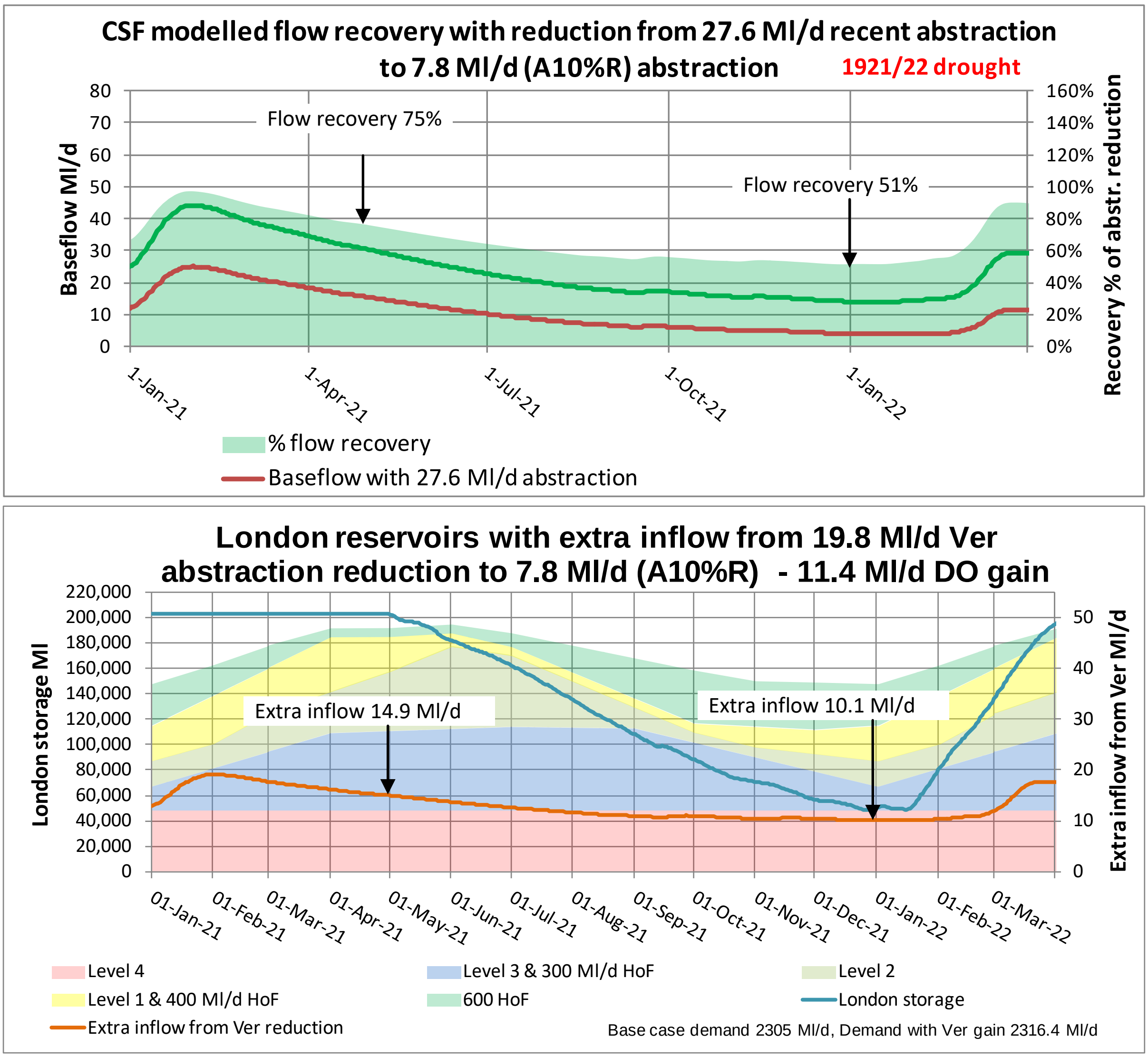


Figure A22 - CSF modelling of London DO gain from Ver abstraction reduction in 1921

At the start of the drawdown of the London reservoirs in May 1921, the increased flow from the River Ver would have been 14.9 Ml/d, 75% of the 19.8 Ml/d abstraction reduction. At the point of maximum drawdown of the reservoirs in December 1921, the flow increase from the Ver would have been 10.1 Ml/d, 50% of the Ver abstraction reduction.

The second most severe drought for London's supplies in the past 100 years would have been the 18 month drought of 1933/34. Figure A23 shows the Ver flow recovery:

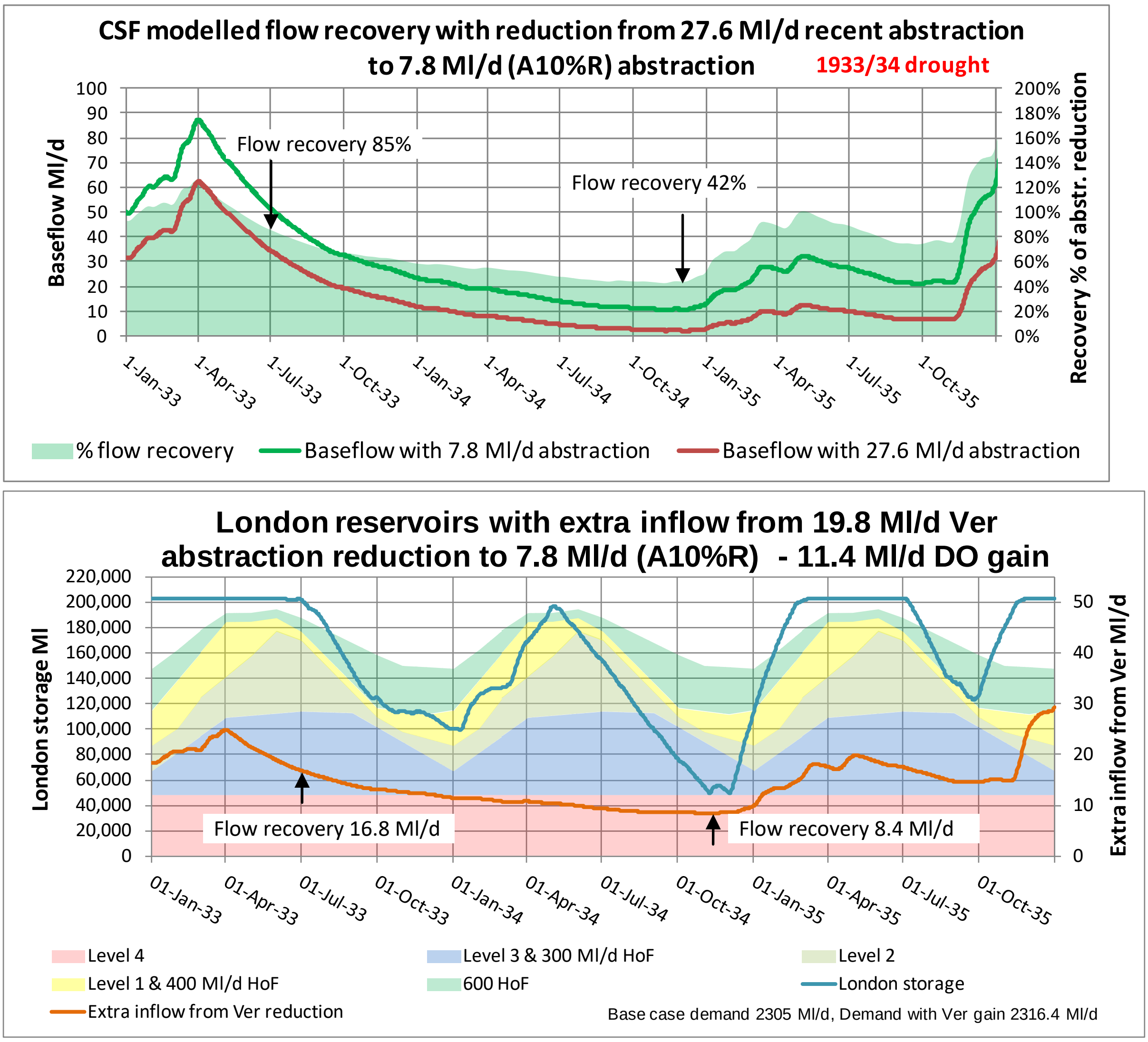


Figure A23 - London DO gain from Ver abstraction reduction in 1933/34 drought

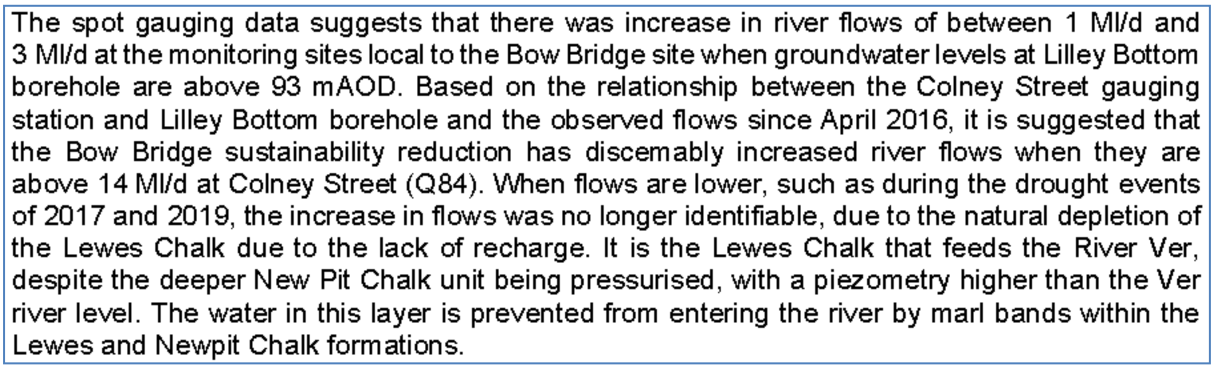
The drought of 1933/34 is typical of the 2-year droughts to which London's supplies are susceptible. It was almost the same severity for London's supplies as the 1921 drought. The CSF modelling shows that at the start of reservoir drawdown in July 1933 the additional flow from the Ver would have been 16.8 Ml/d, 85% of the 19.8 abstraction reduction. At maximum drawdown of the London reservoirs in November 1934, the Ver recovery would have fallen to 7.0 Ml/d, 36% of the abstraction reduction. The average flow recovery over the 17-month duration of the drought would have been about 54% of the 19.8 Ml/d abstraction reduction.

The modelled 53% recovery of London deployable output from the Ver abstraction reduction is lower than the equivalent 71% recovery for the modelled Mimram reduction – see Section 4.7. This is because the modelled underflow needs to be relatively high in the Ver catchment to achieve the catchment water balance whilst matching the measured groundwater levels and river flows – on average the modelled Ver underflow is 16.5 Ml/d, which is 33% of the average modelled baseflow of 50 Ml/d. In the Mimram catchment, the modelled underflow is only 16% average modelled baseflow.

A10 Comments on Affinity Water's Ver NEP report

Affinity Water's conclusion on effectiveness of the Bow Bridge reduction

Affinity Water's report on the River Ver in March 2020[29] was prepared under the Water Industry National Environment Programme (WINEP), primarily to address failure of the River Ver to achieve Water Framework Directive 'Good Ecological Status'. The report focused on the effectiveness of the 5.82 Ml/d sustainability reduction at Bow Bridge in 2016. The report summary describes the effect of the Bow Bridge reduction as follows:



The spot gauging data suggests that there was increase in river flows of between 1 Ml/d and 3 Ml/d at the monitoring sites local to the Bow Bridge site when groundwater levels at Lilley Bottom borehole are above 93 mAOD. Based on the relationship between the Colney Street gauging station and Lilley Bottom borehole and the observed flows since April 2016, it is suggested that the Bow Bridge sustainability reduction has discernably increased river flows when they are above 14 Ml/d at Colney Street (Q84). When flows are lower, such as during the drought events of 2017 and 2019, the increase in flows was no longer identifiable, due to the natural depletion of the Lewes Chalk due to the lack of recharge. It is the Lewes Chalk that feeds the River Ver, despite the deeper New Pit Chalk unit being pressurised, with a piezometry higher than the Ver river level. The water in this layer is prevented from entering the river by marl bands within the Lewes and Newpit Chalk formations.

The report summary goes on to say *"that there have been no clear improvements in the ecological status since the Bow Bridge sustainability reduction".*

Basis of Affinity Water's Bow Bridge conclusion

The finding that the 5.82 Ml/d abstraction reduction would lead 1 to 3 Ml/d of flow recovery, but only when Lilley Bottom GWLs are above 93 mOD, comes from the analysis of measured spot flows and GWLs following the abstraction reduction in April 2016. The analysis is shown in Figure 83 of the Ver NEP report and the accompanying text on page 121, which is copied below:

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[29] River Ver AMP6 NEP Report Technical Report 1.6 – Sustainability Reductions and River Restoration. Affinity Water March 2020. Official Sensitive.

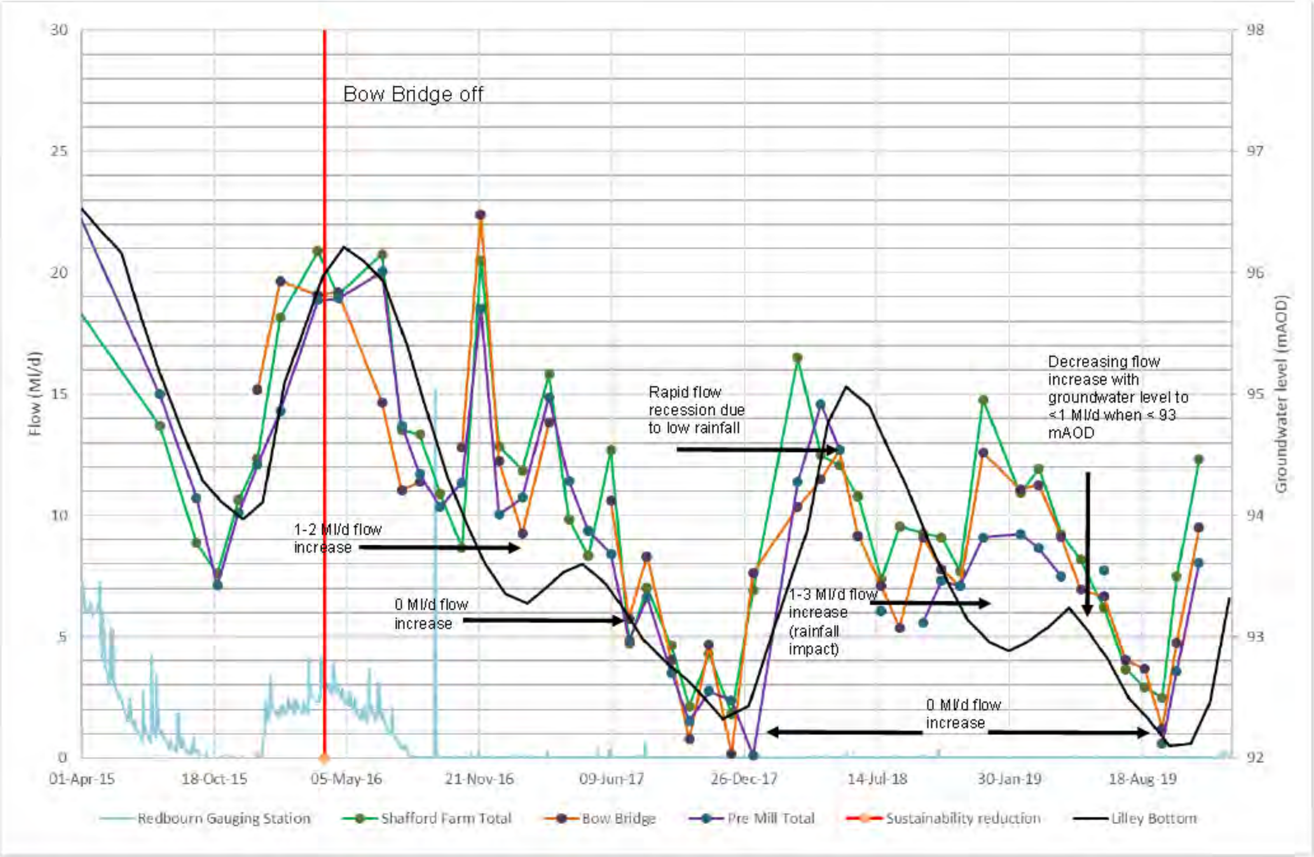

Figure 83 Spot flows in the vicinity of Bow Bridge plotted against groundwater level at Lilley Bottom

Figure 83 plots the spot gauging data from Shafford Farm, Bow Bridge and Pre Mill (the three closest spot gauging sites to Bow Bridge source) against groundwater level at Lilley Bottom on a secondary y-axis. The spot gauging trace follows the groundwater level trend during the recession of 2016, until groundwater levels reach 94 mAOD. From this point, groundwater levels continue to decline steeply whilst the rate of recession in the spot gauging data is less steep. It is proposed that the deviation in the relationship between groundwater levels and river flow could be regarded as the response to the Bow Bridge sustainability reduction. The difference between the black line (groundwater level) and spot gauging data ranges from 1-2 Ml/d, however when groundwater levels reach 93.2 mAOD, they converge once again, suggesting that during low groundwater levels, the river is not receiving the water that is no longer abstracted.

Figure A24 - Affinity analysis of flow recovery from the Bow Bridge abstraction reduction

The differences in patterns of changes in Ver flows and Lilley Bottom GWLs in winter 2018/19 could also be explained by the spot flows including surface run-off, the tendency of GWL changes to lag flow changes and the fact that Lilley Bottom is in the Mimram valley (Lea catchment, not Colne), about 15 km from St Albans. Although the Ver spot flows follow the Lilley Bottom GWLs quite well in 2015/16, there are big differences in the timing of the rising hydrograph limbs in 2017, as well as the rainfall impacts referred to on Affinity's Figure 83.

Overall, it seems hard to draw any valid conclusions from this analysis and the estimated flow increase of 1-3 Ml/d seems hard to justify. Equally, the conclusion of no flow increase when Lilley Bottom GWLs are less than 93 mOD appears to be based on weak evidence.

Impact of Bow Bridge reduction on flows at Redbourn

The Ver NEP report, page 126, also refers to the relationship between flows at Redbourn and groundwater levels at Lilley Bottom, including the drying of Redbourn flows when Lilley bottom GWLs fall below 94 mOD. The report concludes from this that:

> *"the generally good relationship between groundwater levels and river flows persists regardless of whether abstraction is taking place, suggesting that the flow at Redbourn gauge is not impacted significantly by Bow Bridge abstraction."*

However, the persistent relationship between GWLs and flows at Redbourn can be explained by the interpretation of chalk stream flow drivers in Section 2.1 of this report and Figure 1. This interpretation says that chalk stream flows and regional groundwater levels have a fixed relationship in the form of the equation $Q = ah^{2.5}$, and that the regional groundwater levels are lowered by abstraction. On that basis, the unchanging relationship between GWLs and flow is an unalterable aspect of natural chalk stream behaviour and is no justification for the conclusion that "*flow at Redbourn gauge is not impacted significantly by Bow Bridge abstraction*".

Use of Lilley Bottom GWLs as a surrogate for unaffected Ver flows

The Ver NEP report, pages 128-129, including Figure 87 (copied on next page as Figure 30), puts forward a comparison of Ver flows and Lilley Bottom GWLs in the similar droughts of April 1990 to October 1992 and April 2016 to October 2018. The analysis shows that in two 5 month periods of similarly low summer GWLs in 1991 and 2017, there were similarly low flows in the River Ver at Hansteads, despite a total reduction in Ver abstraction of about 18 Ml/d (39% reduction) between 1991 and 2017. The NEP report concludes that this is more evidence that reduced abstractions have minimal influence on flows. There would appear to be several flaws in this argument:

1. If river flows are dependent largely on regional GWLs, as described in Section 2.1 of this report, when the GWLs are the same (as in the two periods examined in 1991 and 2017), then the river flows must also be the same, regardless of the abstraction.
2. In 1991, the total abstraction in the Mimram valley was about 17.5 Ml/d and it had reduced to 10.5 Ml/d in 2017, a 40% reduction, similar to the % reduction in the Ver over the same periods. Therefore the Lilley Bottom GWLs are likely to have been increased by a similar amount to the Ver GWLs, driving similar changes in flows.
3. Although the flows in the drought periods compared in NEP Figure 87 are similar on average, there are large differences in flows at some times which are disguised by plotting the flows on a log scale. This shows the difficulty and unreliability of this type of analysis.

It can be concluded that this aspect of the Ver NEP analysis was somewhat questionable.

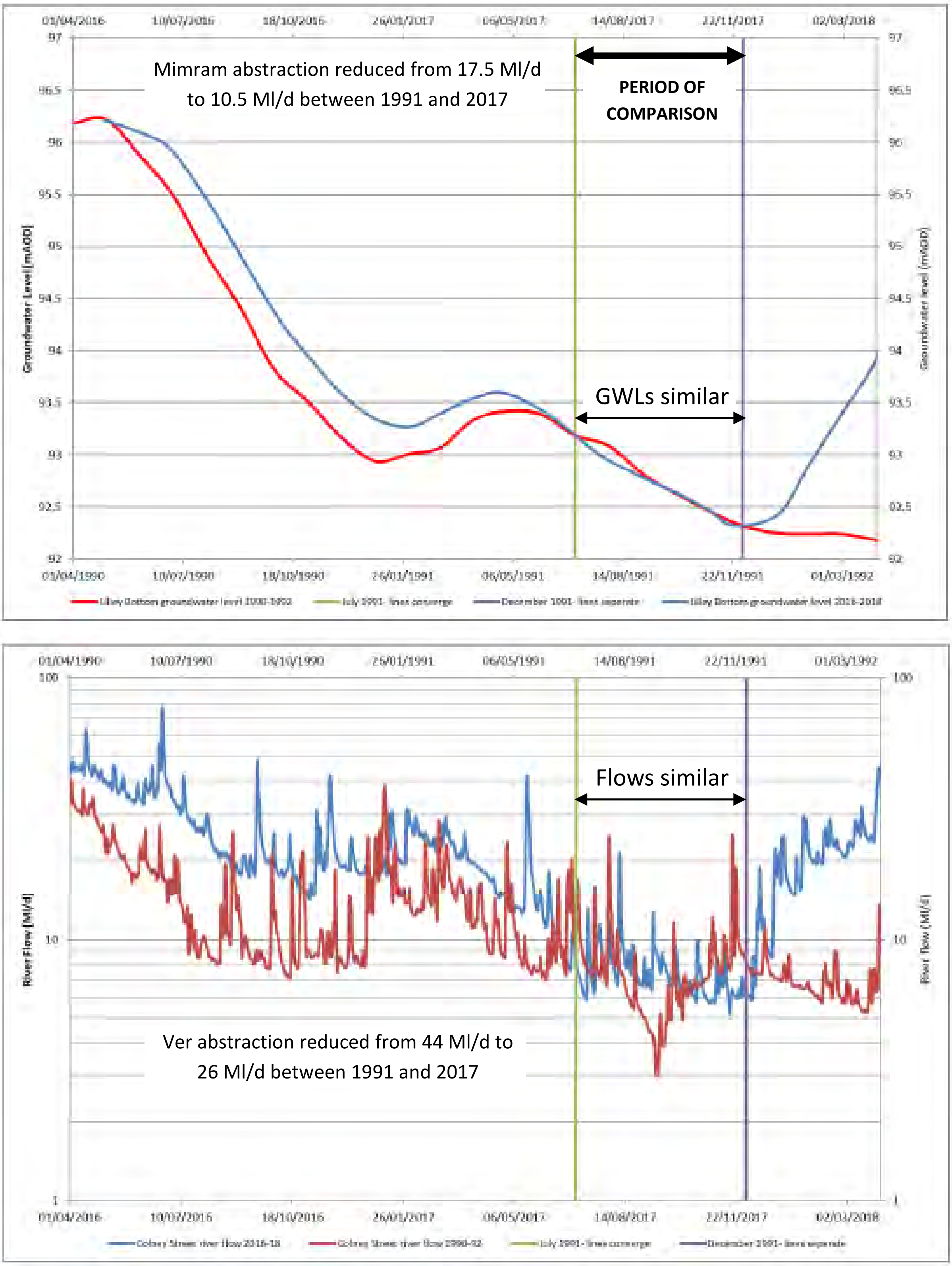

Figure 89 Drought comparison of river flows vs groundwater levels

Figure A25 - NEP report use of Lilley Bottom GWLs to assess Ver flow reductions

Kensworth Lynch signal tests

The NEP report page 27 refers to a planned 10 day outage of the c.6 Ml/d abstraction at Kensworth Lynch in 2011, an unplanned two month outage in 2014 and a planned eight week outage in 2015. The report concludes that lack of significant measured flow increases in these three signal tests demonstrated that any reduction in abstraction from Kensworth Lynch would not benefit river flows in the Upper Ver catchment directly or indirectly.

The CSF modelling of the 6 Ml/d Bow Bridge reduction, as plotted on Figure 22 of this report, shows that the maximum two month duration of the switch-offs would have been far too short to allow the recovery of regional groundwater levels needed to induce any significant flow recovery. Therefore, the NEP report conclusion from the lack of impact of the Kensworth Lynch abstraction is probably not justified.

Lack of assessment of flow benefits from the Friars Wash reduction

Apart from the questionable analysis using Lilley Bottom GWLs as described above, the NEP report makes no reference to the measured flow increases following the Friars Wash reduction, as shown by the Figures B6 and B7.

The NEP report also makes no reference to the Environment Agency's modelling of the substantial flow recovery from a 6 Ml/d abstraction reduction, as shown on Figure 23 of this report. There is no explanation of why the EA's modelled flow recovery has been ignored, apart from a reference on page 96 of the report (dated 2020) to a new model being developed *"to replicate the dual piezometry phenomenon".* No output from this model is yet available for review. The NEP report appears not have considered the need for the revised model to replicate the measured flow recovery from the Friars Wash reduction, which can be seen on Figure A7.

Affinity Water's 'dual piezometry' justification of lack of flow recovery

The Ver NEP report explains the lack of measured low flow response to the Bow Bridge reduction in terms of the abstraction being taken from beneath low permeability marl layers in the chalk, which are shown on the geological cross-sections in Figure 8 of this report. Evidence of the effect of the marl layers is shown by differences in the piezometric heads registered by the Bow Bridge abstraction boreholes (cased through the upper chalk layer) and the nearby observation borehole – the piezometric heads beneath the marl layers are several metres higher than heads in the near-surface chalk or the nearby river levels. Piezometric head differences drive artesian conditions in a number of places in the upper Colne and Lea valleys and have been used historically to supply water to water cress beds[30]. These head differences, referred to as 'dual piezometry', are shown on Figure 74 of the NEP report, with parts re-plotted at a larger scale on Figure 76, as copied on the next page:

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[30] Artesian conditions in the Chilterns Chalk aquifer (NW of the London Basin) and the implications for surface water–groundwater interaction: Marsili, Karapanos et al. March 2022. https://sp.lyellcollection.org/content/early/2022/03/16/SP517-2020-144

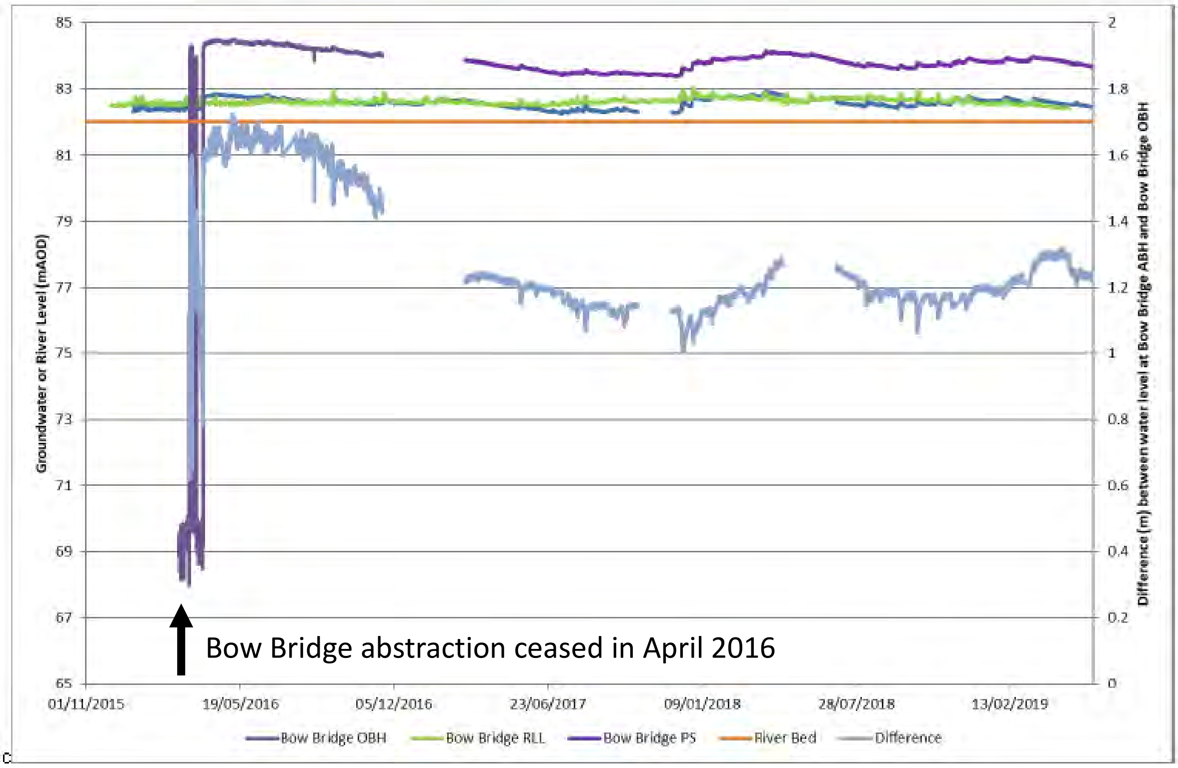


Figure 74 Recovery following Bow Bridge sustainability reduction in the Lewes and New Pit Chalk

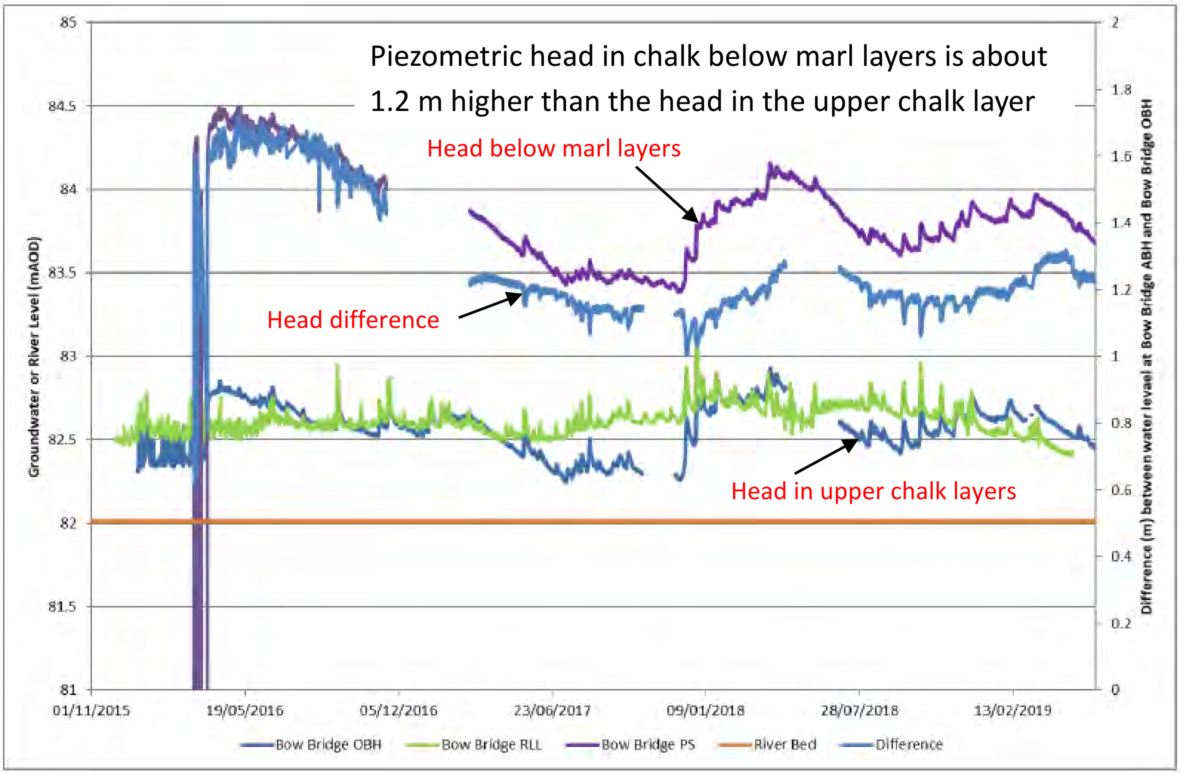
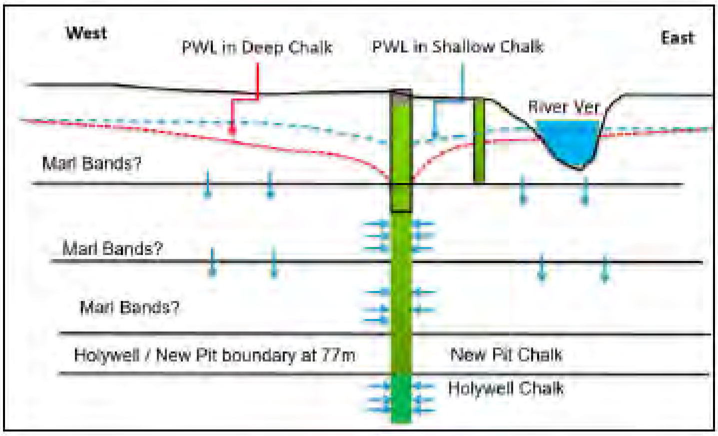


Figure 76 Recovery following Bow Bridge sustainability reduction in the Lewes and New Pit Chalk (zoomed in y axis)

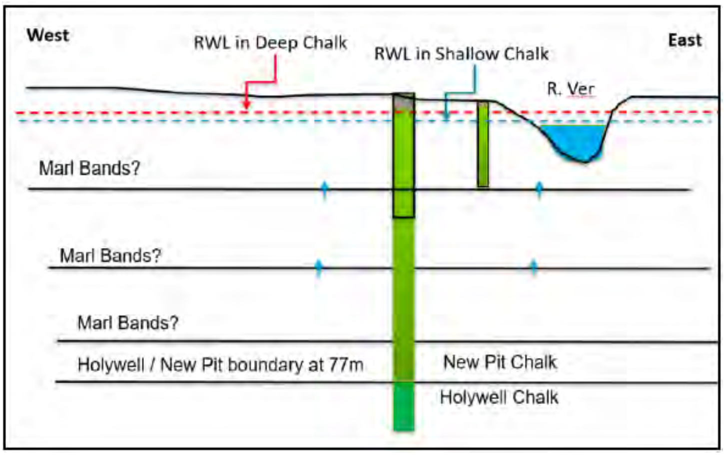
Figure A26 - Measured 'dual piezometry' between upper and lower chalk layers

The ‘dual piezometry’ theory argues that abstraction can be made from chalk beneath the marl layers without significantly influencing GWLs near the surface or river flows. This concept is illustrated by Figures 77 to 79 in the NEP report which are reproduced below, adjacent to boxes with the corresponding explanatory text copied from page 117 of the NEP report (with slight abbreviations):



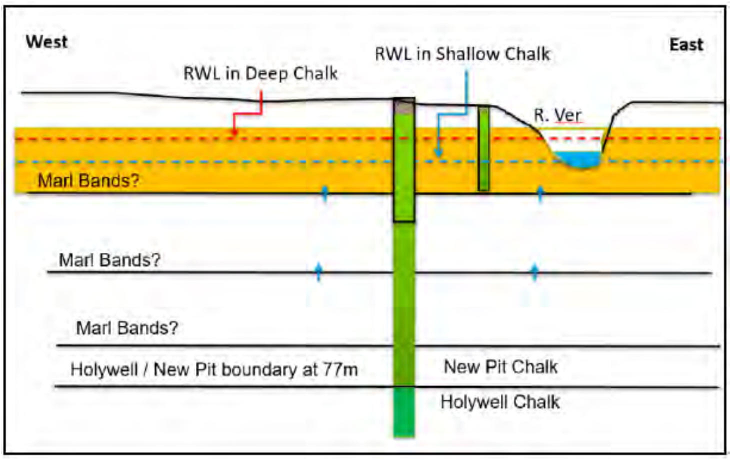
The abstraction is primarily supplied by water derived from the New Pit and Holywell Chalk formations, so the greatest drawdown and cone of depression is seen here. Due to the suction effect of pumping, some vertical leakage is induced downwards from the Lewes Chalk, through the marl bands. This produces a smaller cone of depression in the shallow Chalk, which may be at the expense of river flow if groundwater level piezometry would have been higher than river level without the abstraction effect.

Figure 77 Ver conceptual model under pumping conditions (average groundwater levels)



Under average groundwater level conditions, without the leakage effect from pumping, there is a higher piezometric level in both the Lewes and New Pit Chalk. The piezometry in the New Pit Chalk is over 1 m above river level, whilst the level in the Lewes Chalk is similar to river level. This means that there are potential gains from the Lewes Chalk to the Ver (or at least not losses to the shallow Chalk). Under these conditions, potential river flow increases as a result of the sustainability reduction could be expected.

Figure 78 Ver conceptual model during non-pumping conditions (average groundwater levels)



GWLs fell in the 2017 drought, causing the WL in the Lewes Chalk to dip below the river level. Meanwhile, the piezometry in the New Pit Chalk remained over 1 m above river level and the Lewes Chalk GWL, causing losses from the river. The decline in river flow despite the head in the New Pit Chalk being above the river level, suggests that the water naturally pressurised in this layer cannot move upwards through the marl bands to feed the shallow Chalk and the river. It suggests that the downward leakage created by pumping suction is greater than the upward movement of water without abstraction. It also explains why low flows persist in droughts, without abstraction, and suggests that increases in river flow from reduced abstraction in droughts, may be limited.

Figure 79 Ver conceptual model during non-pumping conditions (low groundwater levels)

Figure A27 - NEP report explanation of the 'dual piezometry' concept

Although the marl layers are doubtless less permeable than the chalk, they are not totally impermeable, so they reduce the connectivity between upper and lower chalk strata, but do not prevent it altogether. This is recognised on NEP report Figures 77 to 79. The reduced connectivity between the upper and lower chalk strata seems likely to slow the response of river flows and GWLs to abstraction from below the marl layers, but not to eliminate it.

There is evidence that the upper and lower chalk layers are hydraulically connected and the abstraction from the lower chalk does affect river flows, despite the presence of marl layers:

1. The Friar's Wash abstraction reduction led to measured river flow increases and an average flow recovery of about 80% (see Figures B6 and B7) despite abstraction coming from Holywell/New Pit chalk below the marl layers (see geological section on Figure A3).

2. After the Bow Bridge abstraction ceased, the piezometric head below the marl layers rises and falls in the same way as in the upper chalk layers as shown by comparison with the nearby Batchwood Golf Club observation borehole GWLs in Figure A28:

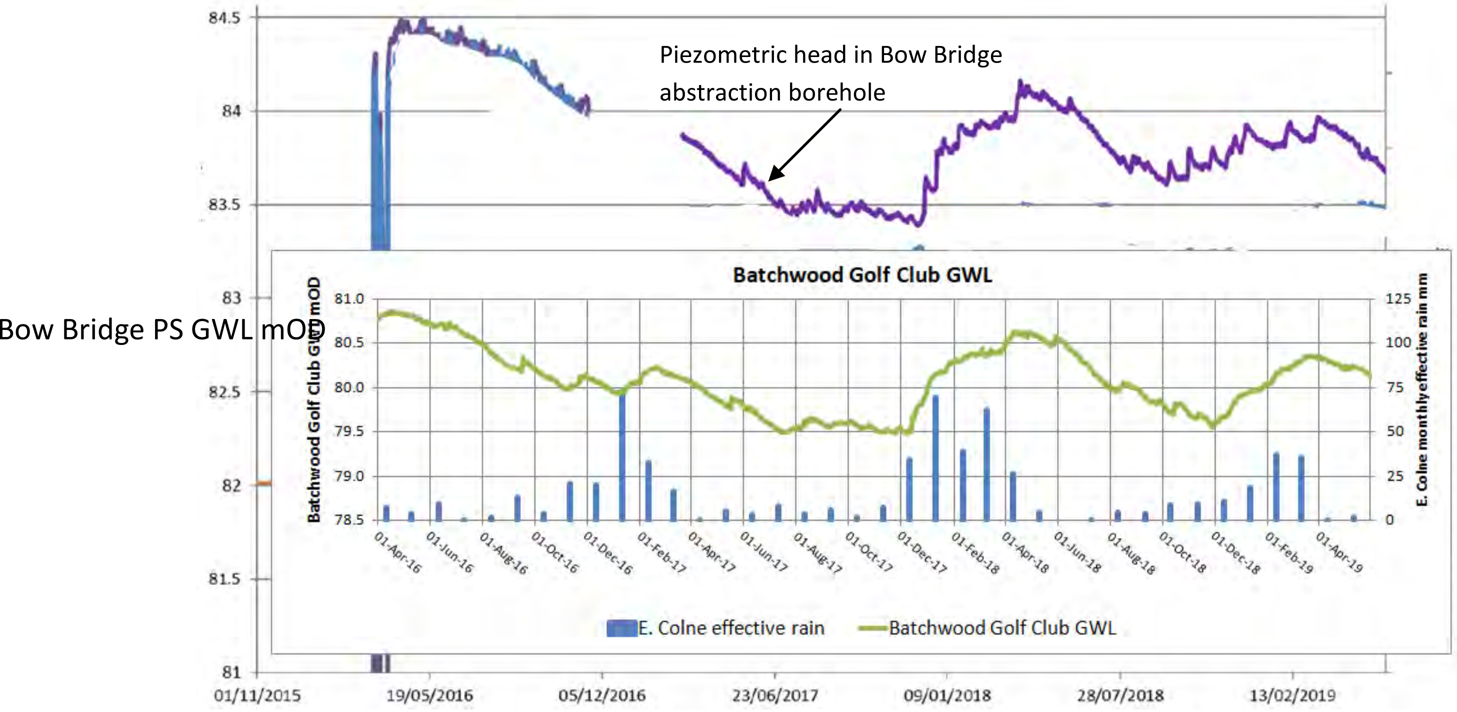


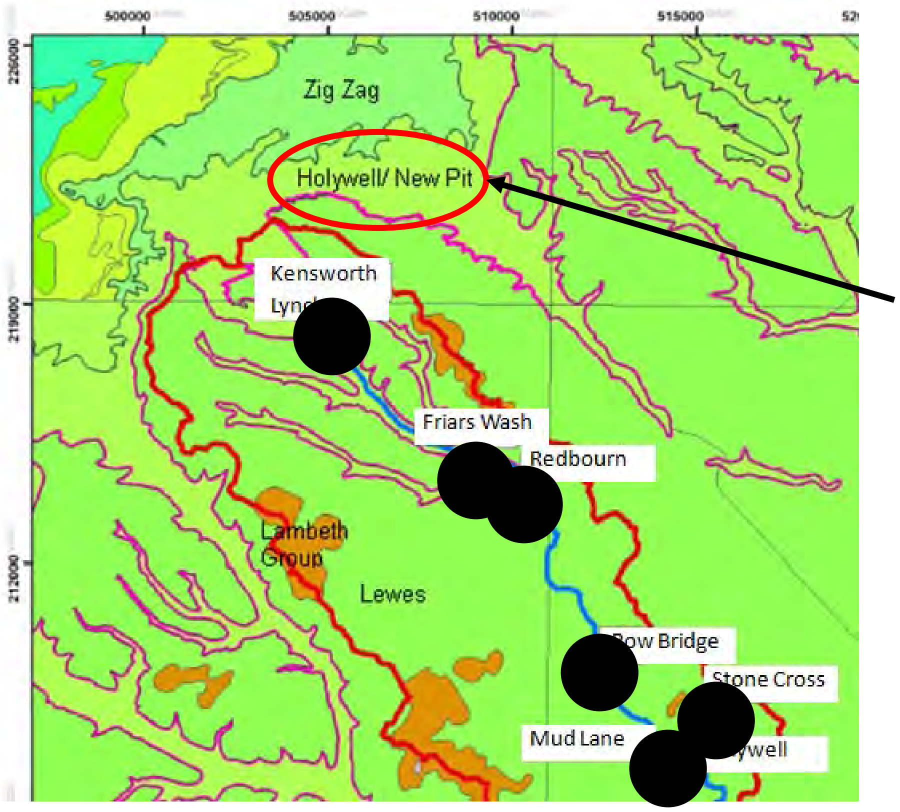
Figure A28 - Deep and shallow GWLs near Bow Bridge after abstraction reduction

After the cessation of abstraction, the piezometric heads below the marl layer in the Bow Bridge abstraction borehole rise with the winter recharge and fall in the summer recession, following the same trend as the nearby Batchwood Golf Club OBH. This shows that:

- The deep chalk below the marl layers is receiving recharge from effective rain, similarly to the upper chalk layers

- The deep chalk below the marl layers is drained by river and aquifer outflows, similarly to the upper chalk layers

The response to effective rain in the winter of 2017/18 shown in Figure A28 suggests that recharge reaches the Holywell/New Pit chalk below the marl layers with similar timing to the upper Lewis chalk layers, implying a relatively short hydraulic connection with the surface. The nearest up-slope surface outcrop of the Holywell/New Pit chalk is about 15 km to the north of Bow Bridge in the scarp slope outside the Ver catchment as shown in Figure 34:



Holywell/New Pit outcrop about 15km north of Bow Bridge

Figure A29 - Proximity of Holywell/New Pit outcrop to Bow Bridge abstraction borehole

The long distance of the Holywell/New Pit outcrop from Bow Bridge and the limited area of outcrop suggests that the recharge of the Holywell/New Pit chalk below the marl layers is coming from the surface above, through the marl layers and not from the distant outcrop. The prompt response to recharge displayed by piezometric heads below the marl layers provides strong evidence of hydraulic connection to the surface nearby.

The NEP report puts forward the concept of ‘dual piezometry’ as an explanation of a) the perceived lack of measured flow recovery from abstraction reductions, b) the lack of measured flow recovery during signal tests and c) the tendency of flow recovery to be low in droughts and more at other times, when groundwater levels are higher. However, all these phenomena can be explained more simply and more convincingly by the interpretation of chalk stream behaviour set out in Section 2 of the main report and encapsulated in the CSF lumped parameter modelling:

- River flow recovery following abstraction reductions or signal tests requires regional groundwater levels to rise to drive the flow increases – full recovery of GWLs and flows can take about 2 years, as illustrated in CSF modelling of the Bow Bridge abstraction reduction in Figure 22.
- The tendency for flow recovery to be low in droughts and progressively higher as GWLs rise, as measured at Friars Wash, can be explained by the physics of the flow-GWL relationship, as explained in Section 2.4 of the main report.

This explanation appears to be well supported by measured data and modelling.

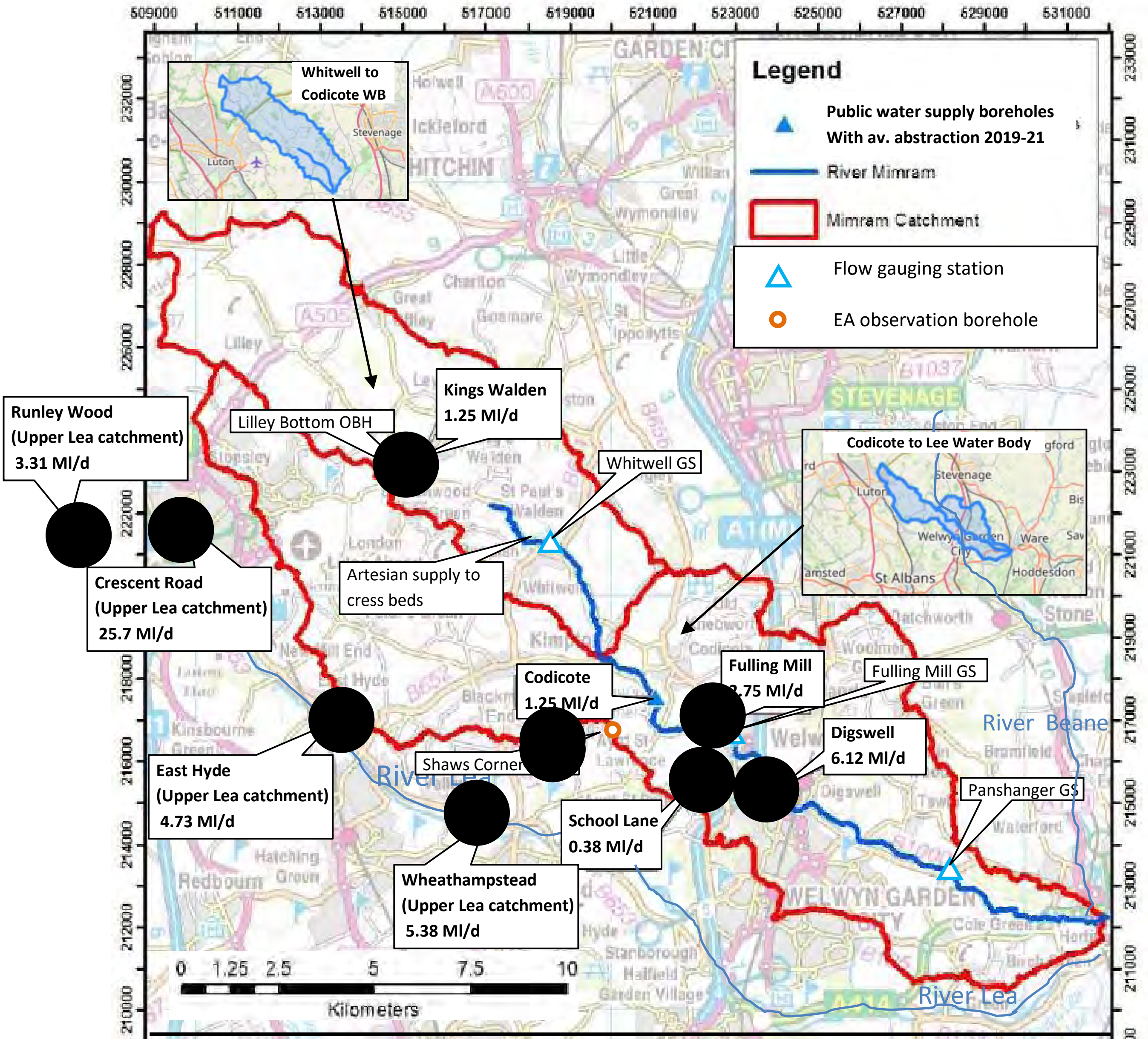
It can be concluded that whereas partially confining layers and ‘dual piezometry’ do exist in the chalk, there is still sufficient hydraulic connection throughout the chalk for abstraction from the deep Holywell/New Pit chalk to affect the Lewis chalk piezometry and river flows above. The response of river flows to Ver abstraction reductions can be explained by the interpretation of chalk aquifer behaviour in Section 2 of the main report.

Appendix B - River Mimram case study

Contents

B1 Mimram location, geology and abstraction history

The approximate locations of public water supply abstractions from groundwater in the Mimram catchment and nearby rivers are shown in Figure B1 **(redacted)**:

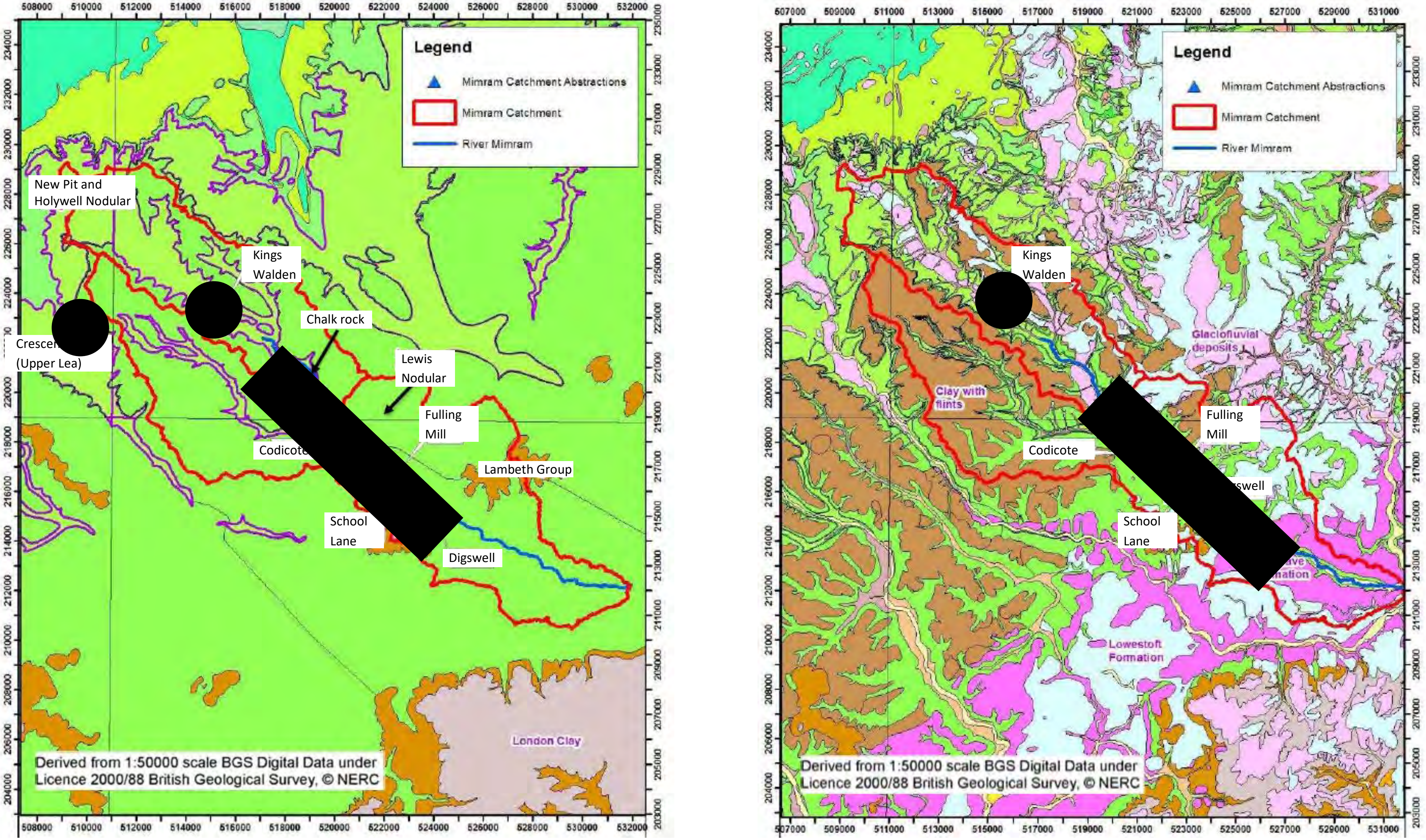


Base map copied from Mimram NEP report Figure 2

Figure B1 - Mimram catchment and abstraction locations

The recent actual average abstraction in the Mimram topographic catchment, 2019 to 2021, was 11.0 Ml/d. However, in 2019 to 2021, there were about 40 Ml/d of abstractions in the adjacent Upper Lea catchment at the locations shown in Figure B1. These abstractions seem very likely to affect the regional water table and flows in the Mimram catchment.

The solid geology and superficial deposits of the Mimram catchment are shown on Figure B2 and geological sections are shown on Figure B3:

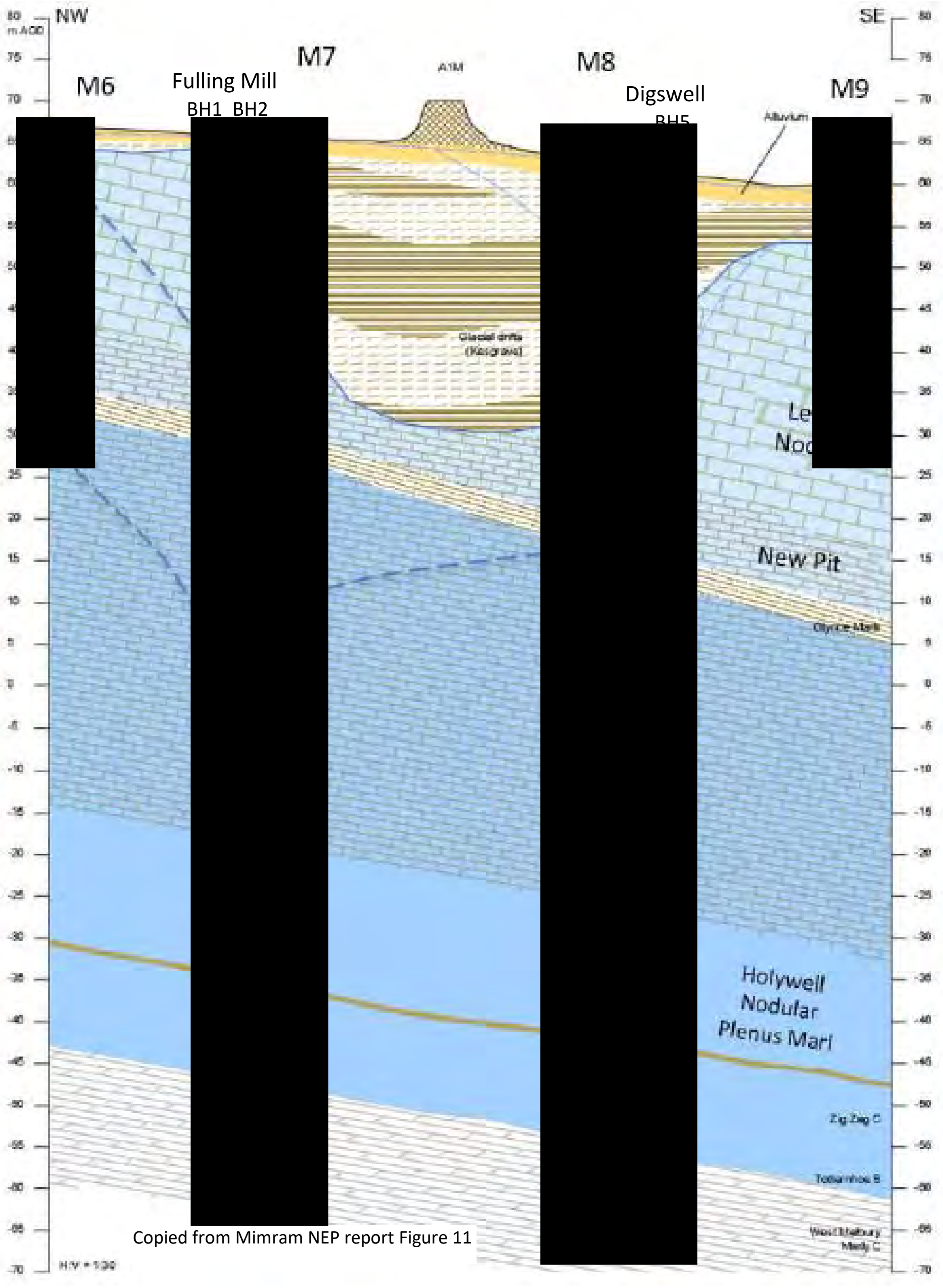


a) Solid geology

b) Superficial deposits

Maps copied from Mimram NEP report Figure 10

Figure B2 - Solid and drift geology of River Mimram, with PWS borehole locations



[redacted]

[redacted]

[redacted]

[redacted]

Copied from Mimram NEP report Figure 11

Figure B3 - Conceptual long section of the middle Mimram

The growths in abstraction in the Mimram catchment and Lea chalk are shown in Figure B4:

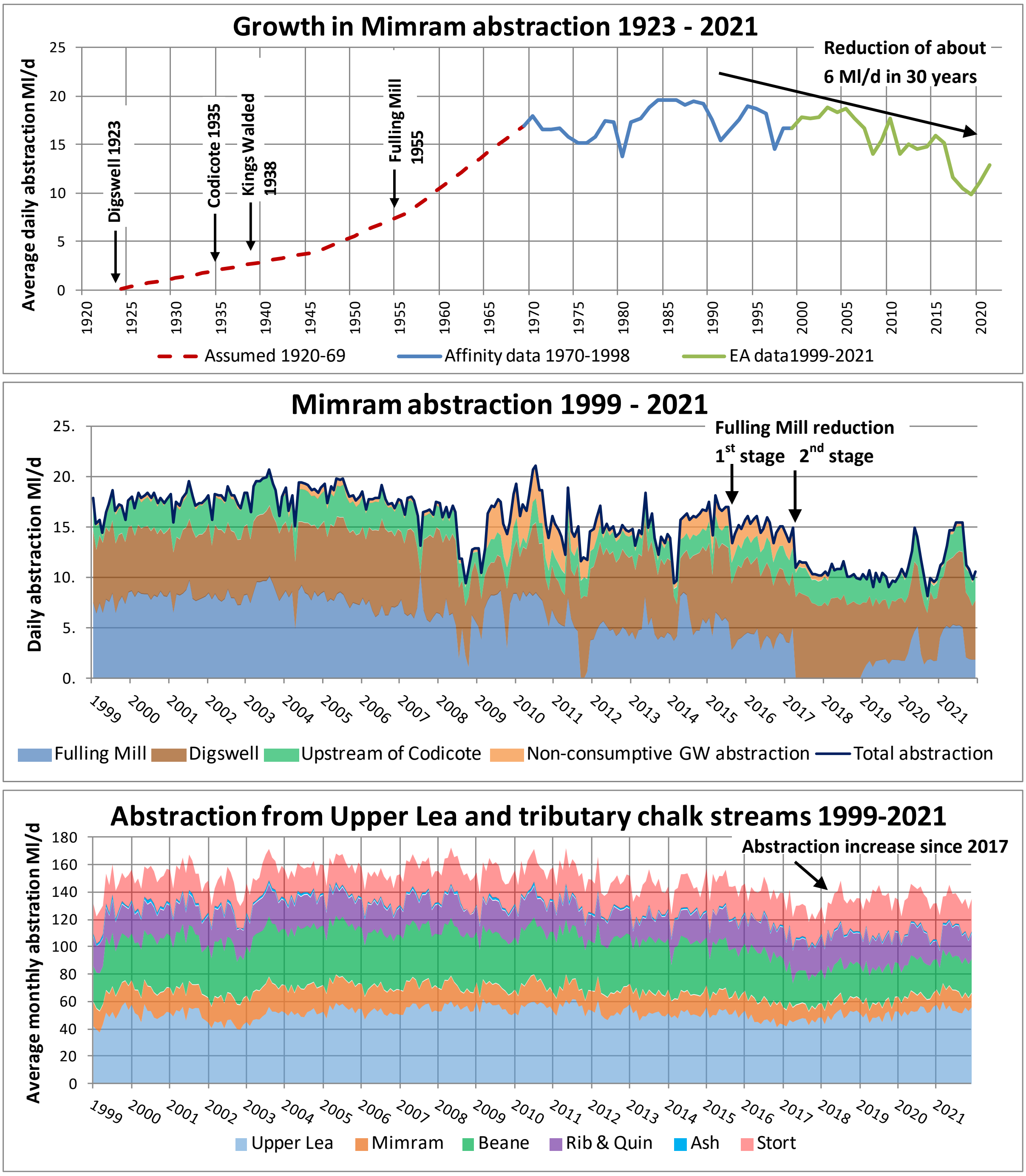


Figure B4 - Abstraction growth in Mimram and whole Lea catchments

Figure B4 shows that abstraction reductions in the Mimram catchment have been relatively small and not consistently maintained. The Fulling Mill reduction was nominally a 9.09 Ml/d reduction. However, the first stage of the reduction in 2015 was not maintained. The second stage in 2017 was immediately replaced by increased abstraction at Digswell. Abstraction at Fulling Mill resumed in 2019 and was at pre-2017 levels for several months in both 2020 and 2021. The lower plot in Figure B4 shows that total abstraction from the Lea chalk has actually increased since the Fulling Mill reduction in 2017. Abstraction increases in the adjacent Upper Lea and Beane catchments since 2017 may have affected the regional GWLs in the Mimram catchment, negating the effect of the Mimram reductions.

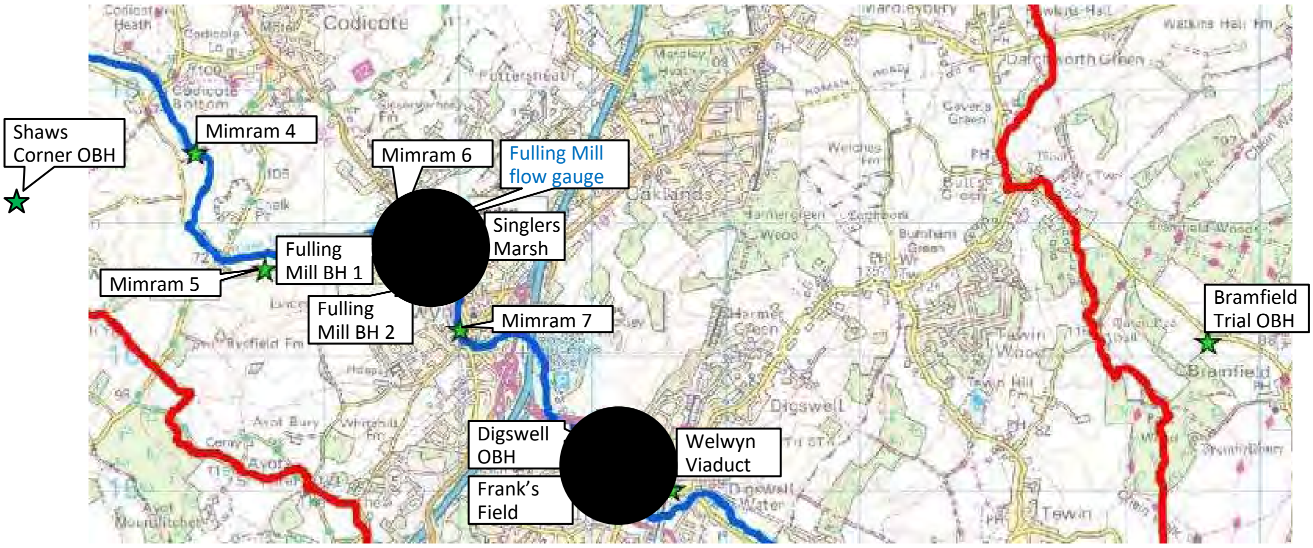
As mentioned when considering the measured effect of abstraction changes in the Ver catchment, flow changes from abstraction reductions can only be measured if there are:

- Similarly lengthy periods, at least 10 years each, containing comparable droughts
- Substantial and sustained differences in abstraction between the two periods

Neither of these criteria is met by the Fulling Mill reductions or by any other abstraction changes in the Mimram catchment. Realistically, it is not feasible to analyse measured flow changes from the Mimram abstraction reduction of only about 6 Ml/d, spread over the 30 year period since 1990.

B2 Relationship between Mimram flows and GWLs

In addition to the EA's Lilley Bottom and Shaw Cross observation boreholes shown on Figure 35, Affinity Water have a number of OBHs in the Fulling Mill and Digswell area at locations as shown on Figure 39:



[redacted]

[redacted]

Figure B5 - Location of OBHs in Fulling Mill and Digswell area

Groundwater levels and river flows in the Mimram catchment are closely linked in the manner described in Section 2.2. This can be seen in the plot of GWLs and river baseflows in the Fulling Mill and Digswell area shown in Figure B6:

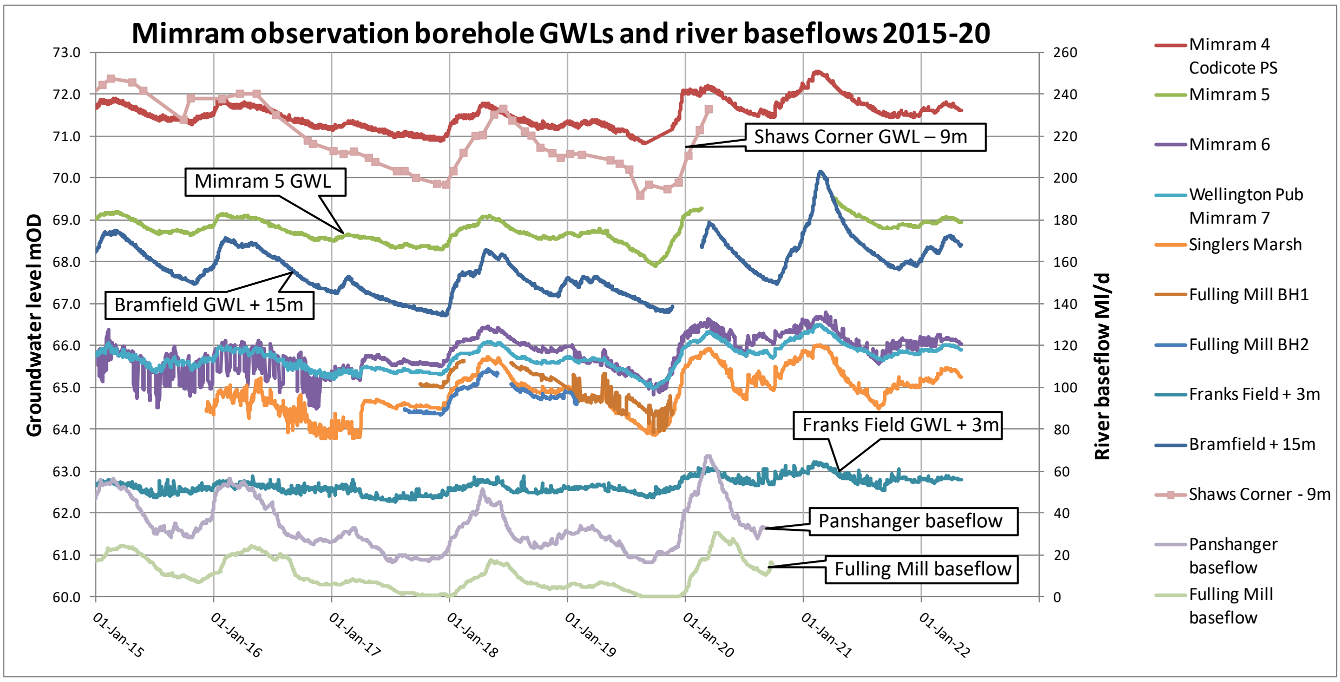
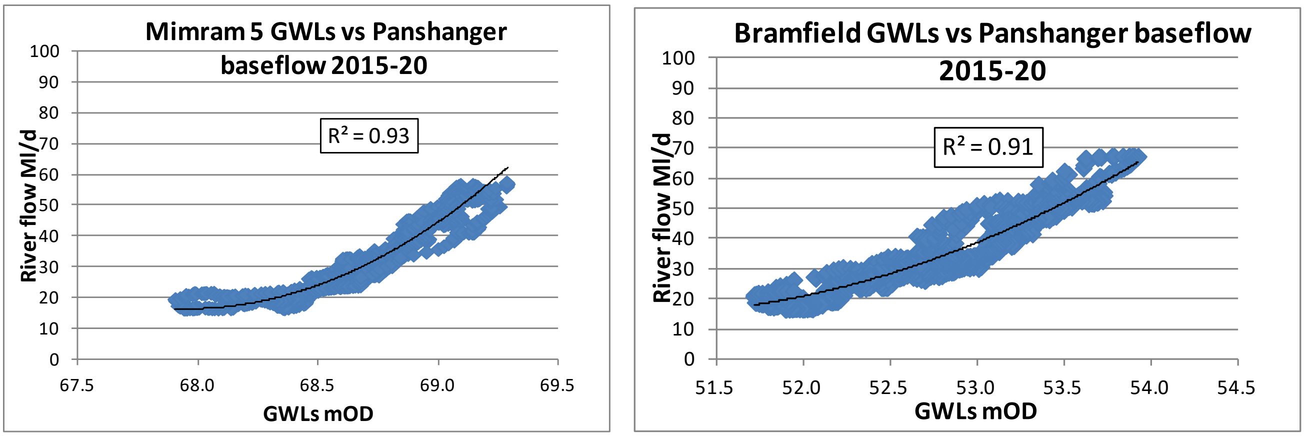


Figure B6 - Middle/upper Mimram GWLs and flows 2015-20

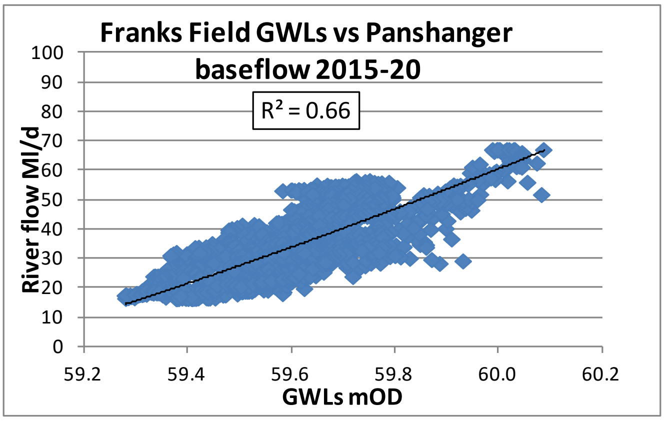
Commenting on the relationships between GWLs and flows that can be seen in Figure B6 at different locations:

1. All the GWLs follow a similar pattern, suggesting they are all part of the regional water table with its seasonal fluctuations.
2. The Bramfield OBH (ground level 94.9 mOD, depth 150m) penetrates to the Holywell chalk, but follows the same pattern of GWL fluctuations as the less deep OBHs which only penetrate to the Lewis or New Pit chalk, eg Mimram 4, 5,6 and 7 which are each about 32 to 38m deep.
3. The limited records (2017-19) for the Fulling Mill BHs 1 and 2, over 100m deep and penetrating to the Holywell chalk, follow the same pattern as the less deep OBHs.
4. The GWL fluctuations are larger in the Bramfield and Shaws Corner OBHs which are both located several km from the river.
5. GWL fluctuations are much less in shallow boreholes close to the river like the Franks Fields OBH which is 8.5 m deep and penetrates to the Lewes chalk.
6. River flows at both Fulling Mill and Panshanger are linked to GWLs in the manner described in Main Report Section 2.2.

Plots of Panshanger baseflows against Mimram 5, Bramfield and Franks Field GWLs are shown on Figure B7:



a) Borehole 35m deep into Lewes chalk b) Borehole 150m deep into Holywell chalk

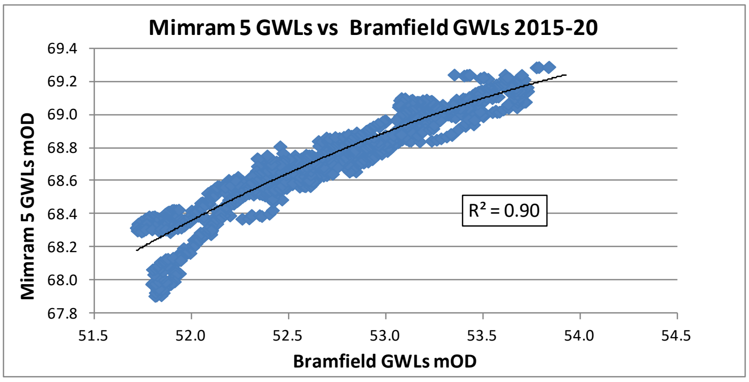


c) Borehole 8m deep into Lewis chalk

Figure B7 – River flows vs Mimram observation borehole GWLs

The gauged baseflows at Panshanger follow good relationships with the recorded GWLs in both the deep Bramfield borehole in to the Holywell chalk and the less deep Mimram 5 borehole into the Lewis/New Pit chalk. There is a much less good fit between the Panshanger flows and the GWLs in the shallow Franks Fields borehole which just penetrates into the Lewis chalk.

As would be expected from the good correlations shown in plots a) and b in Figure B7, there is also good correlation between the Mimram 5 GWLs in the Lewis chalk and the Bramfield GWLs about 6 km away in the Holywell chalk, as shown in Figure B8:



GWLs in the 35m deep Mimram 5 OBH into the Lewis/New Pit chalk correlate well with the GWLs in the 150m deep Bramfield OBH into the Holywell chalk.

Figure B8 - Correlation between Lewis chalk GWLs and Holywell GWLs

The behaviour of boreholes penetrating to different levels of the chalk can be seen clearly in the plots for GWLs 2017-19 in the Fulling Bridge area shown in Figure B9:

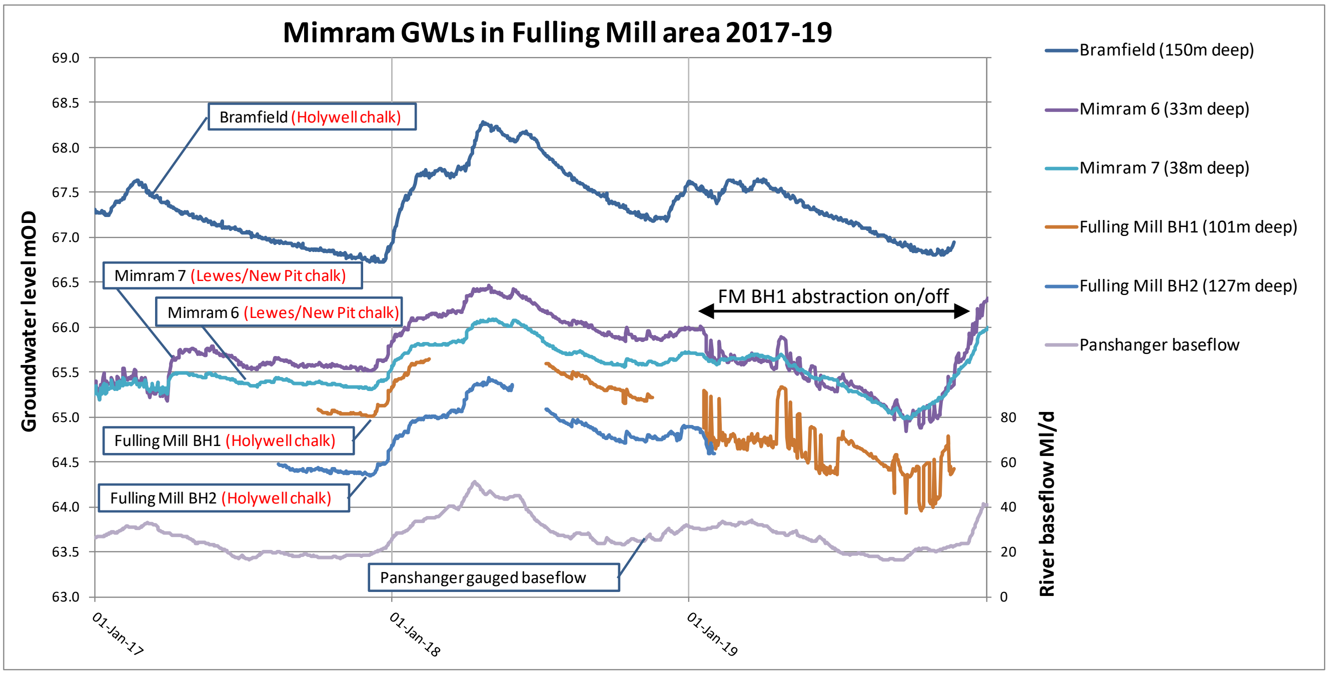


Figure B9 - GWLs in different chalk layers in Fulling Mill area 2017-19

This plot shows that GWLs deep in the Holywell chalk and nearer the surface in the Lewes/New Pit chalk behave almost identically. The GWLs in the different chalk layers rise in unison during period of the aquifer recharge from December to May 2018. The GWLs then fall in unison during the recessions, as the aquifer is drained by the river outflows and throughflow. In 2019, when abstraction from the Holywell chalk by Fulling Mill BH2 fluctuated, there were matching fluctuations in GWLs in the Lewis chalk at Mimram 7, 430m away.

The conclusion from this analysis is that the water table in the Mimram valley behaves as a single aquifer, with river flows strongly linked to GWLs. Water levels in the Lewes/New Pit chalk and Holywell chalk appear to be hydraulically linked, so abstraction will affect water levels in both layers, regardless of whether the water is pumped from the Lewes/New Pit or Holywell chalk.

B3 Validation of CSF and HRGM models for the River Mimram

CSF lumped parameter model for the River Mimram

The CSF modelling methodology described in Main Report Section 2.3 has been used in a lumped parameter model for the River Mimram. The model features are:

- Covers 102-year period 1920 to 2021, including droughts of 1921, 1934 and 1944
- Effective rain since 1920 taken from EA daily data for Lee chalk record 6600TH
- Abstraction data from latest EA records and Mimram NEP report
- Daily GWLs simulated at the Lilley Bottom observation borehole site
- River flows simulated for the Panshanger, Fulling Mil and Whitwell gauge sites
- Effective catchment area for recharge 134 km^2 (as for topographic catchment)

The model uses the strong relationships between river flows and GWLs shown in Figure B10:

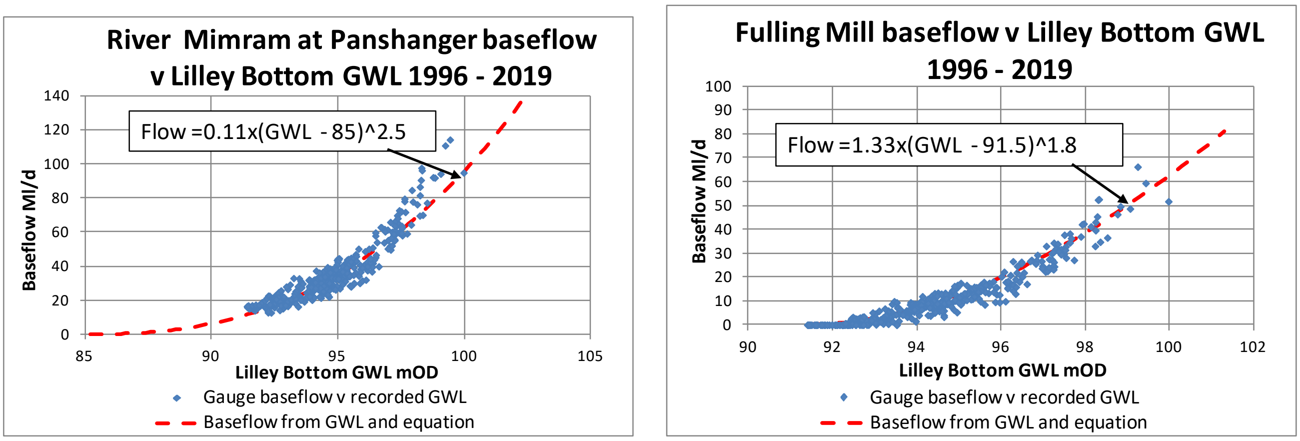


Figure B10 - Measured flows vs GWLs used in CSF Mimram model

For modelling of the recent actual abstraction scenario of 16.4 Ml/d, starting in 1920 and ending in 2020 on a date when the modelled storage is the same as the modelled starting storage, the water balance over the 100 year period is:

Inputs	Ml/d
• Average aquifer recharge	67.4
• Average leakage from supplies to aquifer	0.8
• Average STW discharge to aquifer	0.1
Total inputs	68.3
Outputs	
• Average river outflow at Panshanger	44.6
• Average underflow from catchment	7.3
• Average abstraction	16.4
Total outputs	68.3

The CSF model was calibrated to give best fits to recorded groundwater and river flow records in the period 1979 to 2021 (the Lilley Bottom GWL record started in 1979):

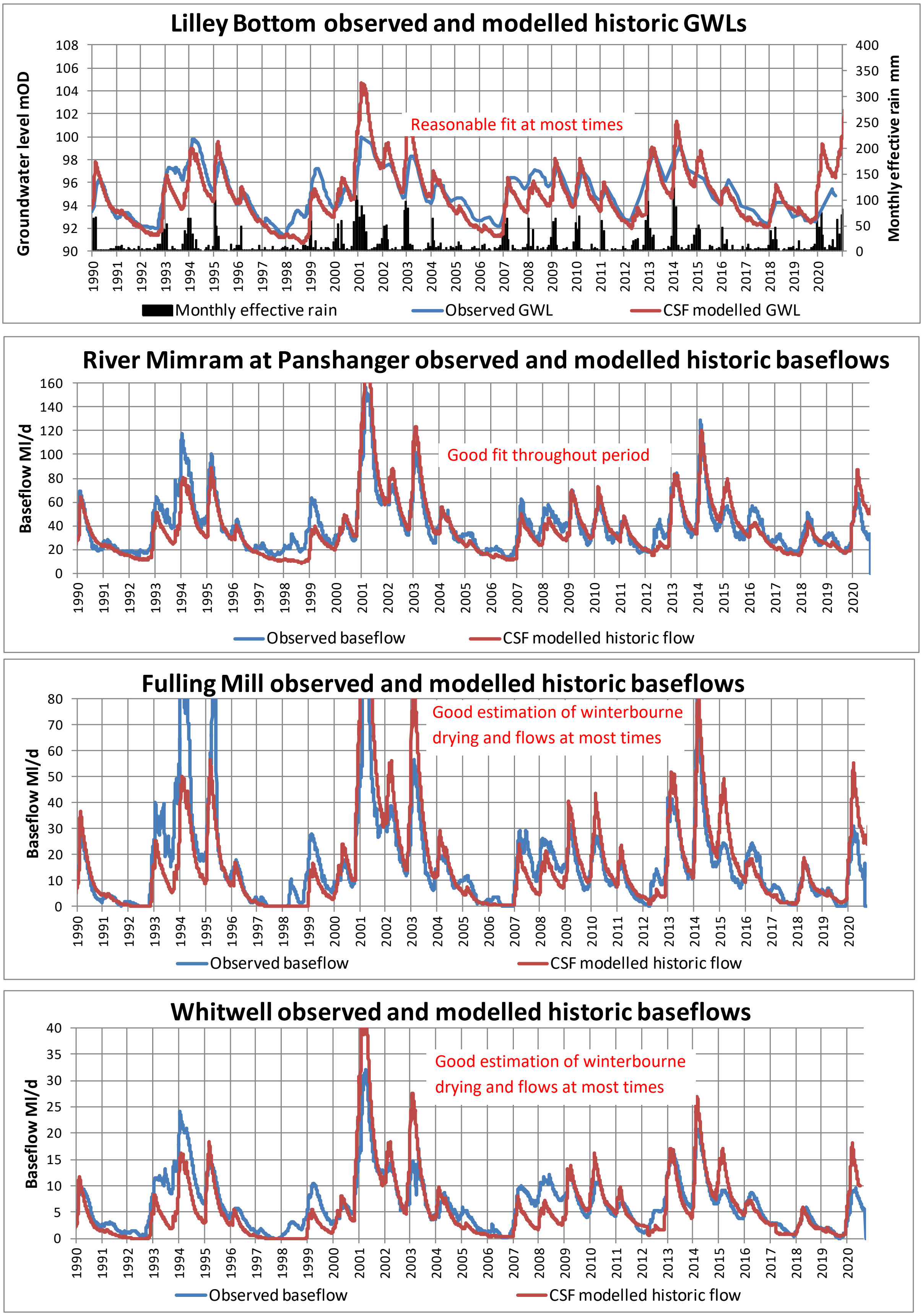


Figure B11 - Validation of CSF River Mimram modelled GWLs and flows 1992-2020

As can be seen in Figure B11, the CSF model gives a close fit between modelled and historic measured GWLs and baseflows throughout the 30-year period, 1990 to 2020, for which the model was calibrated.

More validation evidence for the CSF model can be seen by comparing modelled and historic baseflows at Panshanger between 1957 and 1990, ie before the period for which the model was calibrated:

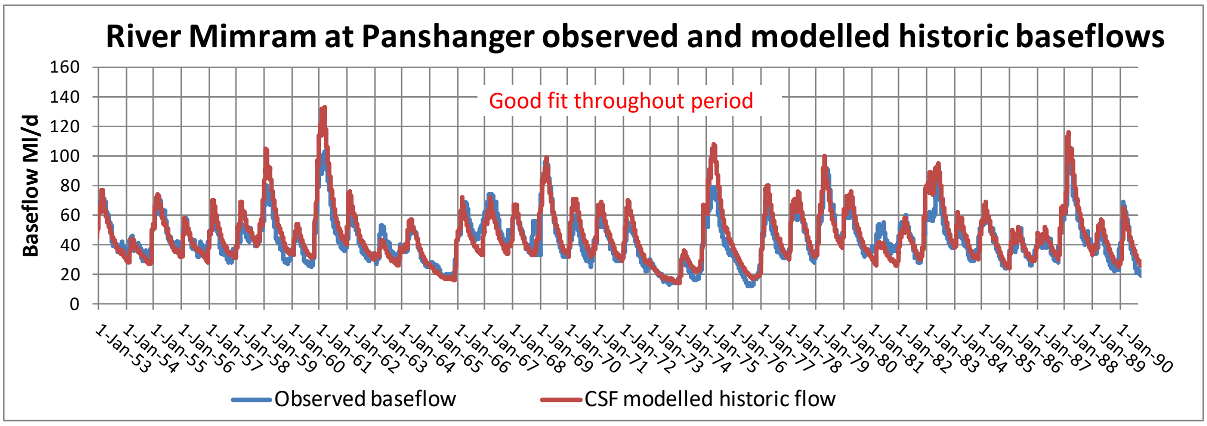


Figure B12 - CSF Mimram model validation: Panshanger flow 1956-1990

The CSF model also provides a good fit between observed and modelled flows throughout the 35 year period of available flow data for which the model was not calibrated.

Comparison of validation of the HRGM and CSF models

A comparison of validation plots for the HRGM and CSF models is shown in Figure 47 on the next page. The quality of fit between modelled and recorded flows and GWLs is similar for the two models:

- Both models provide quite a good fit to Lilley Bottom GWLs and Panshanger medium to low flows, although the HRGM model tends to over-estimate high flows and the amplitude of regional variations. This suggests that either model can be used to estimate flow recovery in the lower river from abstraction reductions and compliance with EFIs at Panshanger.

- The HRGM model significantly overestimates the frequency and duration of drying of the winterbourne reaches. The CSF model provides a reasonable match to the frequency of drying of the winterbourne, suggesting it is a better tool for assessing the impacts of abstraction on frequency and duration of drying of winterbourne sections.

In the absence of any significant and sustained abstraction changes in the Mimram which might allow measurement of flow benefits, the availability of both the HRGM and CSF models provides alternative means of assessing EFI flow compliance and effectiveness of any future abstraction reductions.

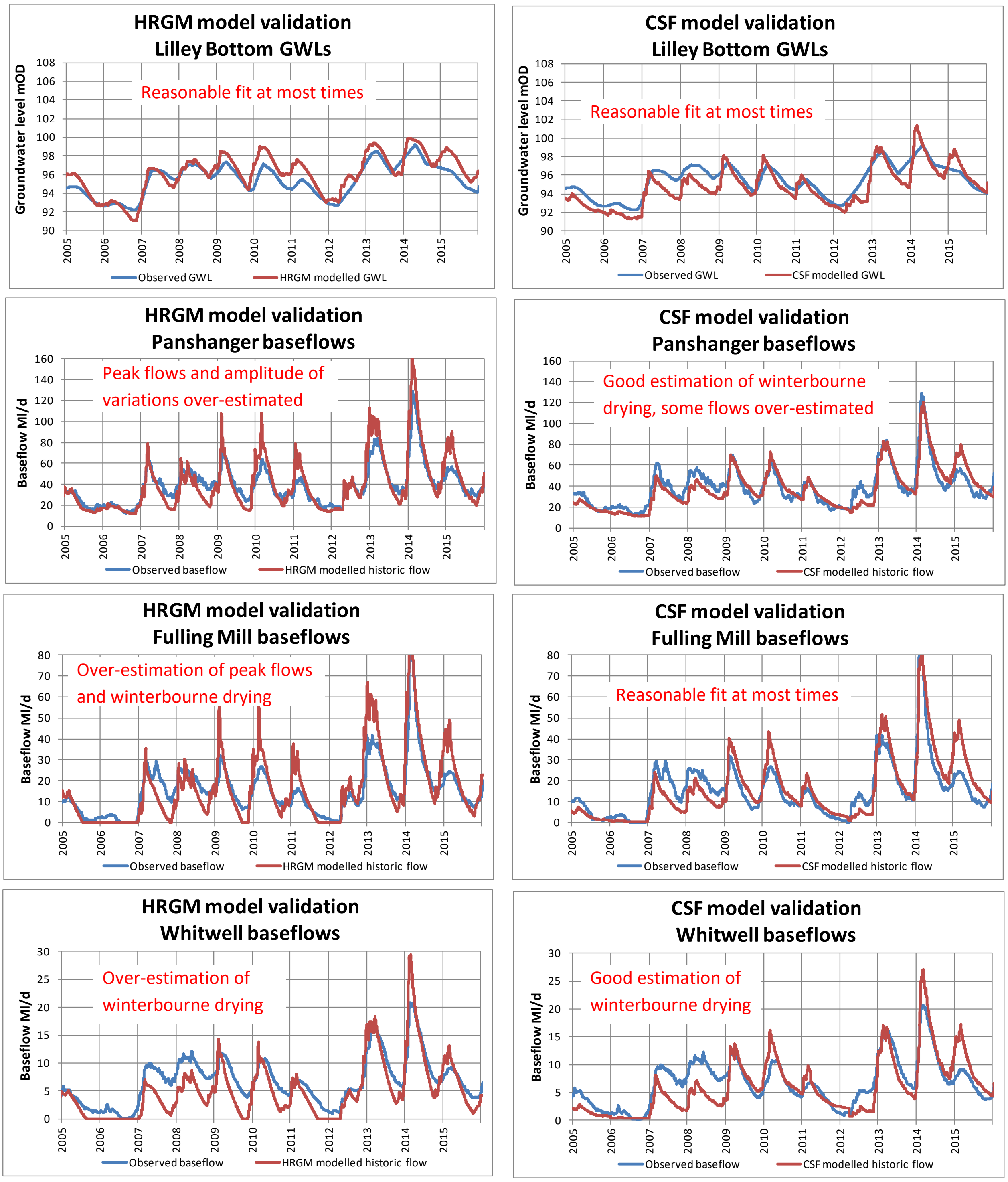


Figure B13 - Comparison of validation of HRGM and CSF models

The differences in validation of modelling of the lower Mimram flows at Panshanger can also be seen on the scatter plots in Figure B14:

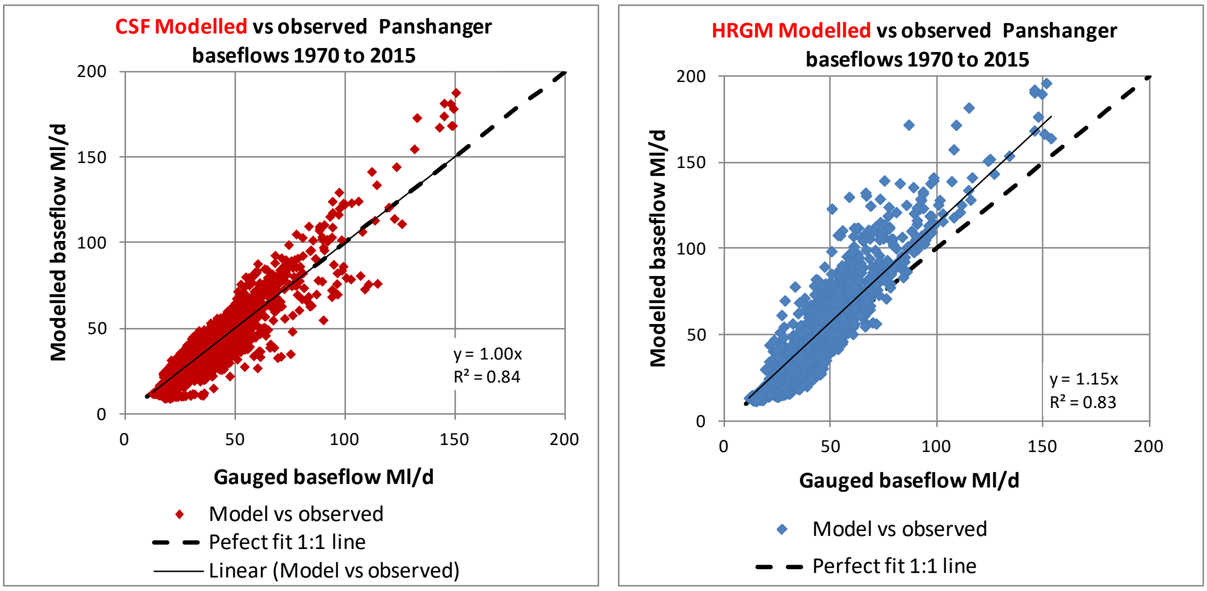


Figure B14 - Comparison of CSF and HRGM model validation for Panshanger flows

These validation plots show that the HRGM and CSF models can both provide estimates of abstraction impacts and flow recovery in the lower Mimram at Panshanger gauging station, although the HRGM model is likely to over-estimate impacts and flow recovery. The CSF model should also provide good estimates of the frequency of drying at Fulling Mill and Whitwell, but the HRGM model cannot be reliably used for this purpose at present.

B4 Modelling of recent actual abstraction impacts on the Mimram

The CSF and HRGM modelling of the effect of recent abstractions on flows at Panshanger from 1995 to 2015 are compared in Figure B15. The total recent actual groundwater abstraction is 16.4 Ml/d – 13.8 Ml/d for public water supplies and 2.6 Ml/d non-consumptive for fish farms and gravel workings. These are the figures supplied by the EA in file *'HERTS Artificial Influences Overview_Red.xlsx'* and used in the HRGM model – it is assumed to be the average for 2013-15.

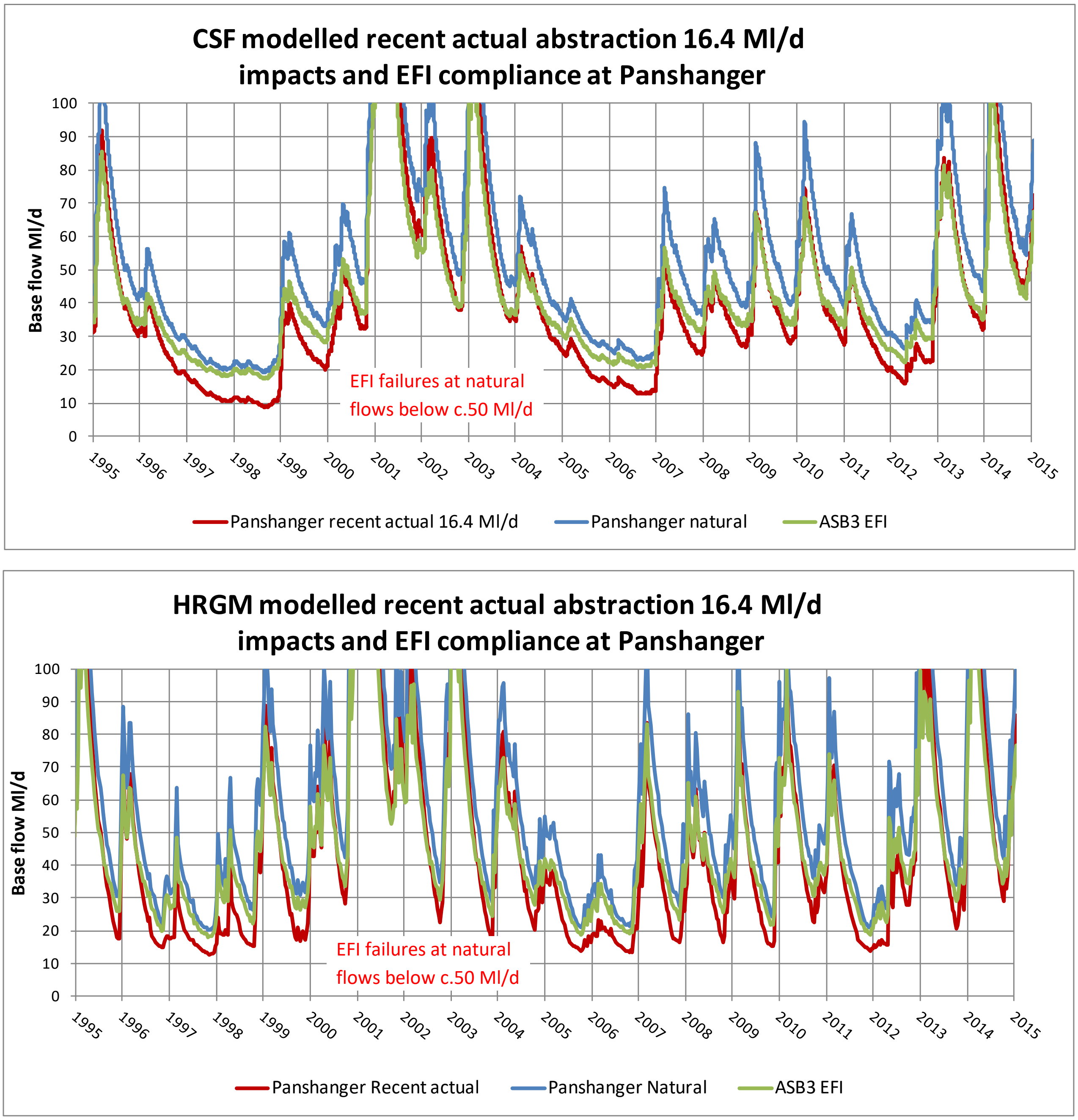
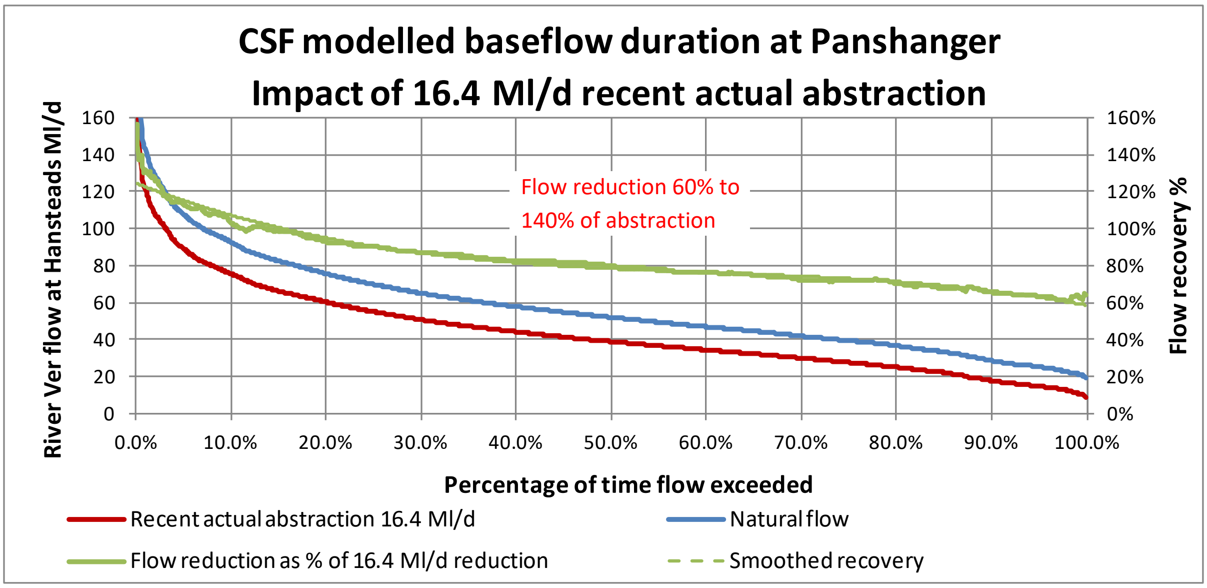


Figure B15 - CSG and HRGM modelling of recent 16.4 Ml/d abstraction at Panshanger

Both models show that, with abstraction of 16.4 Ml/d there is substantial non-compliance with the ASB3 EFI at all natural lows below about 50 Ml/d (natural Q50).

The impact of recent actual abstraction of 16.4 Ml/d on flow durations at Panshanger is shown on Figure B16, which also shows the flow reduction from natural as a percentage of the 16.4 Ml/d abstraction:



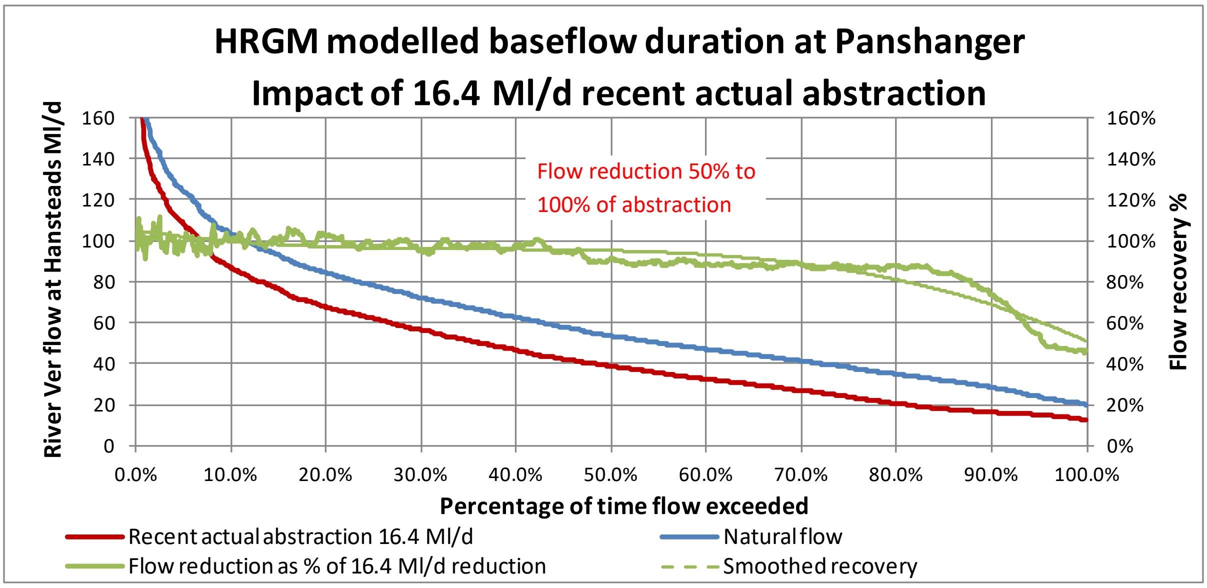


Figure B16 - Modelled flow duration impacts of 16.4 Ml/d recent abstraction at Panshanger

Both models show a similar picture, with the flow reduction about 50% of abstraction at low flows rising to over 100% at high flows. However, the HRGM modelling shows the impact exceeding 80% of the abstraction at most times, but falling quickly to 50% at flows below Q80. The CSF model shows a steadier reduction in the impact as flows fall.

B5 Required abstraction reduction in the Mimram catchment

The two methodologies available for determining acceptable abstraction – using either EFIs or A%R – give broadly similar results for required abstraction reduction in the Mimram catchment.

The EFI methodology gives a recent actual EFI low flow deficit of 12.9 Ml/d at Q95, assuming that the Mimram is in the high sensitivity band ASB3. The EFI methodology gives an allowed total Mimram abstraction of 5.2 Ml/d, determined as in Table B1:

Calculated Natural Low Flow (Q95)	**Estimated % allowable abstraction (ASB%)**	**Estimated sustainable low flow (EFI)**	**Recent Actual Q95 Flow**	**Flow Deficit to EFI at low flow (Q95)**	Abstraction Sensitvity Band	Sustainable abstraction quantity at low flows	Cumulative Discharges	**Available to Abstract (Nat +Dis - EFI)**	Groundwater Abstraction impact on Flow
46.8	10%	42.1	29.2	12.9	ASB3	4.7	0.5	**5.2 Ml/d**	18
HRGM shows 53.6 Ml/d	10% for ASB3	46.8 x 90%	From EA model	42.1 - 12.9		Natural Q95 - EFI	Small STWs	4.7 + 0.5	100% of abstraction?

Notes: 1. Copied from EA worksheet ‘Chilterns flow deficits 2020.xlxs’ provided by EA email dated 9.12.2020

2. John Lawson comments in bottom row

Table B1 - EA allowable abstraction calculation for the lower River Mimram

There are some questionable aspects to the calculation shown in Table B1:

- The natural and recent actual Q95 flows in Table Bf1 don’t match the available HRGM model output (see comments in bottom row)
- The recent actual abstraction impact of 18 Ml/d at Q95 is more than the recent actual abstraction of 16.4 Ml/d provided in EA file *‘HERTS Artificial Influences Overview_Red.xlsx’*.

Nevertheless, CSF modelling of a total 5.2 Ml/d abstraction shows that flows at Panshanger would just comply with the ASB3 EFI (as shown later in Figure B17).

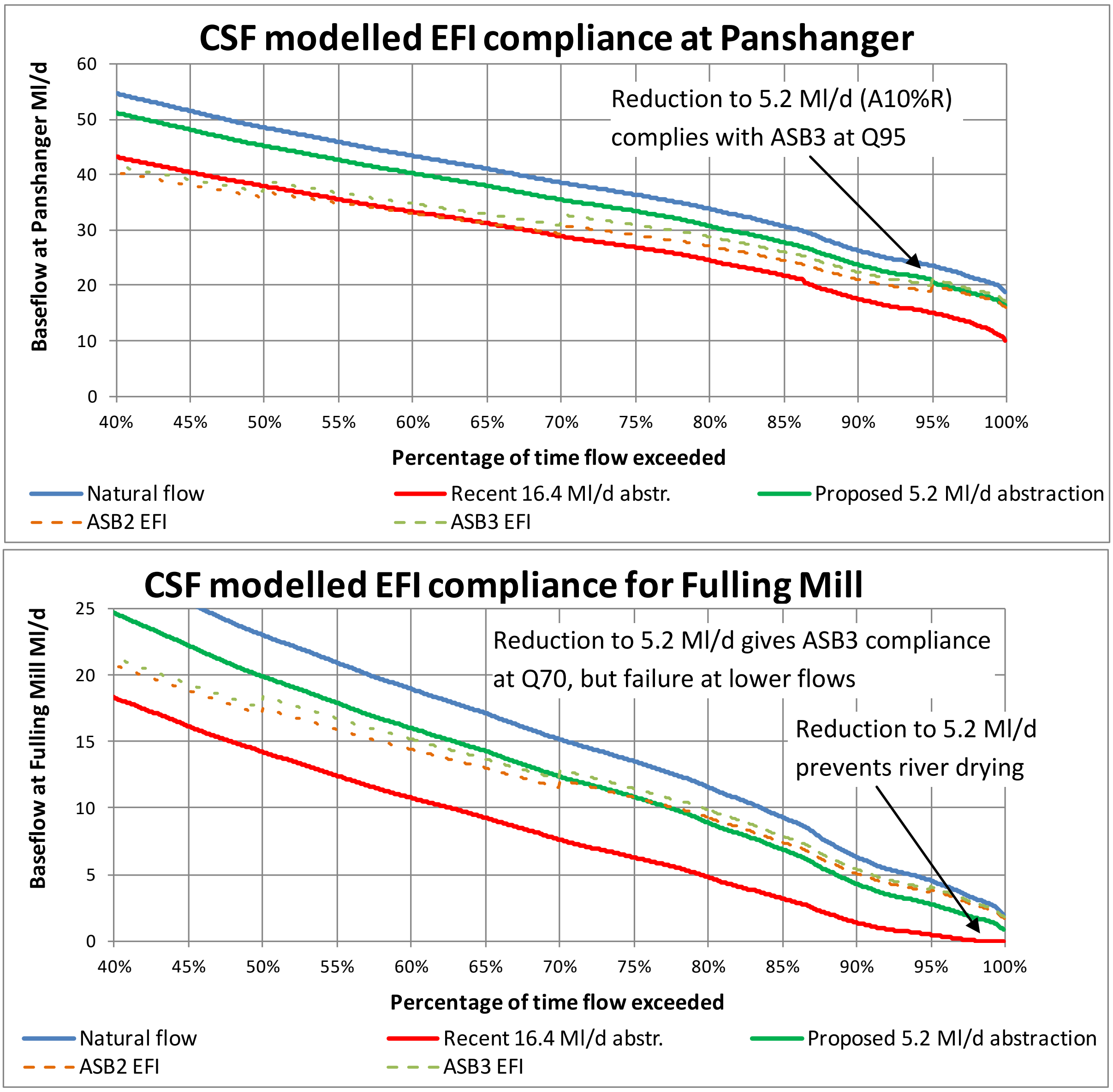
Using the A%R methodology, the CSF modelling shows that the A10%R abstraction of 7.6 Ml/d (average recharge 75.6 Ml/d) complies with ASB2, but not quite ASB3. Therefore, it is suggested that total abstraction from the Mimram should be limited to 5.6 Ml/d, a reduction of 10.8 Ml/d from the modelled 16.4 Ml/d recent actual abstraction.

However, the latest abstraction data from EA shows the average groundwater abstraction in 2019 to 2021 was only 11.27 Ml/d (11.02 Ml/d for public water supplies and 0.25 Ml/d non-consumptive groundwater). Therefore, to achieve a total 5.2 Ml/d abstraction, the required reduction from 2019-21 level of abstraction is only 6.1 Ml/d.

B6 Modelled benefits of Mimram abstraction reduction to 5.2 Ml/d

Compliance with Environmental Flow Indicators

The CSF model has been used to assess the flow benefits from reducing abstraction to 5.2 Ml/d (A10%R). The modelled flow duration compliance with EFIs at Panshanger and Fulling Mill is shown on Figure B17:



Note: Flow durations are calculated for the full 100 years of modelled flows 1920 to 2019

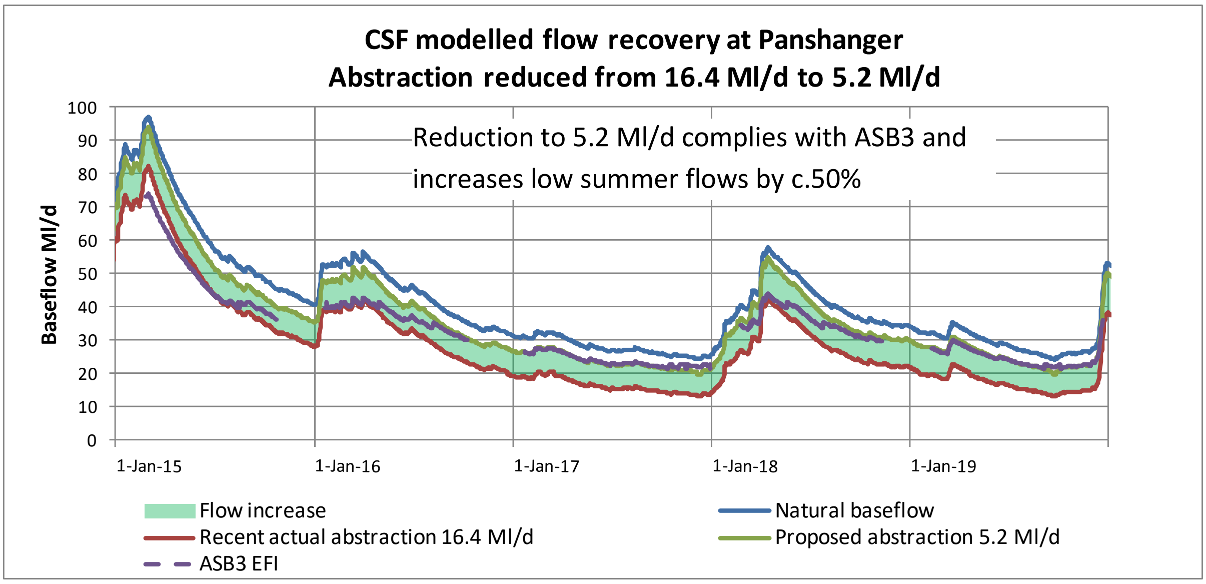
Figure B17 - CSF modelled flow compliance with abstraction cut to 5.2 Ml/d (A7%R)

As can be seen on Figure B17, reduction of total Mimram abstraction to 5.2 Ml/d (equivalent to A7%R) gives Panshanger flow compliance with the ASB3 EFI target. Reduction of abstraction to A10%R (7.5 Ml/d) does not quite meet the ASB3 EFI target at Q95. Summer flows at Panshanger would be increased by about 30-60% compared with flows that have occurred with the recent abstraction of about 16 Ml/d.

Reduction of total abstraction to 5.2 Ml/d would prevent the river from drying at Fulling Mill as it did in 2011, 2017 and 2019. Summer flows would be greatly increased, but would still fail the ASB3 EFI at flows below about Q70. Achievement of the ASB3 EFI at Q95 would require the abstraction to be reduced to just 1 Ml/d.

Improvement of flows in typical years

With total abstraction reduced to 5.2 Ml/d, the CSF modelled increases in flows at Panshanger and Fulling Mill for the 5-year period 2015 to 2019, including the 2019 drought, are shown in Figure B18:



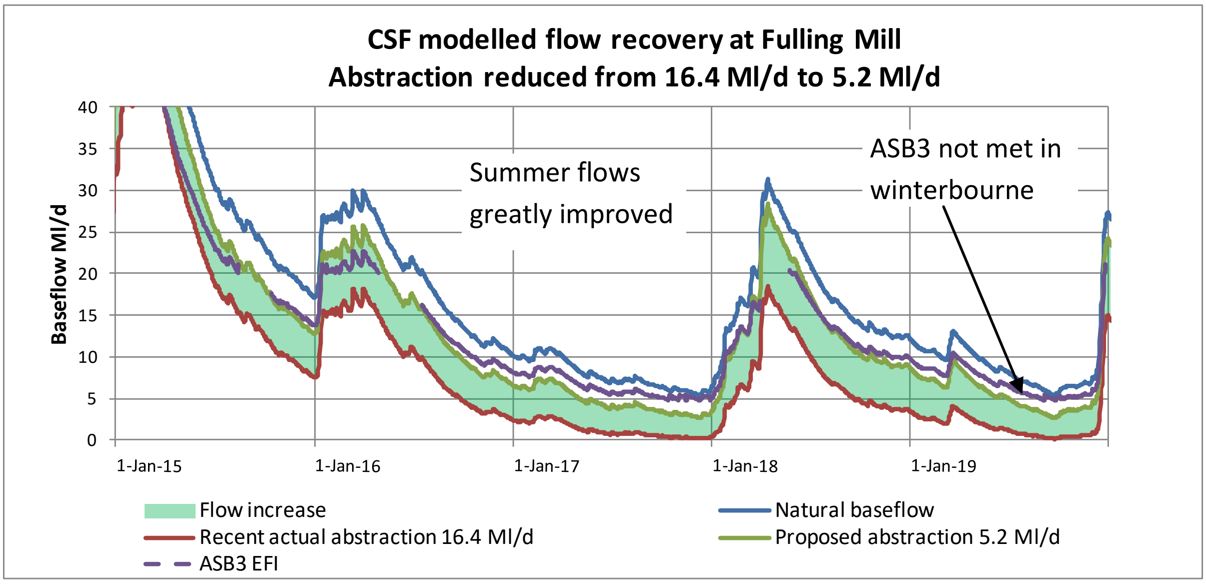


Figure B18 - CSF modelled Mimram flow recovery at 5.2 Ml/d abstraction, 2015-2019

The plots shown in Figure B18 cover two 'average' years, 2015 and 2016, and the drought of 2018-19. It can be seen that reduction of abstraction to 5.2 Ml/d (gives a big improvement in flows, recovering to close to natural flows at both Panshanger and Fulling Mill. ASB3 EFI flows at Panshanger would be achieved at all times, including the drought of 2019.

It is suggested that this degree of compliance with ASB3 EFIs at Fulling Mill is acceptable, taking account of the great improvement in summer flows shown in the lower plot in Figure B18. Total compliance with the ASB3 at Fulling Mill would require the total abstraction to be reduced to just 1 Ml/d, but would give only a marginal overall improvement to summer flows. This shows the impracticality of the Q95-EFI as a tool for assessing flow acceptability in the winterbourne reaches of chalk streams.

B7 Benefit of Mimram flow recovery for London's supplies

The GARD model of the London supply system has been linked to the CSF Mimram model to assess the deployable output (DO) gain for London's supplies if Mimram abstraction is reduced from 16.4 Ml/d to 5.2 Ml/d – a reduction of 11.2 Ml/d. Modelled flow recovery at Panshanger in 1921/22, the most severe drought of the last century for London's supplies, is shown in Figure B19:

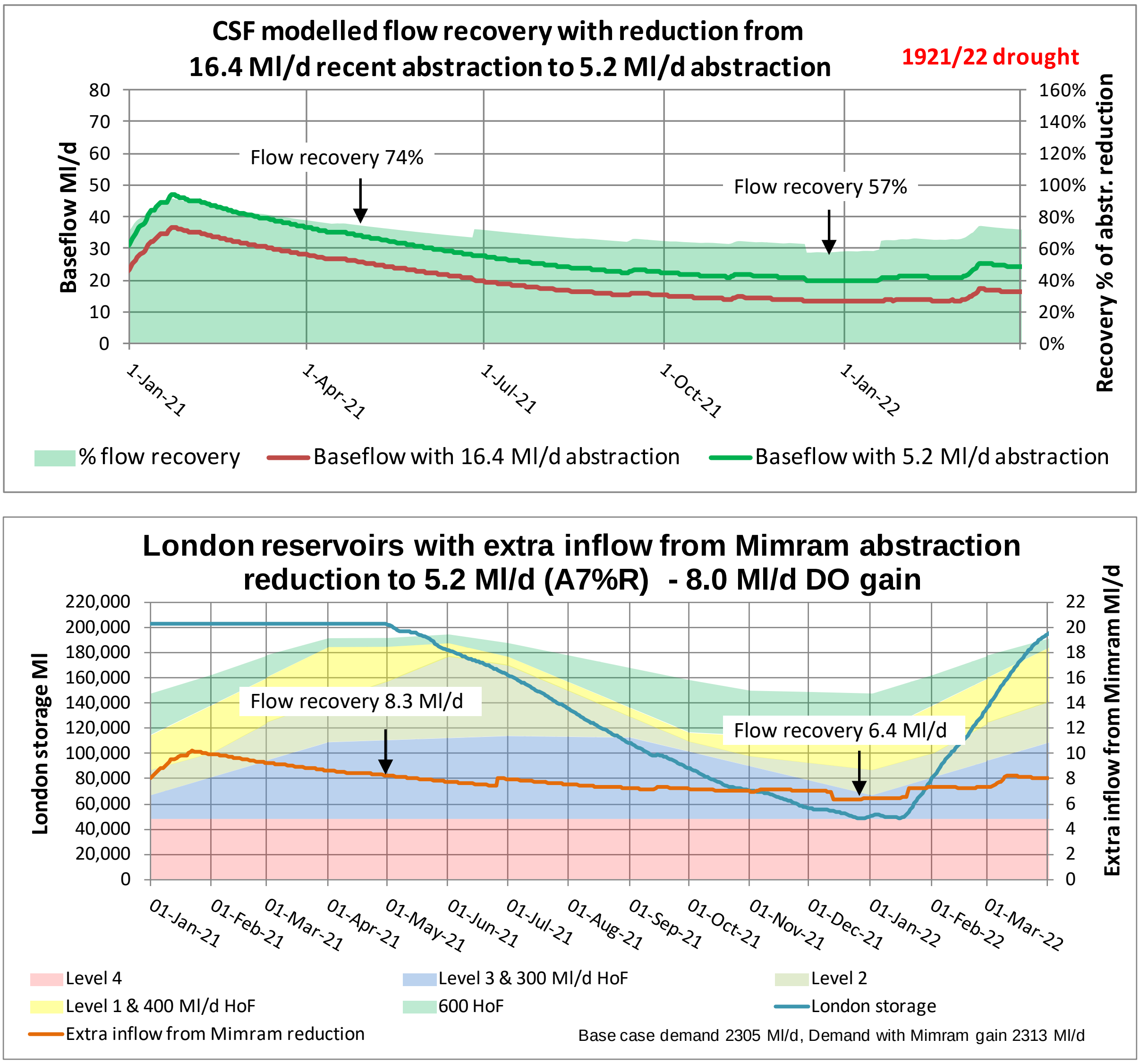


Figure B19 - Modelled river flow gain and DO gain for London in drought of 1921/22

The modelling shows a London deployable output gain of 8.1 Ml/d from the 11.2 Ml/d abstraction reduction – a recovery of 72%, substantially more than the modelled recovery for a River Ver abstraction reduction, as described in Section 3.9. The reason for the higher recovery than for the Ver is that the modelled underflow needed in the Mimram catchment to achieve a balance of modelled catchment inputs and outputs is substantially less than the modelled Ver underflow. More details of modelling are given in Appendix A. In other words, for the Mimram, a higher proportion of the reduced abstraction goes into increased river flow instead of increased underflow.

For London's supplies, the drought of 1933/34 is marginally less severe than the 1921 drought, but is of a longer duration. The modelled flow recovery and benefit to London's supplies is shown in Figure B20:

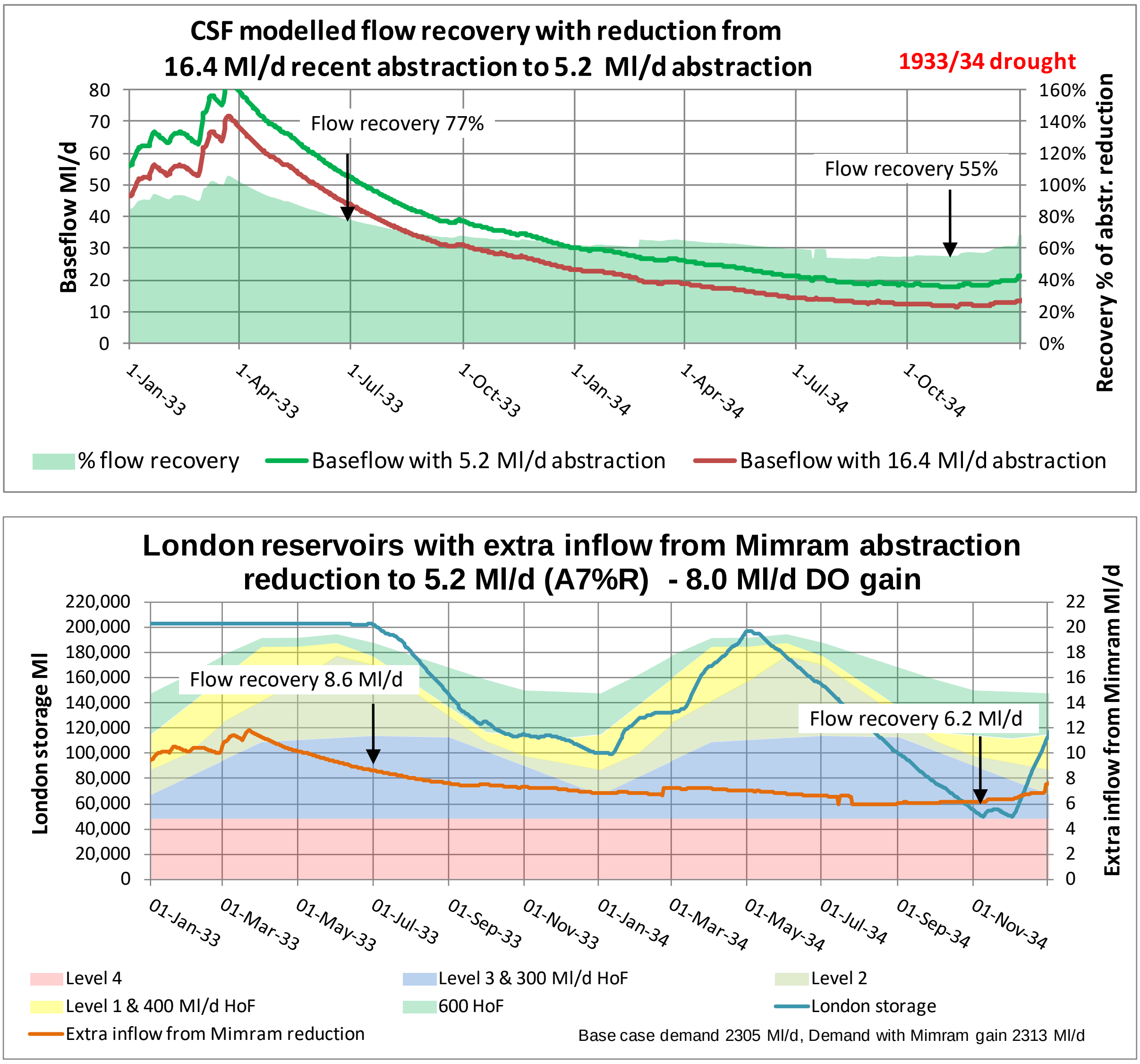


Figure B20 - Modelled river flow gain and DO gain for London in drought of 1933/34

The deployable output gain of 8.1 Ml/d, 72% recovery of the 11.2 Ml/d abstraction reduction, is less than the 80%-90% recovery assumed in the Chalk Streams First proposal for improvement to the Lea and Colne chalk streams (based on other water company groundwater modelling[31]), but still would allow major chalk stream flow improvement with relatively little loss of regional supply.

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[31] Chalk Streams First, page 16 https://chalkstreams.org/chalk-streams-first/

B8 Comments on Affinity Water's Mimram NEP report

Affinity Water's conclusion on effectiveness of the Fulling Mill reduction

Affinity Water's report on the River Mimram in August 2020[32] was prepared as a WINEP investigation primarily to address failure of the River Mimram to achieve Water Framework Directive 'Good Ecological Status', with flows categorised a 'does not support good'. The report focused on the effectiveness of the nominal 9.09 Ml/d sustainability reduction at Fulling Mill – a 3.49 Ml/d licence reduction in April 2015 and an additional 5.6 Ml/d in April 2017. The report summary on page 14 describes the effect of the Fulling Mill reduction as follows:

> *"Analysis suggests that flows in the lower catchment (Panshanger gauging station) have not increased as a result of the sustainability reduction. This suggests that recharge (or lack thereof) is the primary driver of river flow in the Mimram and that the potential for the river to gain baseflow from this abstraction reduction under low flows may be limited."*

There are further comments about lack of flow improvements from sustainability reductions in the report's conclusions on page 194:

> ***"Are there agreed actions that are taken to mitigate low flows/velocity?***
>
> *Yes, there are several agreed actions aimed at mitigating low flows in the Mimram catchment and these are listed below:*
>
> - *2015-2018 – Stepped 9.09 Ml/d Fulling Mill sustainability reductions.*
> - *2016-date – Inclusion of Fulling Mill and Digswell sources in the Abstraction Incentive Mechanism (AIM) metric.*
> - *September 2018 – Abstraction reduction at Digswell under low groundwater levels through signing of Section 20 agreement.*
>
> *Despite all that has been implemented to date, the Mimram still experiences low flows during droughts."*

Biological monitoring has been carried out before and after the abstraction reductions and associated river restoration schemes, but the NEP report summary concludes *"there has not been enough time since their completion to determine the response to the schemes."*

Actual amounts of abstraction reductions since 2015

The NEP report describes the complexity of the phased Fulling Mill reduction and its link to Digswell abstractions, as shown in Figure B21:

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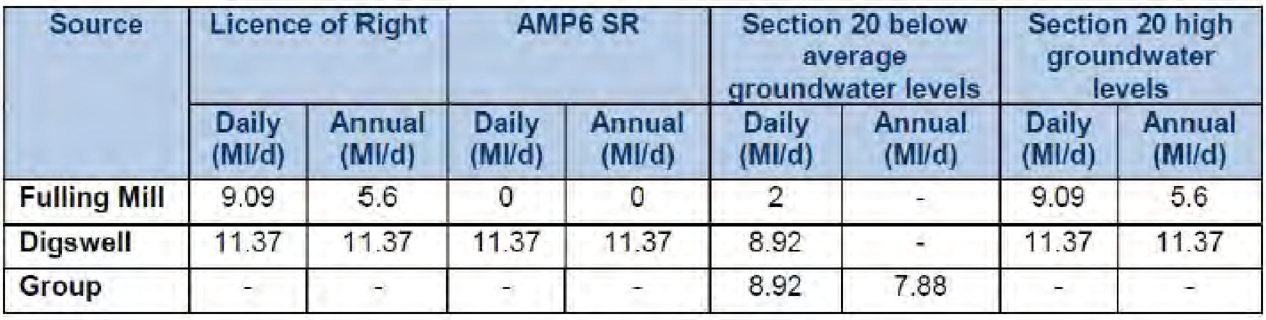
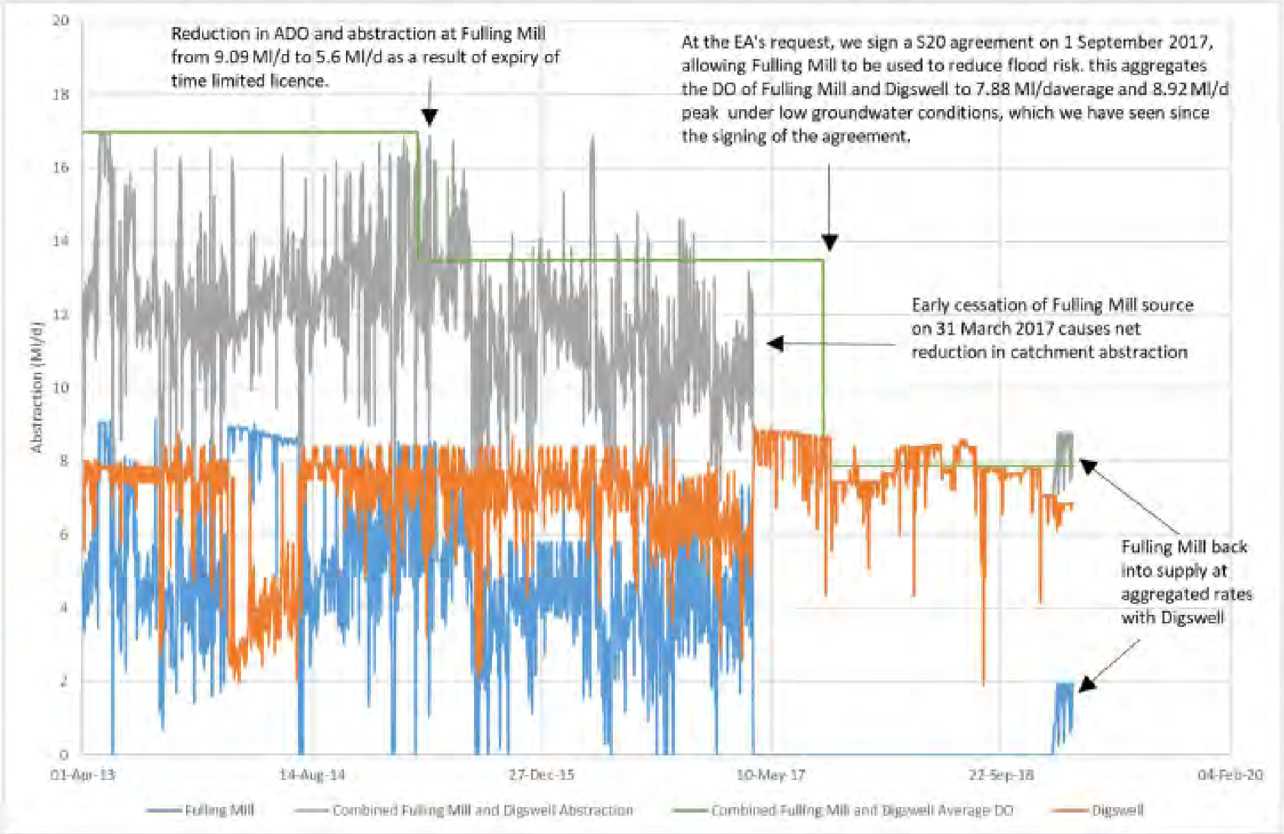
[32] River Mimram AMP6 NEP Report Technical Report 1.3 – Sustainability Reductions and River Restoration. Affinity Water March 2020. Official Sensitive.



Source	Licence of Right		AMP6 SR		Section 20 below average groundwater levels		Section 20 high groundwater levels	
	Daily (Ml/d)	Annual (Ml/d)	Daily (Ml/d)	Annual (Ml/d)	Daily (Ml/d)	Annual (Ml/d)	Daily (Ml/d)	Annual (Ml/d)
Fulling Mill	9.09	5.6	0	0	2	-	9.09	5.6
Digswell	11.37	11.37	11.37	11.37	8.92	-	11.37	11.37
Group	-	-	-	-	8.92	7.88	-	-



Reduction in ADO and abstraction at Fulling Mill from 9.09 Ml/d to 5.6 Ml/d as a result of expiry of time limited licence.

At the EA's request, we sign a S20 agreement on 1 September 2017, allowing Fulling Mill to be used to reduce flood risk. this aggregates the DO of Fulling Mill and Digswell to 7.88 Ml/daverage and 8.92 Ml/d peak under low groundwater conditions, which we have seen since the signing of the agreement.

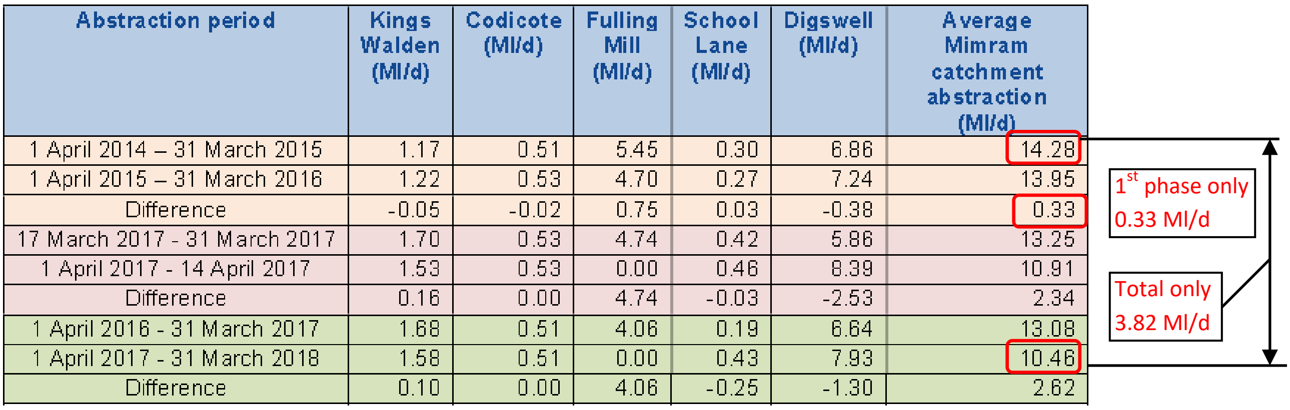
Early cessation of Fulling Mill source on 31 March 2017 causes net reduction in catchment abstraction

Fulling Mill back into supply at aggregated rates with Digswell

Copied from Affinity Water Mimram NEP report Figure 69

Figure B21 - Sustainability reduction implementation in the Mimram catchment

Although the nominal magnitude of the sustainability reduction was a deployable output loss of 9.09 Ml/d, the NEP report recognises that the actual reduction in abstraction since 2015 has been much less, as shown in Table B2, showing changes in their public water supply abstractions, but not changes in private groundwater abstractions over the same period:



Abstraction period	Kings Walden (Ml/d)	Codicote (Ml/d)	Fulling Mill (Ml/d)	School Lane (Ml/d)	Digswell (Ml/d)	Average Mimram catchment abstraction (Ml/d)
1 April 2014 – 31 March 2015	1.17	0.51	5.45	0.30	6.86	14.28
1 April 2015 – 31 March 2016	1.22	0.53	4.70	0.27	7.24	13.95
Difference	-0.05	-0.02	0.75	0.03	-0.38	0.33
17 March 2017 - 31 March 2017	1.70	0.53	4.74	0.42	5.86	13.25
1 April 2017 - 14 April 2017	1.53	0.53	0.00	0.46	8.39	10.91
Difference	0.16	0.00	4.74	-0.03	-2.53	2.34
1 April 2016 - 31 March 2017	1.68	0.51	4.06	0.19	6.64	13.08
1 April 2017 - 31 March 2018	1.58	0.51	0.00	0.43	7.93	10.46
Difference	0.10	0.00	4.06	-0.25	-1.30	2.62

1st phase only
0.33 Ml/d

Total only
3.82 Ml/d

Table copied from NEP report Table 17, with annotations in red

Table B2 - NEP reported Affinity Water abstraction reduction, 2014 to 2018

The Environment Agency's monthly abstraction data up to 2021 show more detail of the abstraction changes since 2014, including changes in private water non-consumptive groundwater abstractions, as shown in Figure B22:

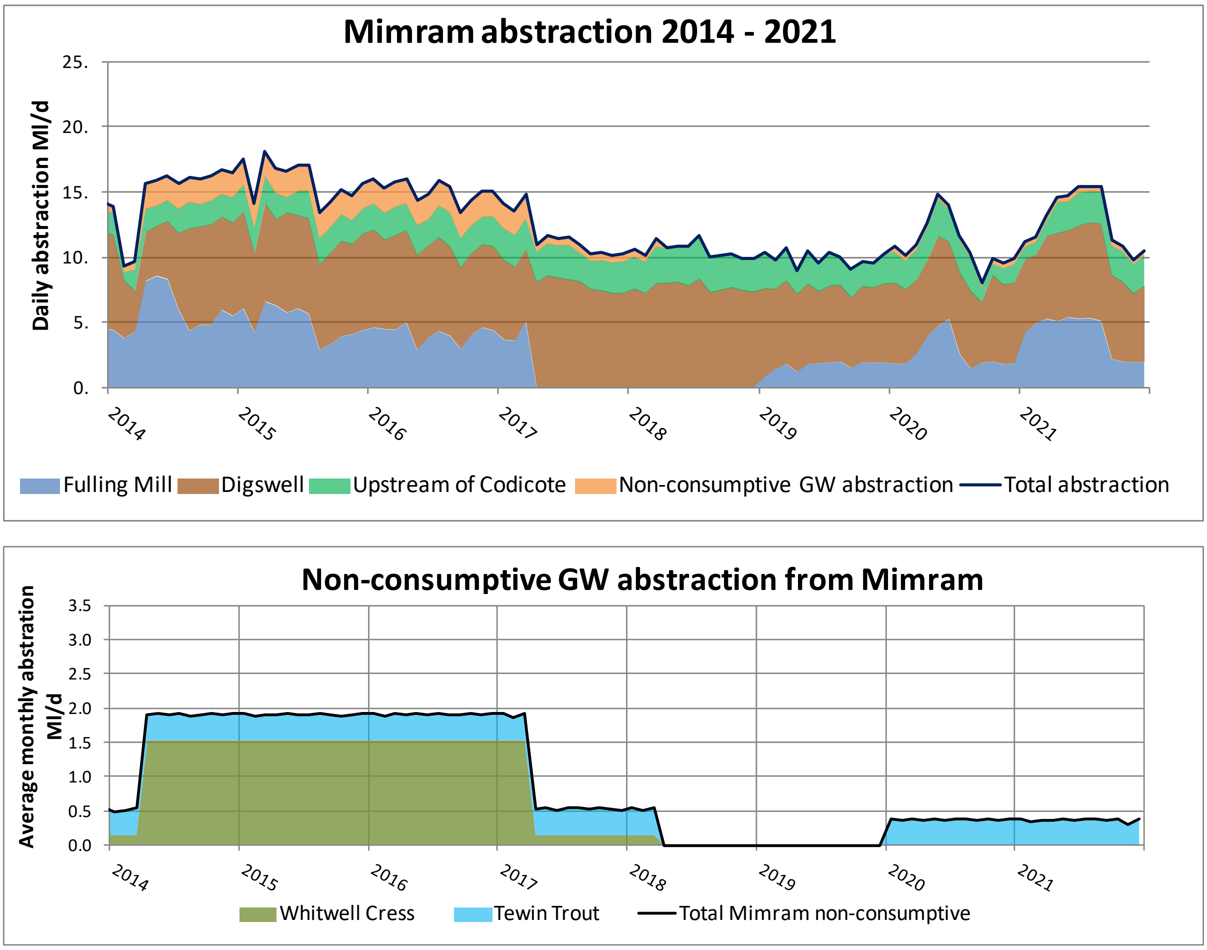


Figure B22 - EA record of groundwater abstraction changes 2014 to 2021

The water cress and fish farm are non-consumptive, so are returned to the river to augment flows at Panshanger gauging station. This augmentation was reduced by about 1.5 Ml/d in April 2017, off-setting flow gains from Affinity Water's 3.8 Ml/d abstraction reduction, especially in the first few months after April 2017, before the GWLs have had time to rise and generate more river flow. The effectiveness of the Fulling Mill sustainability reduction was further reduced by resumption of Fulling Mill abstraction to about 2 Ml/d in 2019, rising to about 5 Ml/d for several months in both 2020 and 2021. The combined effect of reduced augmentation from the water cress and trout farms with resumption of some abstraction at Fulling Mill would have greatly reduced the effectiveness of the nominal 9.09 Ml/d sustainability reduction. It would have been unrealistic to expect any measurable flow increase at the Panshanger gauging station.

NEP report modelling of the Fulling Mill sustainability reduction

The HRGM model covering post-2015 was not available for the NEP report to simulate the actual Fulling Mill reduction, so the NEP used the previous Vale of St Alban's (VSA) model to simulate a stepped reduction of Fulling mill abstraction from about 7.8 Ml/d to zero. The stepped reduction was assumed to start in June 1985, when recorded GWLs were similar to GWLs in April 2015. The modelling showed that GWLs would rise by about 1m over a 5 year period and flows at Panshanger would increase as shown in Figure B23:

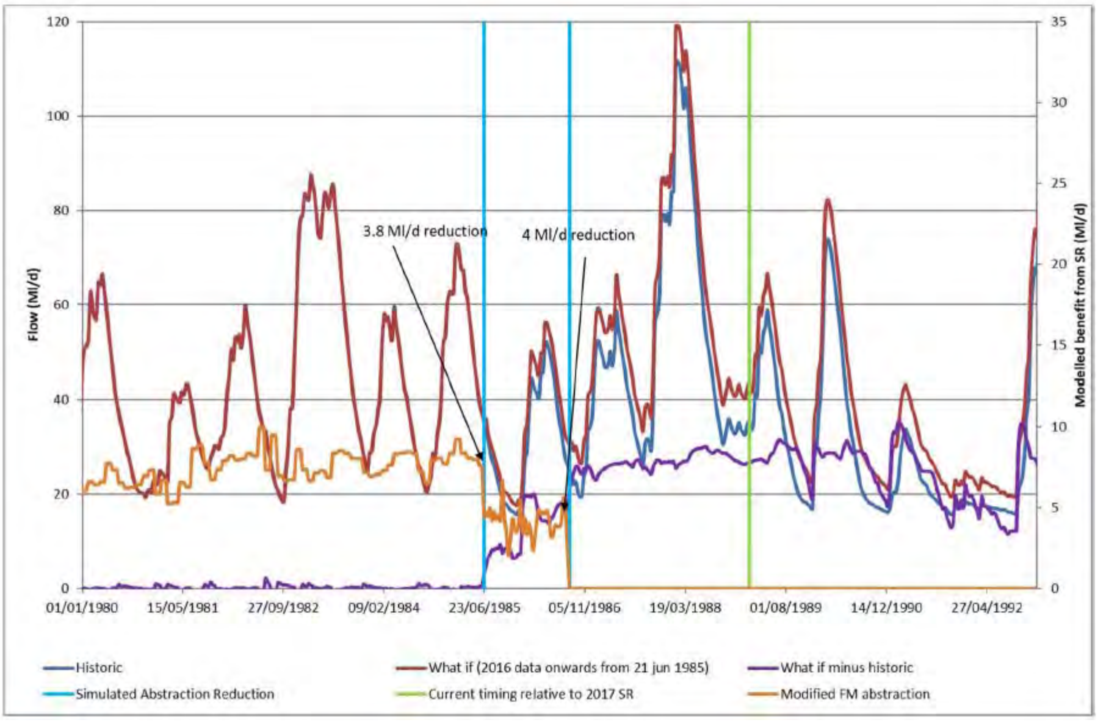


Figure B23 - NEP report modelled Panshanger flows with 7.8 Ml/d Fulling Mill reduction

The modelling showed that the total 7.8 Ml/d reduction would lead to a flow increase building after about 2 years to about 7 Ml/d at Panshanger at most times, but falling to about 3 Ml/d in droughts. The NEP report comments on page 96: *"the river flow responses conceptualised by the VSA model have not been observed to date."* This comment does not appear to recognise that the actual Fulling Mill reduction was only 3.8 Ml/d, it was not maintained and its effectiveness was offset by the concurrent 1.5 to 2 Ml/d reduction of flow augmentation from the water cress and trout farms.

CSF modelling of the actual abstraction changes since 2015

The CSF model has been used to simulate the reduced Panshanger flows that would have occurred if the 2015 abstraction levels had been maintained until 2021. The total abstraction in 2015 is assumed to have been 15 Ml/d – 13.1 Ml/d for Affinity Water's abstractions and 1.9 Ml/d of non-consumptive abstraction for water cress and trout farms. The CSF model allows for the non-consumptive abstraction impact on aquifer storage and GWLs, but with all the abstracted water also contributing to flow at Panshanger. The modelled flow changes are shown in Figure B24:

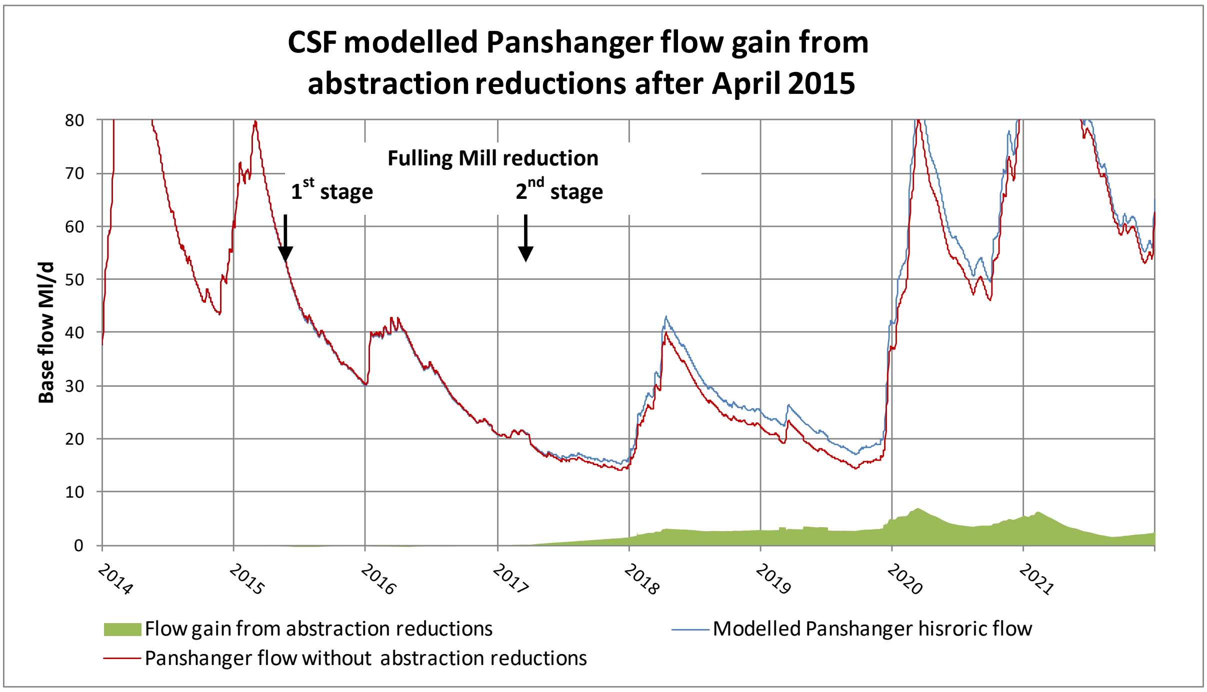
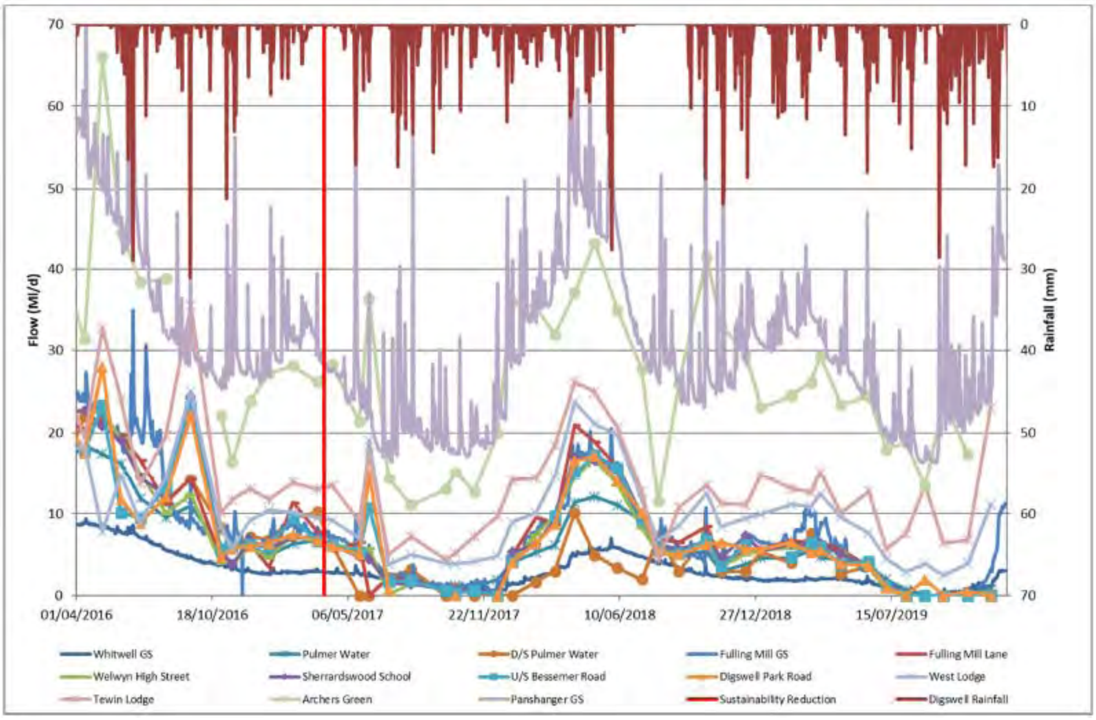


Figure B24 - CSF modelled flow gain from the abstraction reductions post-April 2015

The modelling shows that the flow gain at Panshanger would have been negligible up to mid-2017. The NEP report only considered data up to the end of 2019, by which time the Panshanger flow gain would have been only about 2 Ml/d and, realistically, would not have been detectable by any of the comparative spot flow measurements attempted in the NEP report, such as the examples shown in Figure B25 on the next page. In particular, the average annual accretion profiles in the lower plot on Figure B25 show that the 10 Ml/d flow variations between average and dry years dwarf the flow differences from the relatively small abstraction reductions.

a) Comparative spot flow hydrographs:



Copied from NEP report Figure 85

b) Comparative spot flow accretion profiles:

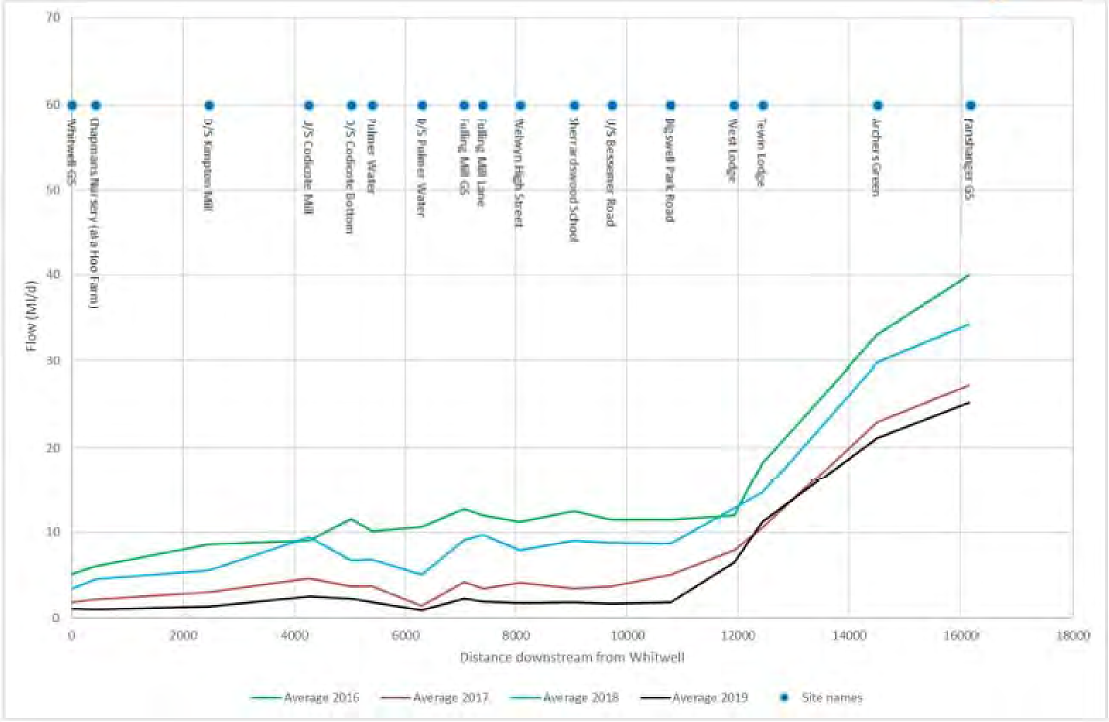


Figure B25 - NEP report spot flow comparisons

Copied from NEP report Figure 87

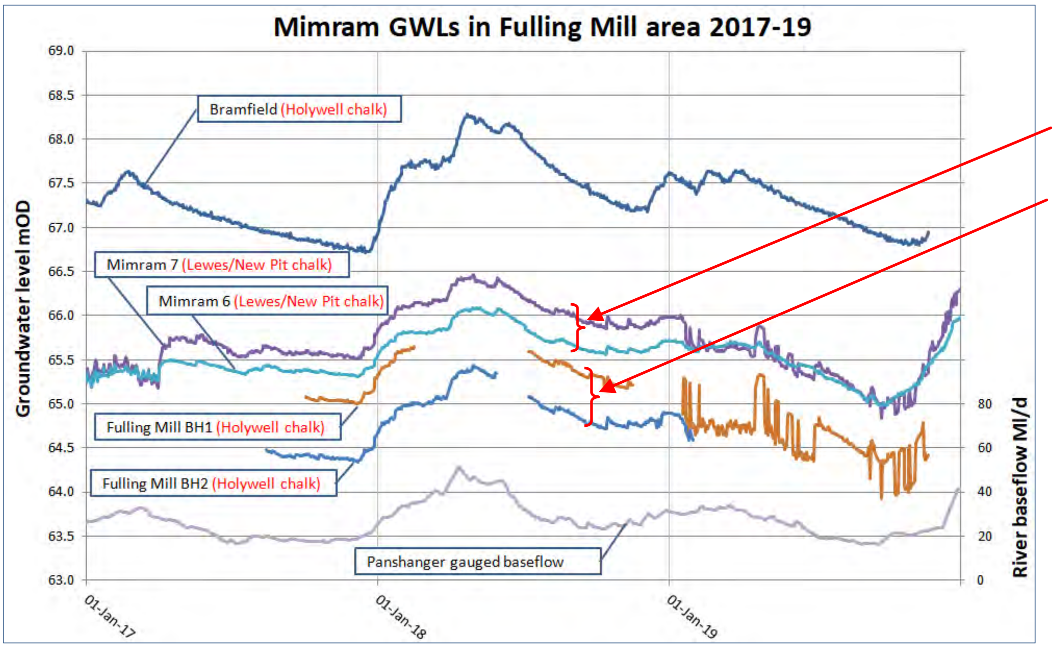
Both these plots show that the natural flow variations between years would have been far greater than would have been caused by abstraction reduction of less than 4 Ml/d and the 2-3 Ml/d flow differences that the CSF modelling predicts. The actual Fulling Mill sustainability reduction was much too small to be detectable by these analyses.

NEP evidence for separate aquifers and 'dual piezometry'

Section 5.2, page 83 of the NEP report argues the case for the existence of separate aquifers and multi-layered piezometry in the Mimram chalk:

> *"Both Mimram 6 and Mimram 7 (33 m and 38 m deep respectively), show a clear pumping signal from the operation of Fulling Mill. Mimram 6 is closer to Fulling Mill borehole 1 (which was utilised more than borehole 2) and therefore shows a greater fluctuation of water levels. Drawdown and recovery at Mimram 6 in AMP6 has been lower than previously observed due to the lower abstraction. In absolute terms, during both pumping and rest conditions, the groundwater level in the Upper Lewes and New Pit Chalk (above the Glynde Marl) (Mimram 6 and Mimram 7) is consistently above the groundwater level in the Fulling Mill abstraction boreholes.*
>
> *This suggests that the monitoring boreholes may be representative of different aquifer units. The occurrence of artesian boreholes at Whitwell is further evidence to the existence of multi-layered piezometry in the River Mimram catchment."*

The GWLs and borehole locations referred to above are shown below:

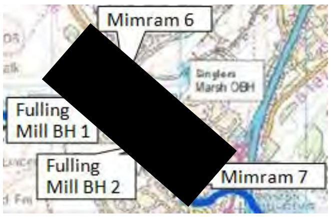


NEP report argues that:

these levels are higher than

these levels,

so might be separate aquifers.



[redacted]

Figure B26 - NEP report evidence of multi-layered piezometry in the Mimram

These data indeed show GWLs recorded in Mimram 6 and Mimram 7 in the Lewes/New Pit chalk were about 0.5 to 1m higher than the recorded GWLs at Fulling Mill BHs 1 and 2 in the Holywell chalk. However, the data also show recorded GWLs at Mimram 7 being about 0.5m higher than recorded GWLs at Mimram 6 during the period April 2017 to December 2018 when there was no abstraction at Fulling Mill. Mimram 7 is about 900m downstream of Mimram 6, so would be expected to have GWLs about 3m lower than Mimram 6, assuming a down-valley GWL gradient of about 1:300 as shown on NEP report Figures 65 to 67.

As argued in Section C2 of this report, the mirroring of short and long term fluctuations in the shallow and deep GWLs strongly suggests hydraulic continuity throughout the aquifer. If there are separate aquifers with no hydraulic connection at different levels of the chalk, it is hard to see how this mirroring of fluctuations could occur. If a deep aquifer in the Holywell chalk is only connected to the surface via an outcrop several km to the north, what causes the GWL rises during periods of recharge which closely match the magnitude and timing of rises in the shallow GWLs above? It is difficult to explain what causes the falls in Holywell chalk GWLs during recessions, also closely matching shallow GWL recessions, if the Holywell chalk aquifer is disconnected from the shallow aquifer and the river.

NEP analysis of periods with similar groundwater levels and different abstraction

The NEP report has tried to show the ineffectiveness of abstraction reductions by comparing river flows in periods with similar groundwater levels before and after the reductions. Based on the Lilley Bottom hydrograph, the dates of 1 April 1990 – 1 October 1992 (orange line) and 1 April 2016 – 1 October 2018 (blue line) were selected, as plotted in Figure 61, which is copied from NEP report Figure 90:

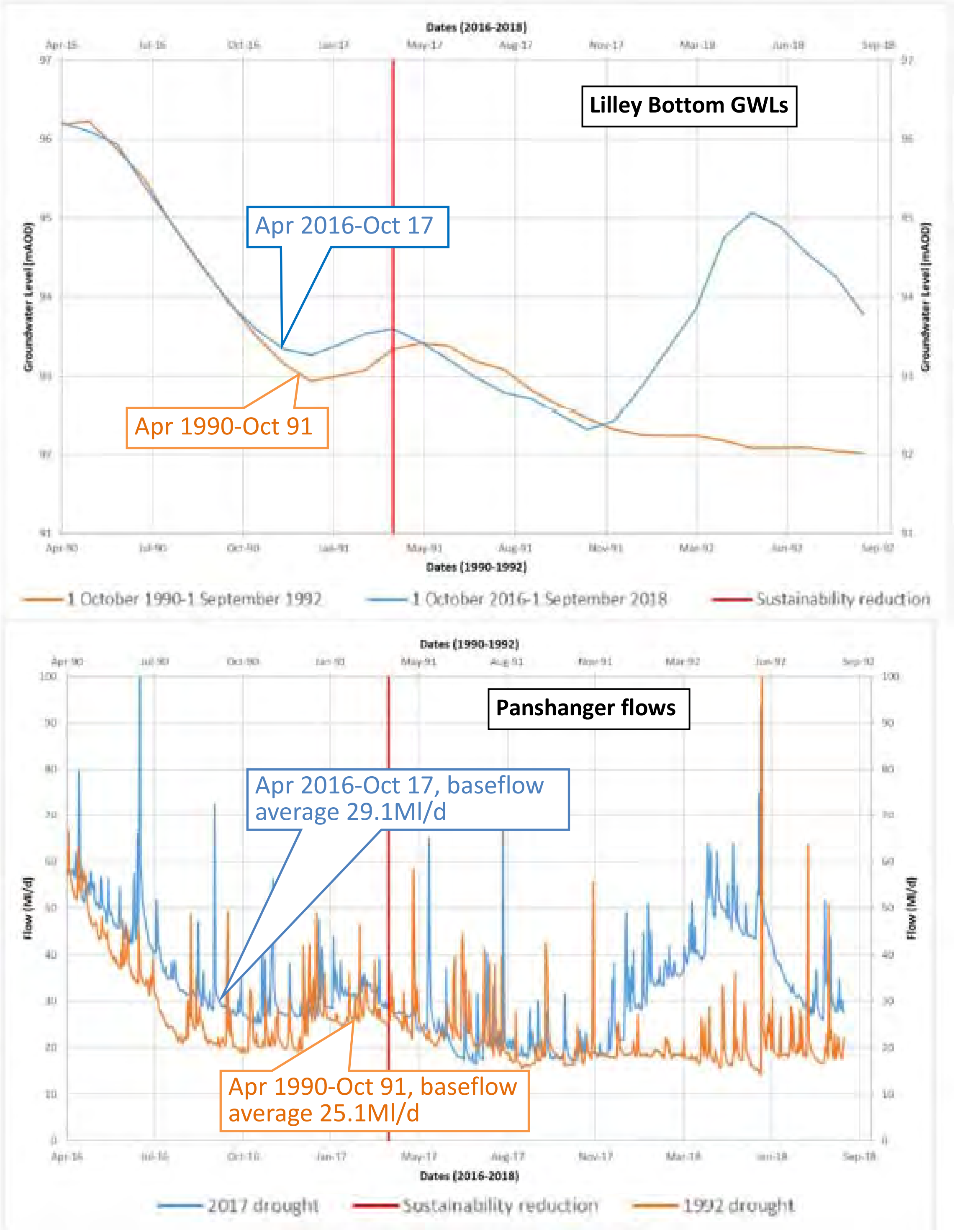


Figure B27 - NEP drought flow comparisons before and after abstraction reductions

The NEP report cites the similar flows and GWLs in the droughts of 1990-91 and 2016-17 as evidence that the river flows are not affected by the c.6 Ml/d abstraction reduction. The report says that these periods, before and after the Fulling Mill sustainability reductions, both saw low groundwater levels that tracked a similar profile from the April of year 1 to the November of year 2 as shown by the upper plot in Figure B27. The report says that this pattern is reflected in the flow hydrographs in the lower plot. The NEP report argues that:

> *“these two drought periods with a similar groundwater level/trend produce similar flow in the Mimram, despite there being around 6 Ml/d more water in the environment than during the early 1990’s drought (calculated by subtracting 11.37 Ml/d (average Mimram catchment abstraction from 2016 to 2018) from 17.39 Ml/d (average Mimram catchment abstraction from 1990 to 1992).”*

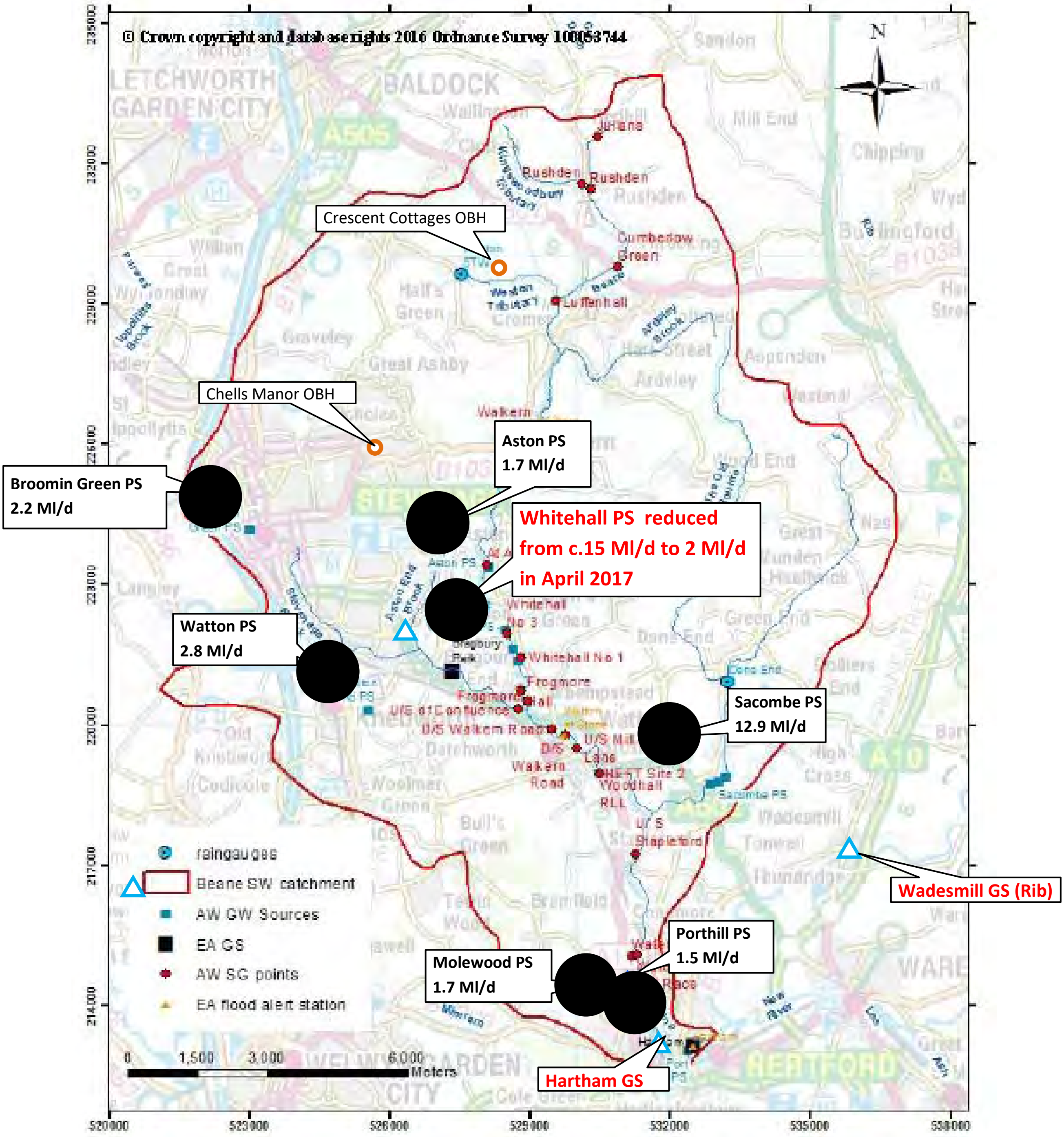
If the interpretation of chalk aquifer behaviour described in Section 2.2 of the main report is accepted, river flows are directly linked to regional GWLs. This hypothesis is supported by the measured Mimram flows and GWLs described in Section C2 of this report. That being the case, if GWLs in two periods are approximately the same, river baseflows must also be approximately the same, so the plots in Figure B27 do not provide evidence of the lack of impact of abstraction.

Appendix C - River Beane Case Study

Contents

C1 Beane location, geology and abstraction history

The approximate locations of public water supply abstractions from groundwater in the Beane catchment and nearby rivers are shown in Figure C1 **(redacted)**:

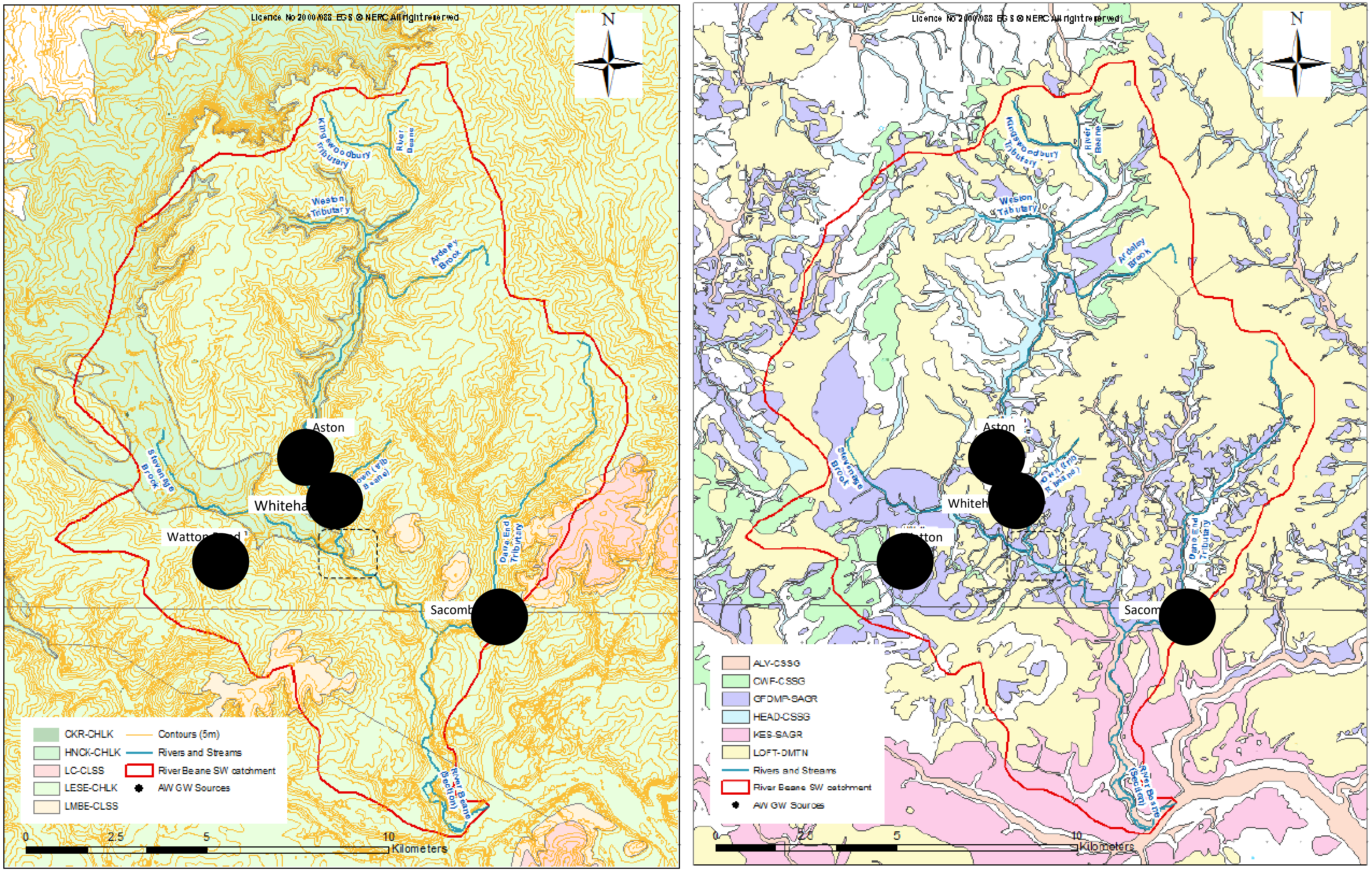


PWS boreholes with av. abstraction 2019-21

Base map copied from Beane NEP report Figure 10

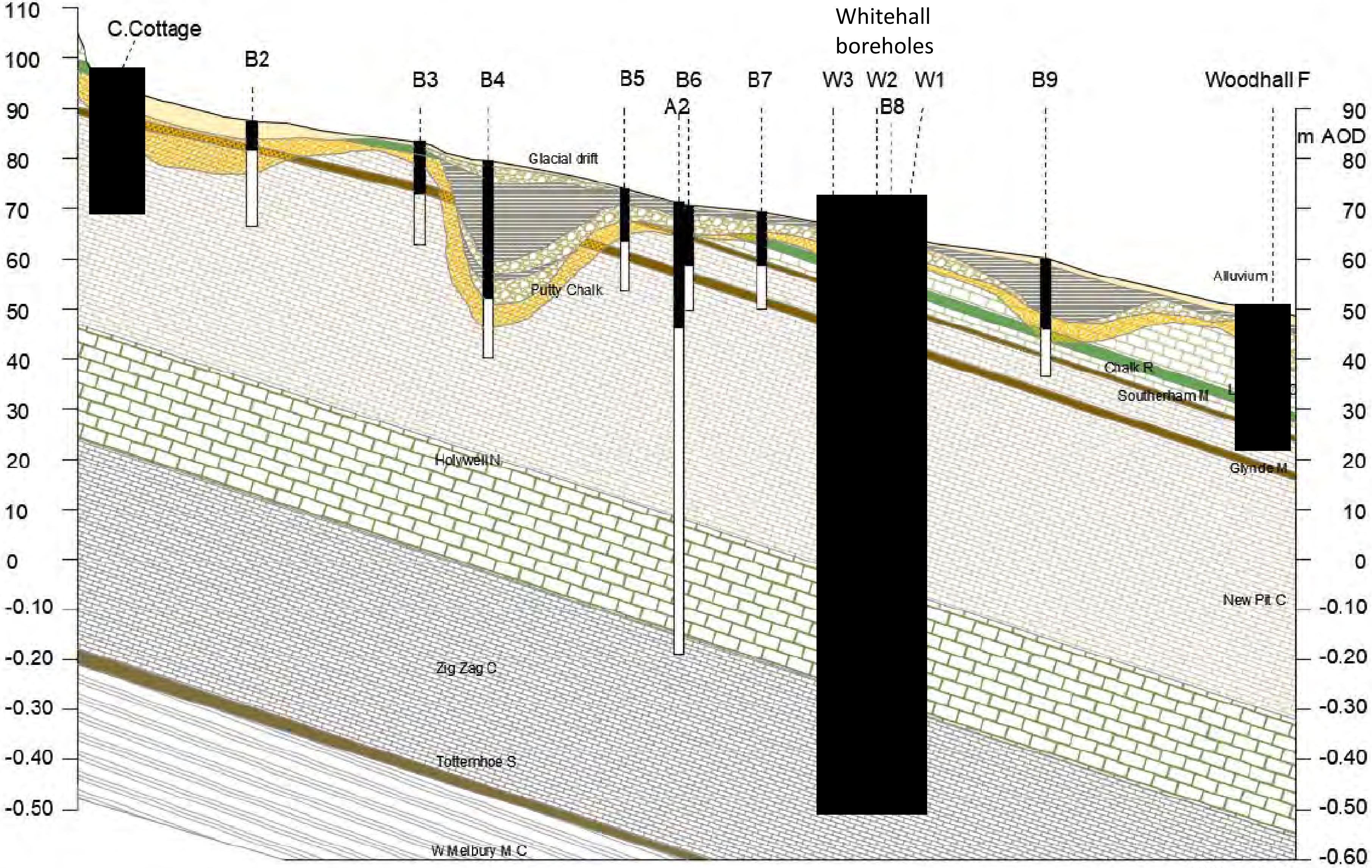
Figure C1 - Beane catchment and abstraction locations

The solid geology and superficial deposits of the Beane catchment are shown on Figure C2 and a geological section is shown on Figure C3:



a) Solid geology Maps copied from Beane NEP report Figure 4 and 5 **b) Superficial deposits**

Figure C2 - Solid and drift geology of River Beane, with PWS borehole locations



Copied from Beane NEP report Figure 7

Figure C3 - North to South cross-section of middle Beane catchment

The growths in abstraction in the Beane catchment and Lea chalk are shown in Figure C4:

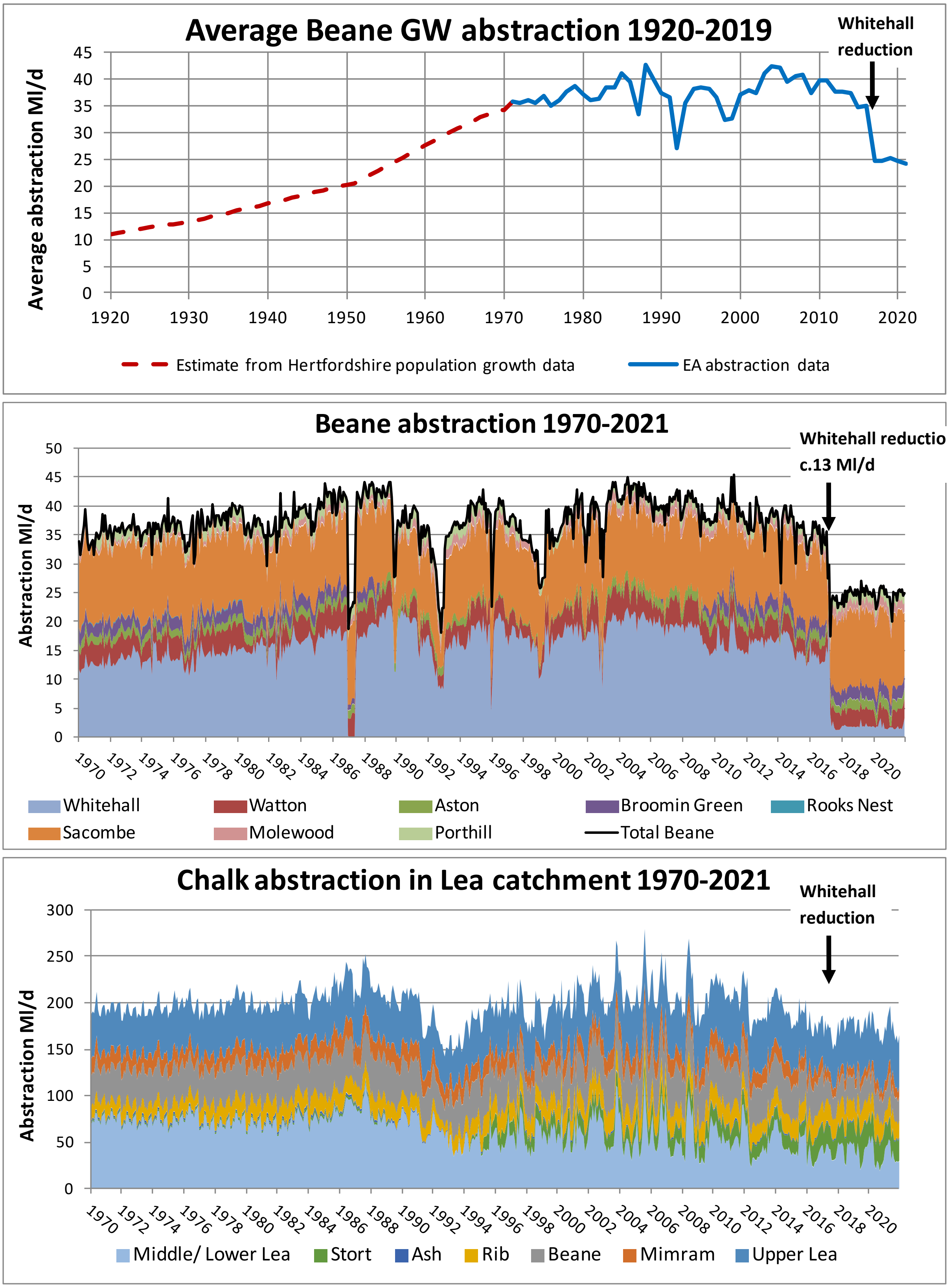


Figure C4 - Abstraction growth in Beane and whole Lea catchments

C2 Relationship between Beane flows and GWLs

In addition to the EA's Crescent Cottages, Chells Manor and Dane End observation boreholes shown on Figure C1, Affinity Water have a series of OBHs mostly in the valley bottom at locations shown on Figure C5:

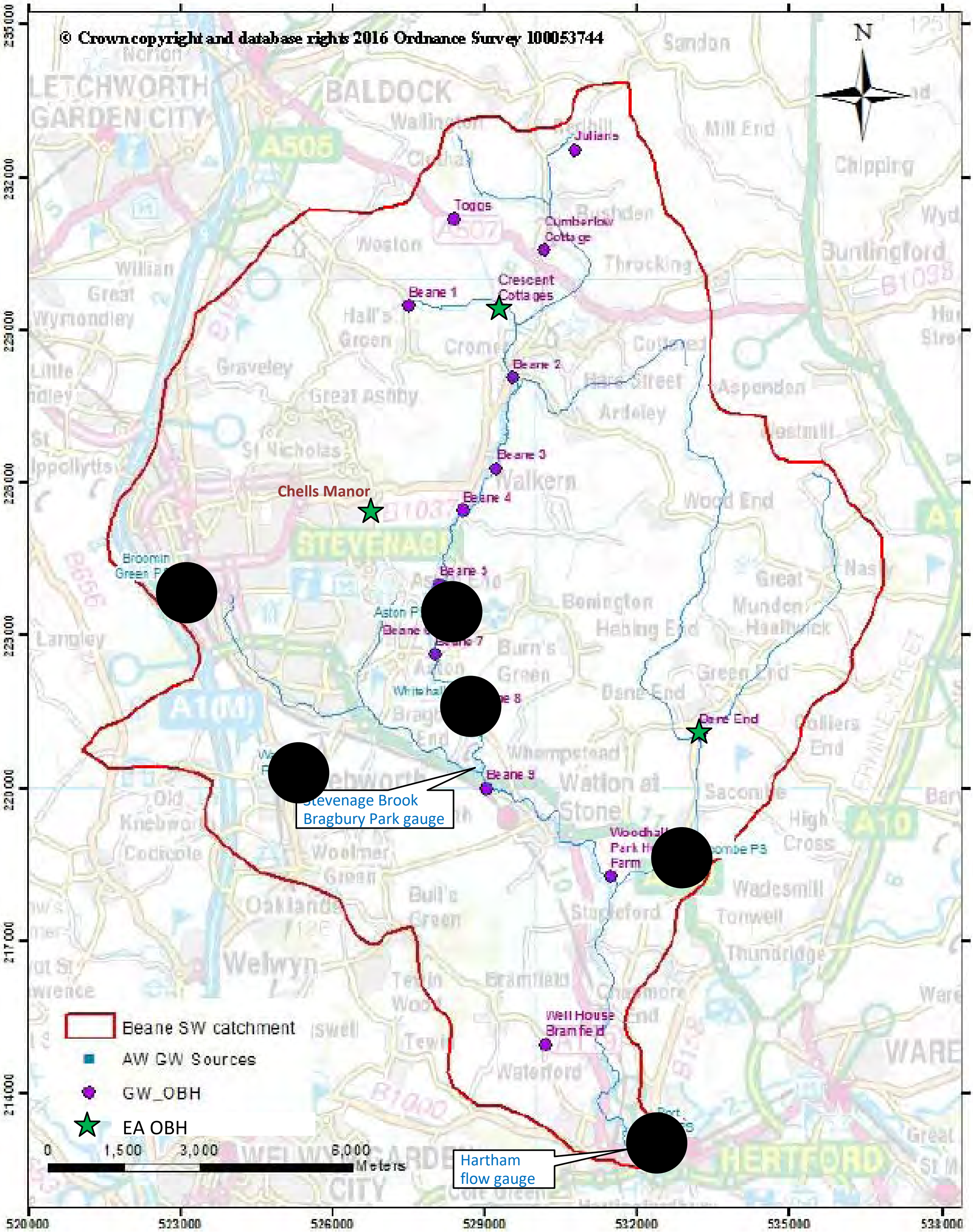


Figure C5 - Locations of OBHs and flow gauges in the Beane catchment

In the Beane catchment there are flow gauges at Hartham on the lower Beane and Bragbury Park on the Stevenage Brook (locations shown on Figure C1). Gauged flows and baseflows at the two gauges, from 2014 to 2021, are shown on Figure C6:

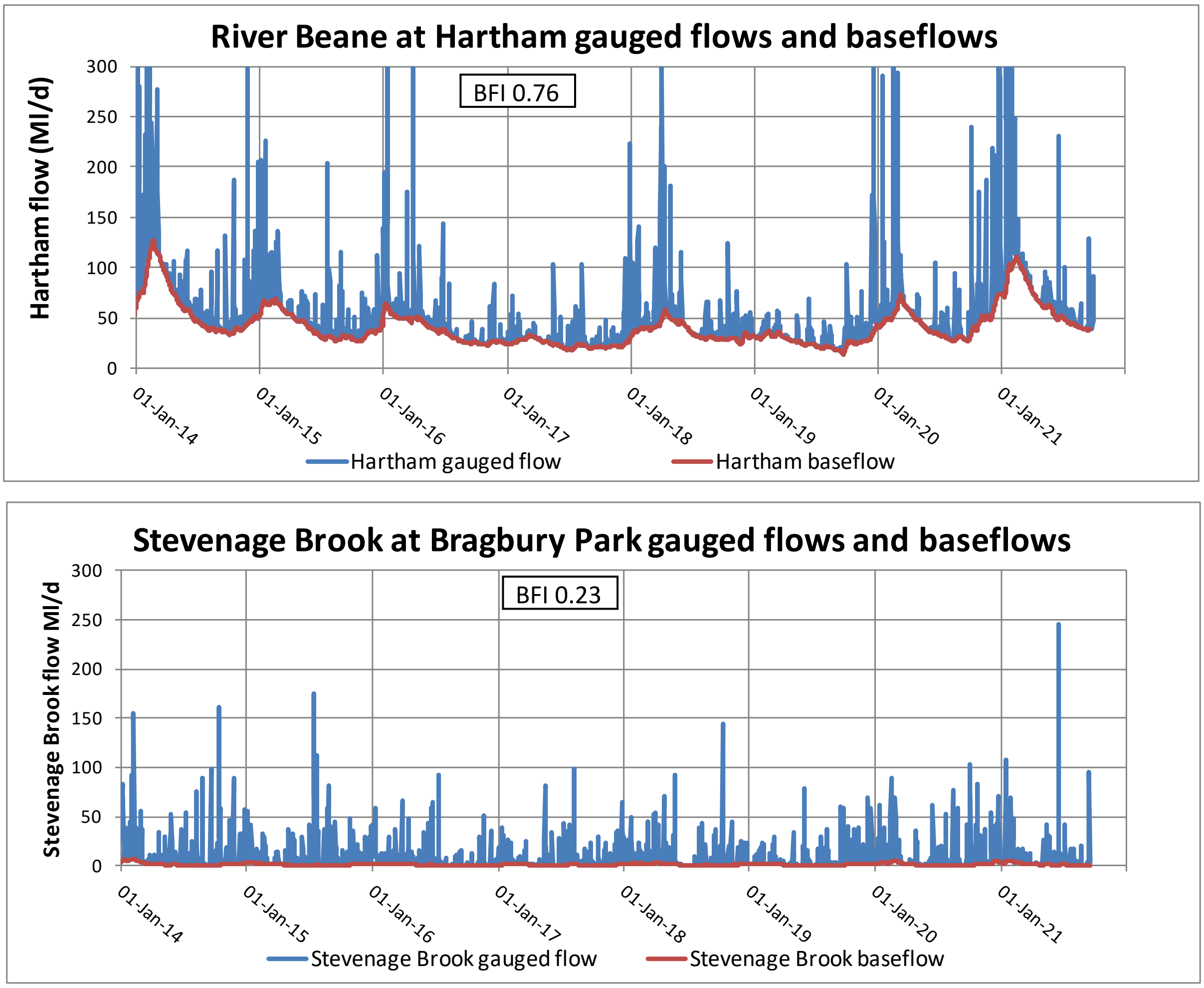


Figure C6 - Gauged flows and baseflows on lower Beane and Stevenage Brook 2014-2021

The River Beane is relatively ‘flashy’ for a chalk stream with a baseflow index (BFI) of 0.76. The Stevenage Brook is extremely flashy with hardly any baseflow and a BFI of only 0.23. Therefore, it appears that much of the surface run-off in the lower Beane comes from the heavily urbanised Stevenage Brook catchment.

As for the Mimram catchment, groundwater levels in the Beane catchment rise and fall together as shown in Figure C7 (from Affinity daily records of valley bottom observation boreholes available from 2014):

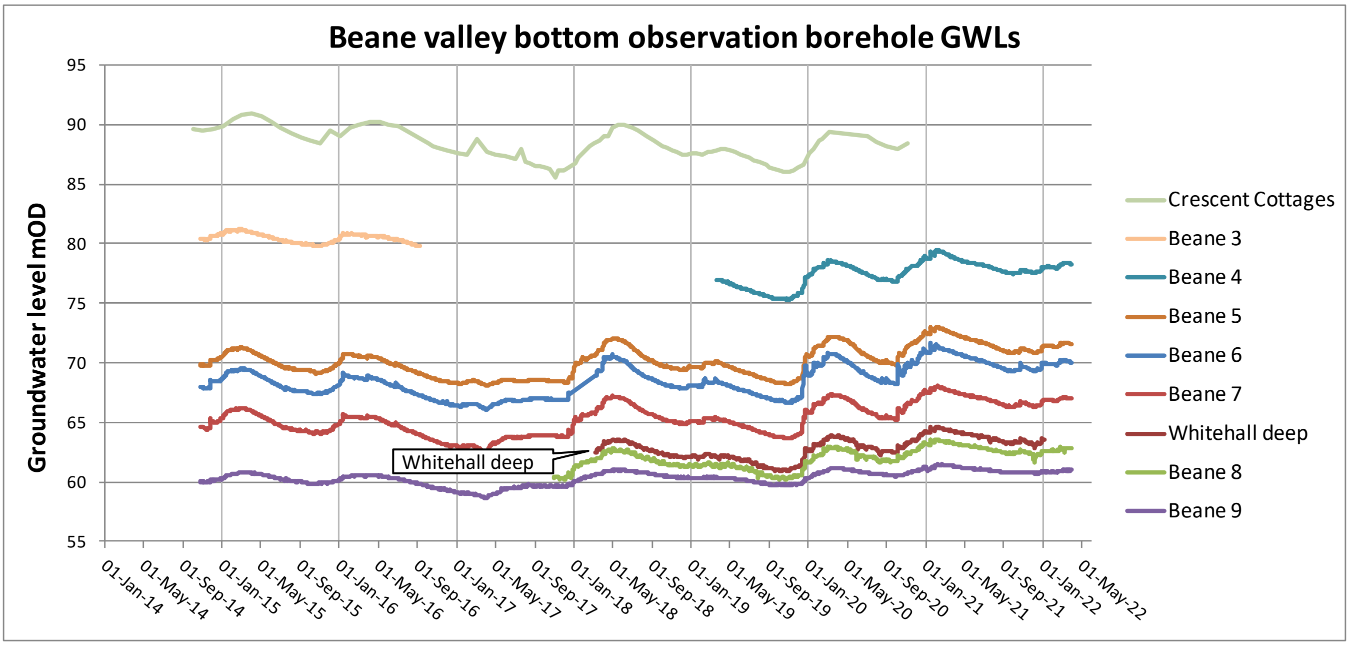


Figure C7 - Middle Beane valley bottom GWLs 2014-22

The valley bottom GWLs rise and fall in unison at all the locations. The geological cross-section in Figure C3 shows that all the observation boreholes are relatively shallow, penetrating about 10m into the New Pit chalk, except for the c. 120m deep Whitehall OBH which penetrates the Zigzag chalk. The GWLs in the deep Whitehall OBH almost exactly follow the GWLs in the nearby shallow Beane 8 OBH.

The longer term GWL records from the EA observation boreholes, which are spread across the catchment, also rise and fall in unison, matching Hartham baseflow fluctuations as shown in Figure C8:

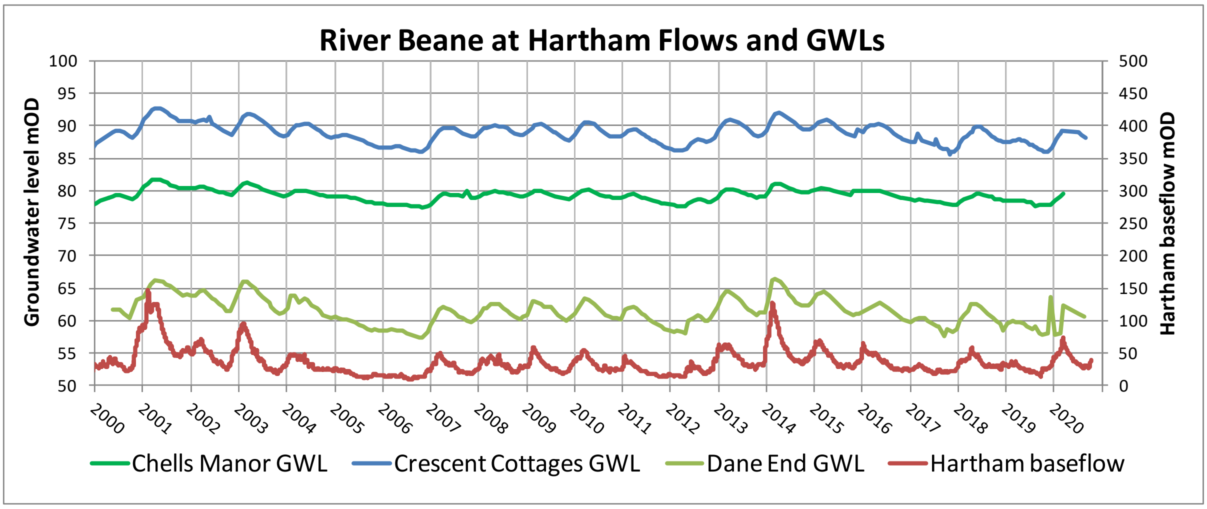


Figure C8 - EA observation boreholes and Hartham baseflows 2000-2020

Further evidence of the strong relationship between groundwater levels in different parts of the Beane catchment is shown in the scatter plots in Figure C9:

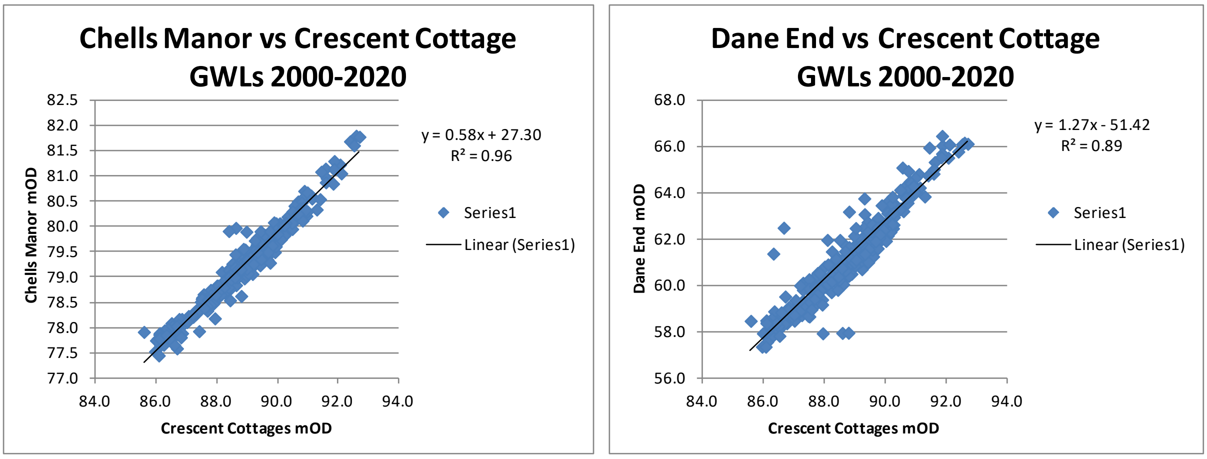
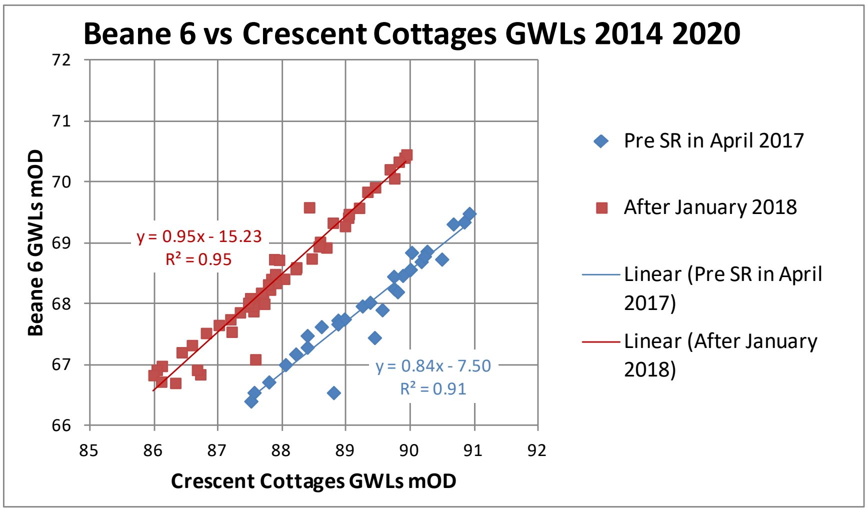


Figure C9 - Correlation of Crescent Cottages, Chells Manor and Dane End GWLs

There is also good correlation between the Crescent Cottage GWLs and the OBHs within the cone of depression of the Whitehall abstraction, for example at Beane 6. However, the Crescent Cottage GWLs lag the Beane 6 GWLs by about 30 days and the relationship changes after the Whitehall sustainability reduction in April 2017, as shown in Figure C10:



Note:

1. Crescent Cottage GWLs are plotted with a 30 day lag behind Beane 6 GWLs.

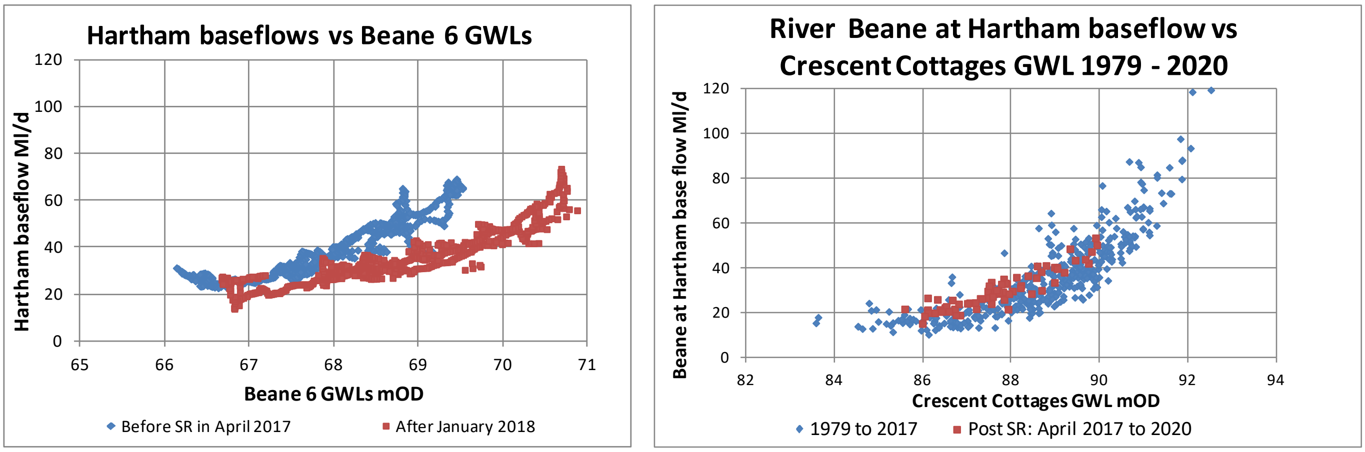
2. Crescent Cottages OBH is 8 km from Whitehall, Beane 6 is 2 km from Whitehall.

Figure C10 - Correlation between Crescent Cottage and Beane 6 GWLs

After the Whitehall sustainability reduction in April 2017, the GWLs at Beane 6, about 2 km from the Whitehall boreholes and within their cone of depression, rose by about 1.5 metres relative to the Crescent Cottage GWLs which are about 8 km from Whitehall boreholes.

The 30-day delay in response to recharge at Crescent Cottages compared with Beane 6 could be due to the higher depth of drift cover at Crescent Cottages or differences in the chalk transmissivity.

The change in Beane 6 GWLs after the sustainability is also evident in the relationships between GWLs and baseflows at Hartham shown in Figure C11:



Note: Crescent Cottages GWLs are plotted with a 30 day lag behind Hartham baseflows. There is no lag between GWLs and baseflows on the Beane 6 plots.

Figure C11 - Correlation of Hartham baseflows with Beane 6 and Crescent Cottages GWLs

The left hand plot shows that there are good ‘$Q=ah^b$’relationships between Hartham baseflows and Beane 6 GWLs, both before and after the Whitehall sustainability reduction. However, the relationship changes after the sustainability reduction because the Beane 6 borehole lies within the cone of influence of the Whitehall borehole abstraction and water levels rose about 1.5 m after the reduction.

The right hand plot in Figure C11 shows similar ‘$Q=ah^b$’ relationships at Crescent Cottages (8 km from Whitehall) before and after the Whitehall reduction, showing that the Crescent Cottages OBH lies outside the Whitehall cone of influence. Although the before and after ‘$Q=ah^b$’ relationships are similar in shape, the ‘after’ points (dark red) are distinctly higher in the right hand plot. This suggests that, in addition to increased river flows due to a higher regional water table after the abstraction reduction, there is an additional increase in flows due to enhanced spring flows from groundwater level recovery within the Whitehall cone of depression.

C3 Validation of CSF and HRGM models for the River Beane

CSF lumped parameter model for the River Beane

The CSF modelling methodology described in main report Section 2.3 has been used in a lumped parameter model for the River Beane. The model features are:

- Covers 102-year period 1920 to 2021, including droughts of 1921, 1934 and 1944
- Effective rain since 1920 taken from EA daily data for Lee chalk record 6600TH
- Abstraction data from latest EA records and Beane NEP report
- Daily GWLs simulated at the Crescent Cottage observation borehole site, which has the longest record of the three EA OBHs (1967 to date).
- River flows simulated for the Hartham gauge site and the Frogmore spot flow site
- Effective catchment area for recharge 135 km^2 (reduced from the topographic catchment of 175 km^2 to allow for the low Beane and Stevenage Brook BFIs)

The model uses the relationships between river flows and GWLs shown in Figure C12:

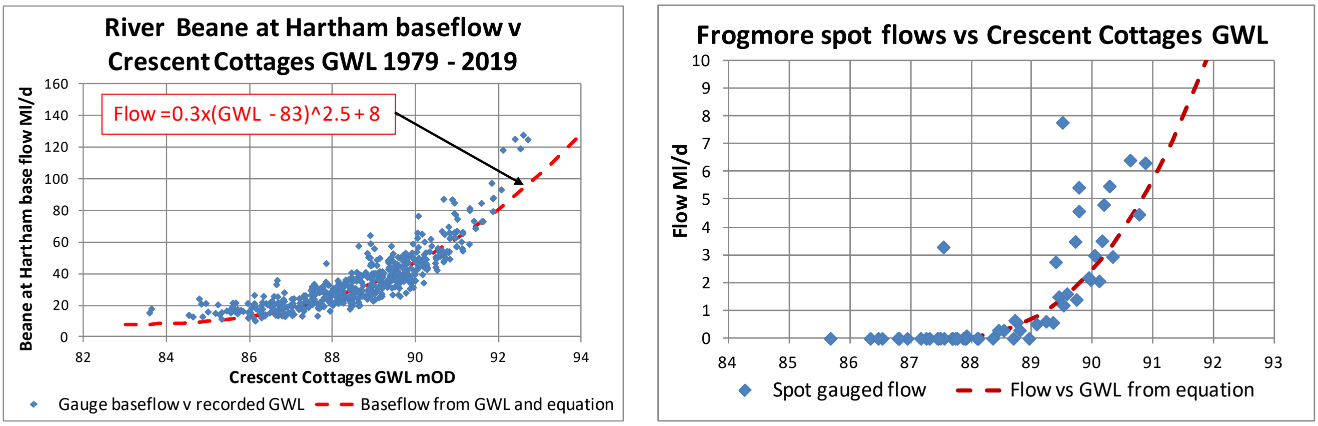
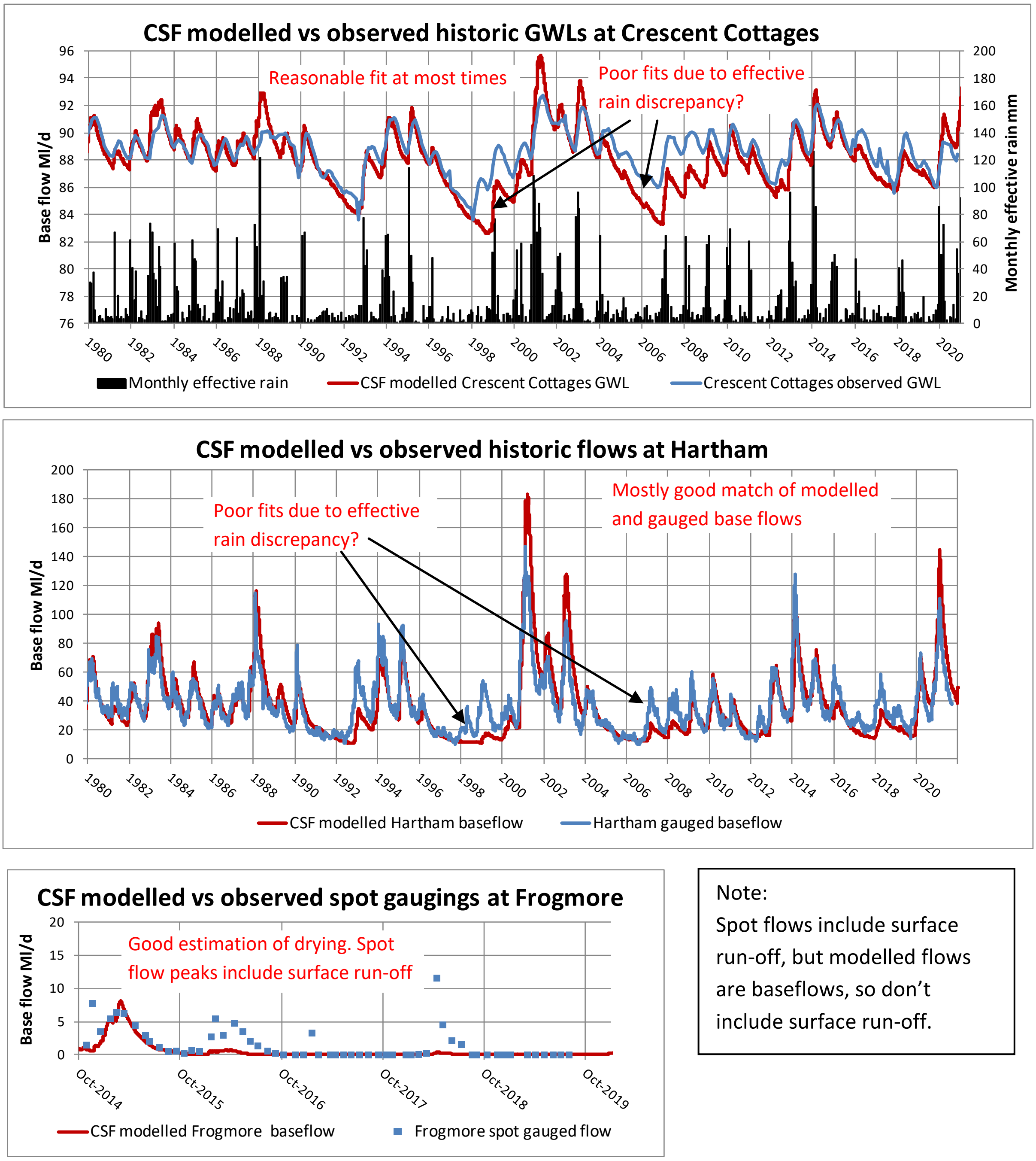


Figure C12 - Measured flows vs GWLs used in CSF Beane model

For modelling of the recent actual abstraction scenario of 27.4 Ml/d, starting in 1920 and ending in 2020 on a date when the modelled storage is the same as the modelled starting storage, the water balance over the 100 year period is:

Inputs	Ml/d
Average aquifer recharge	75.4
Average leakage from supplies to aquifer	2.0
Total inputs	77.4
Outputs	
Average river outflow at Hartham	47.9
Average underflow from catchment	4.9
Average abstraction	24.7
Total outputs	77.5

The CSF model was calibrated to give best fits to recorded groundwater and river flow records in the period 1980 to 2020 (the Hartham flow record started in 1979):


CSF modelled vs observed historic GWLs at Crescent Cottages

Reasonable fit at most times

Poor fits due to effective rain discrepancy?

CSF modelled vs observed historic flows at Hartham

Poor fits due to effective rain discrepancy?

Mostly good match of modelled and gauged base flows

CSF modelled vs observed spot gaugings at Frogmore

Good estimation of drying. Spot flow peaks include surface run-off

Note:
Spot flows include surface run-off, but modelled flows are baseflows, so don't include surface run-off.

Figure C13 - Validation of CSF River Beane modelled GWLs and flows 1980-2020

As can be seen in Figure C13, the CSF model gives a mostly good fit between modelled and historic measured GWLs and baseflows throughout the 40-year period, 1980 to 2020, for which the model was calibrated. The poor fits in the period 1998 to 2008 may be due to discrepancies in the EA's Lee chalk effective rain record 6600TH. When the model is re-calibrated using Affinity Water MORECS 151 effective rain (only available from 1995), there is a much better fit for groundwater levels and flows in the 1998-2008 period, but some less good fits at other times.

More validation evidence for the CSF model can be seen by comparing modelled and historic groundwater levels at Crescent Cottages from 1968 to 1990, ie before the period for which the model was calibrated:

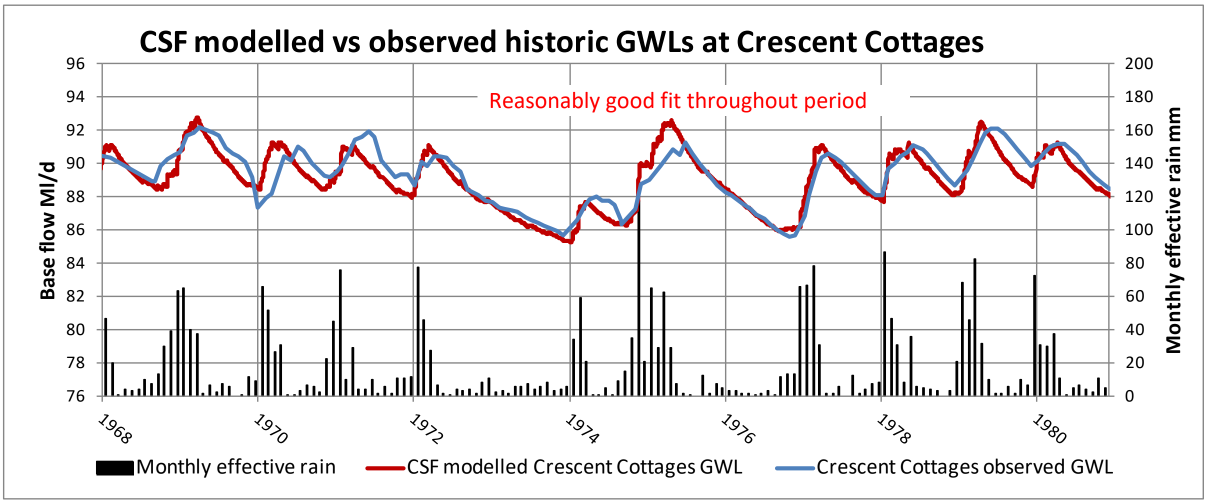


Figure C14 - CSF Beane model validation: Crescent Cottages GWL 1968-1990

The CSF model provides a reasonably good fit between observed and modelled groundwater levels throughout the 12 year period of available GWL data for which the model was not calibrated.

Comparison of validation of the HRGM and CSF models

A comparison of validation plots for the HRGM and CSF models is shown in Figure C15 on the next page. Comparing the goodness of fit for the two models:

- The HRGM model substantially overestimates the seasonal groundwater fluctuations. The CSF model has a generally good groundwater level fit – see also the plots on Figures C13 and C14 – but over-estimates the groundwater recession in the long drought of 2004-06. As previously mentioned this may be due to under-estimation of effective rain in this period: the average monthly effective in the period for the EA data used in the model was 6.5 mm/month, whereas the equivalent Morecs data provided by Affinity Water averaged 13.7 mm/month.

- Both models provide quite a good fit to Hartham flows, suggesting that either model can be used to estimate flow recovery in the lower river from abstraction reductions and compliance with EFIs at Hartham.

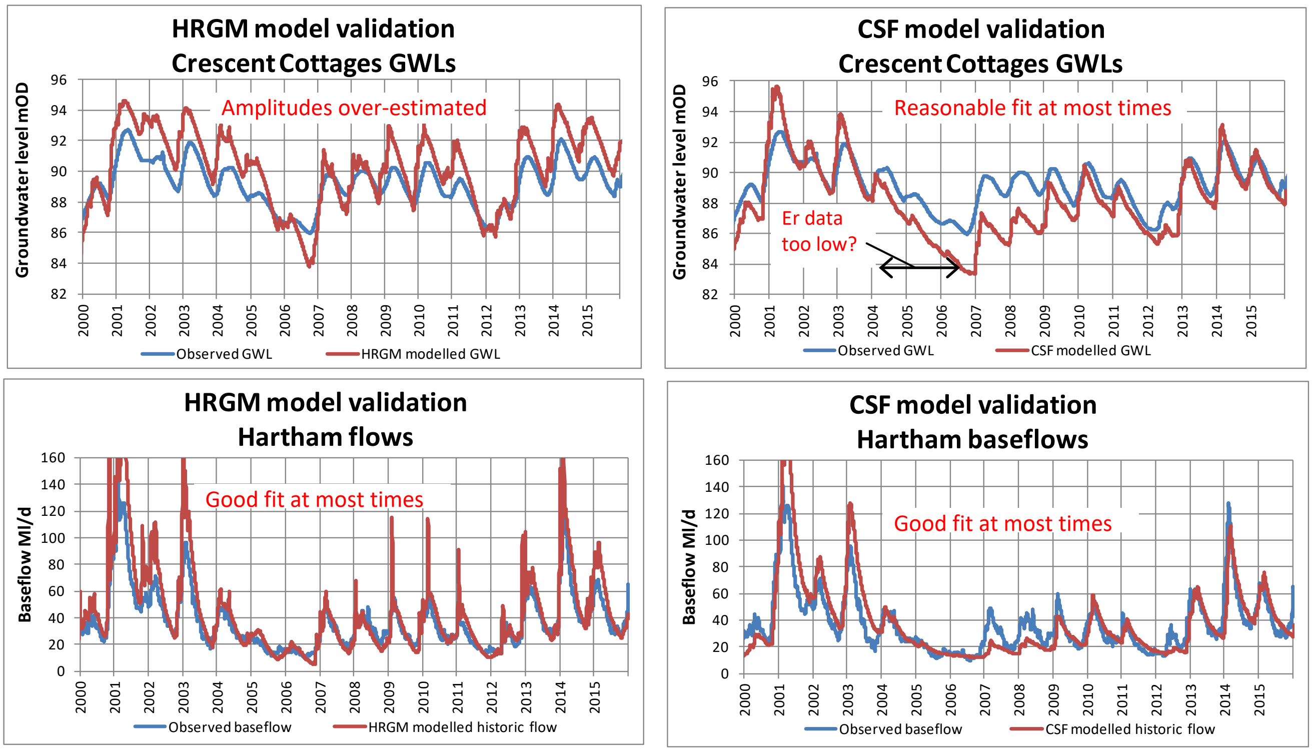


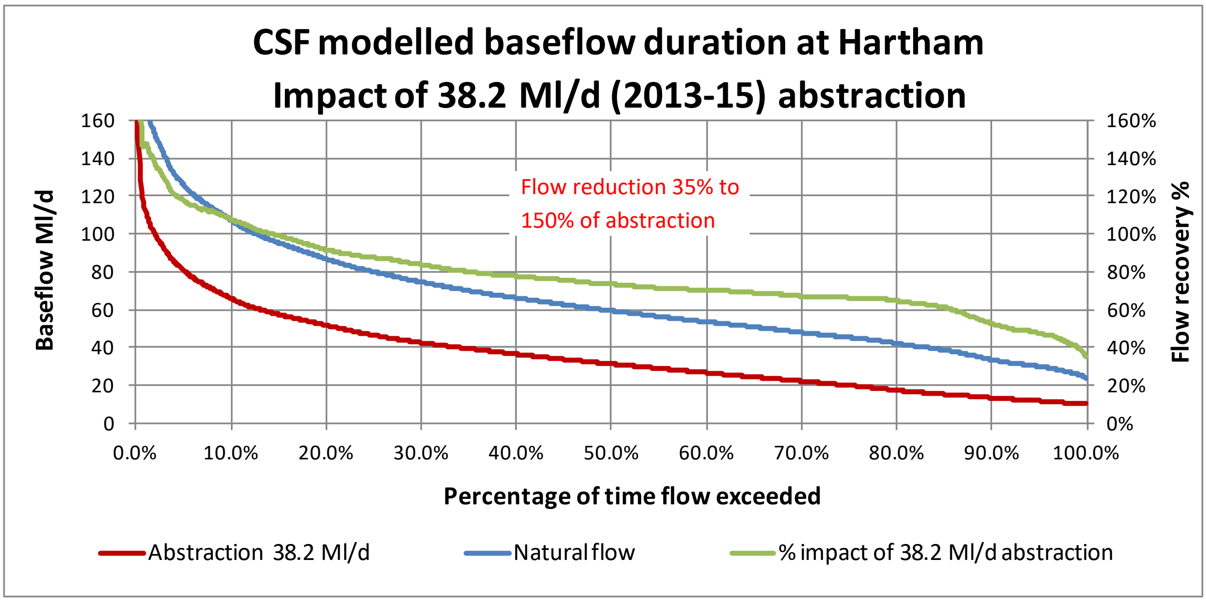
Figure C15 - Comparison of validation of HRGM and CSF models

These validation plots show that the HRGM and CSF models can both provide estimates of abstraction impacts and flow recovery in the lower Beane at Hartham gauging station. The CSF model should also provide good estimates of the frequency of drying at Frogmore (at present HGRM model data is not available for any winterbourne locations in the Beane catchment).

C3 Modelling of pre-SR abstraction impacts on the Beane

The HGRM modelling of 'recent actual' abstraction, simulating the period 1970 to 2015, assumed total Beane groundwater abstraction of 38.2 Ml/d. This is the figure supplied by the EA in file *'HERTS Artificial Influences Overview_Red.xlsx'* – it is assumed to be the average for 2013-15, ie from before the Whitehall sustainability reduction.

The CSF and HRGM modelling of the effect of 'recent abstractions' of 38.2 Ml/d on flows at Hartham from 1995 to 2015 are compared in Figure C16:



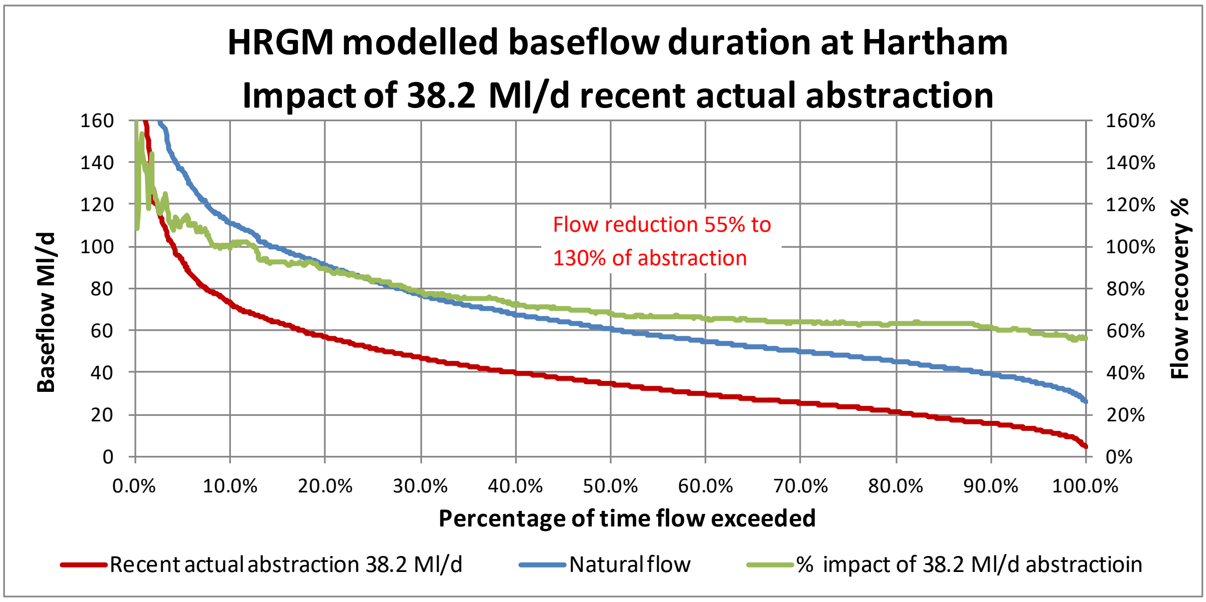


Figure C16 - Modelled flow duration impacts of 38.2 Ml/d recent abstraction at Hartham

Both models show a similar picture, with the flow reduction of about 35-55% of abstraction at low flows, around 70% at average flows and rising to over 100% at high flows.

C4 The effect of the Whitehall sustainability reduction

Magnitude and timing of the reduction

The 13 Ml/d reduction of abstraction at Whitehall in April 2017 was a clear and maintained stepped decrease in the overall Beane abstraction. The average annual Beane catchment recharge is 98 Ml/d, so the Whitehall reduction from about 38 Ml/d to 25 Ml/d lowered abstraction as a percentage of recharge (A%R) from about 39% to 26%. Although the Beane abstraction remained comparatively high after the sustainability reduction, the amount of reduction would be expected to produce a significant increase in river flows, albeit they would still be a long way short of natural flows.

The total abstractions from the Beane boreholes and in the Lea chalk before and after the Whitehall sustainability reduction are shown in Figure C17. From the lower plot it appears that supplies from the Whitehall reduction have been replaced by supplies from elsewhere in the Lea chalk, potentially reducing the effectiveness of the reduction on Beane river flows:

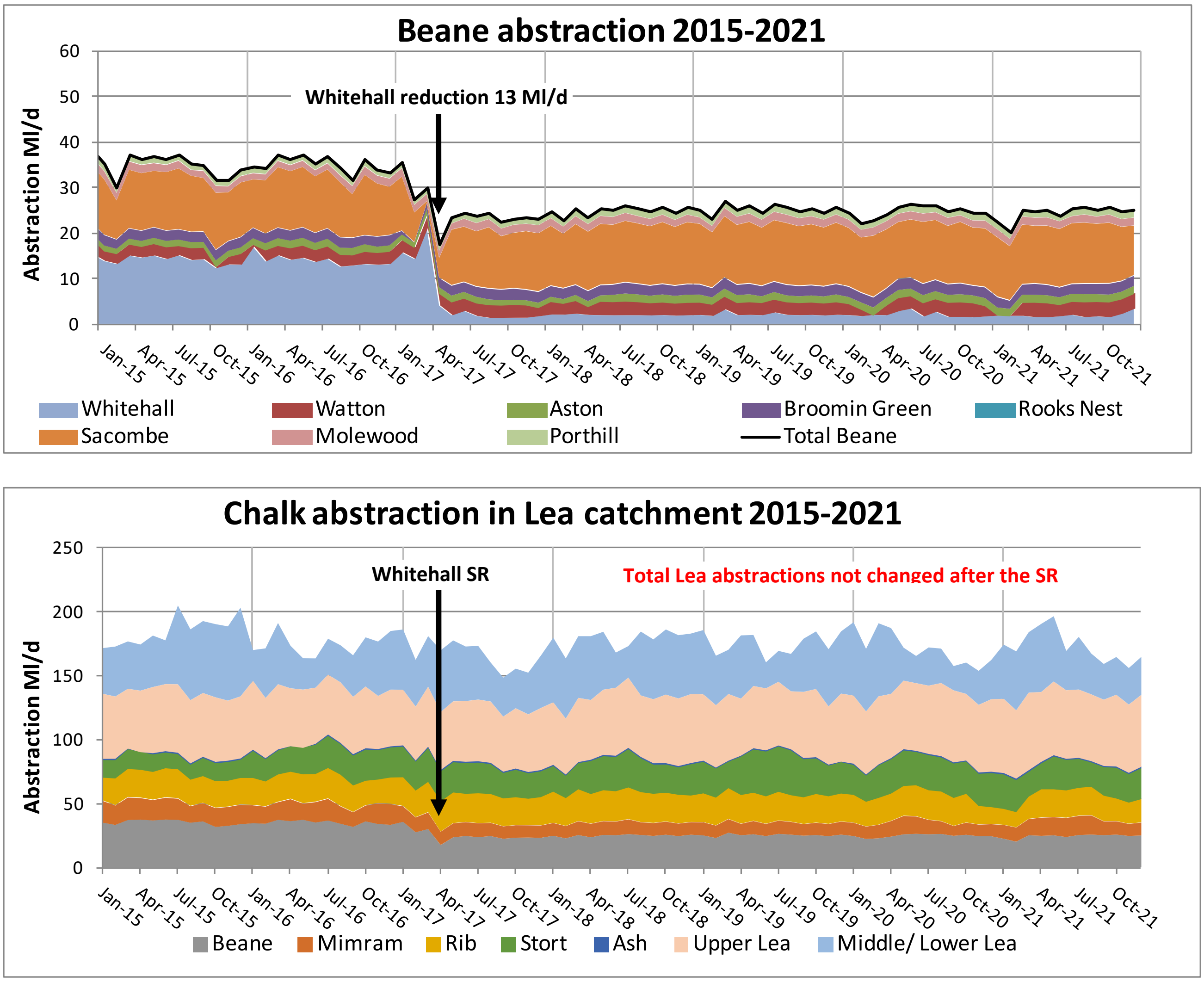


Figure C17 - Changes in Beane and total Lea chalk abstraction 2016-2021

Separation of the effect of an abstraction reduction from the effect of natural flow variations using ‘before-and-after’ flow duration curves requires substantial differences in abstraction between the two periods, similar total effective rain and recharge in each period, and at least 10 years of records before and after reduction, each containing comparable droughts. There have only been 5 years of records since the 2017 Whitehall reduction, so the effects of the reduction cannot be reliably separated from seasonal and climatic flow variations.

Recovery assessment by comparison with River Rib flows and abstractions

Comparison of relative flows and abstractions in the Beane and Rib catchments shows substantial relative flow changes arising from the abstraction changes as shown in Figure C18:

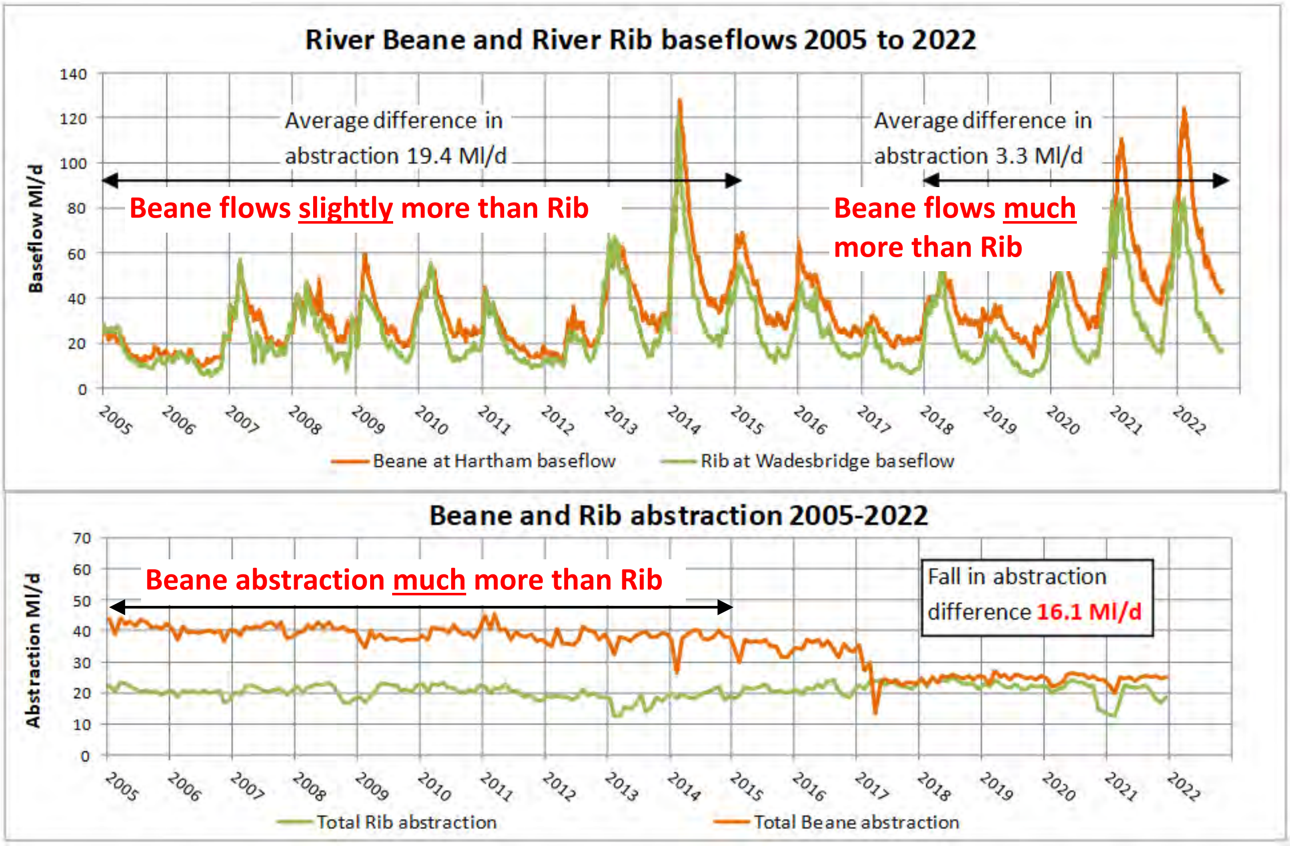
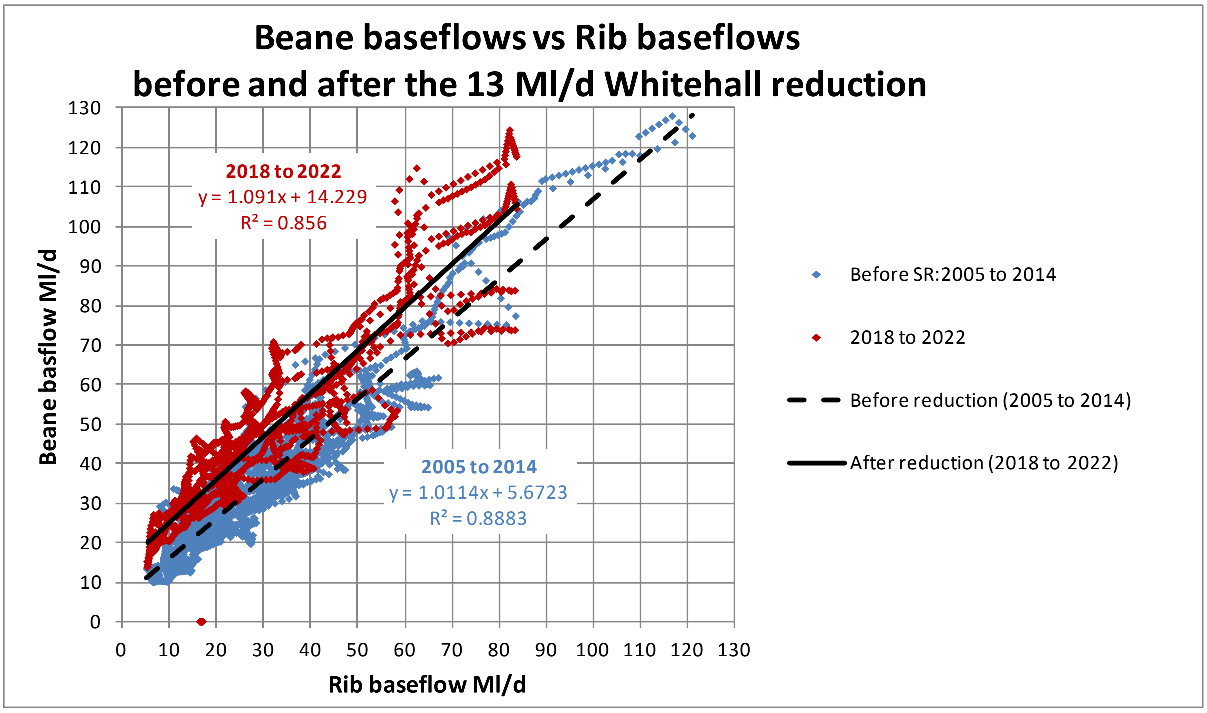


Figure C18 - Relative changes in Beane vs Rib abstractions and flows

This shows that since the 13 Ml/d Whitehall abstraction reduction in 2017, flows in the Beane at Hartham have clearly risen relative to Rib flows. The magnitude of the relative flow impacts from the relative abstraction changes are shown by plotting Beane vs Rib baseflows in Figure C18, comparing the relationship since the Whitehall reduction in 2018 with the relationship from 2005 to 2014, with a 16.1 Ml/d relative change in abstractions between the two periods:



	Relative Beane-Rib abstractions Ml/d		
	Beane	Rib	Diff
2005 to 2014	39.3	20.0	19.3
2018 to 2021	24.7	21.4	3.3
		Relative change	**16.1**

	Beane flow Ml/d	**Relative Beane flow gain 2018-22 vs 2005-14 Ml/d**	**Gain as % of 16.1 Ml/d relative change in abstraction**
Q99	12.4	9.6	59%
Q95	15.0	9.8	61%
Q50	33.6	11.2	70%
Q20	50.0	12.5	78%
Q5	76.0	14.6	91%

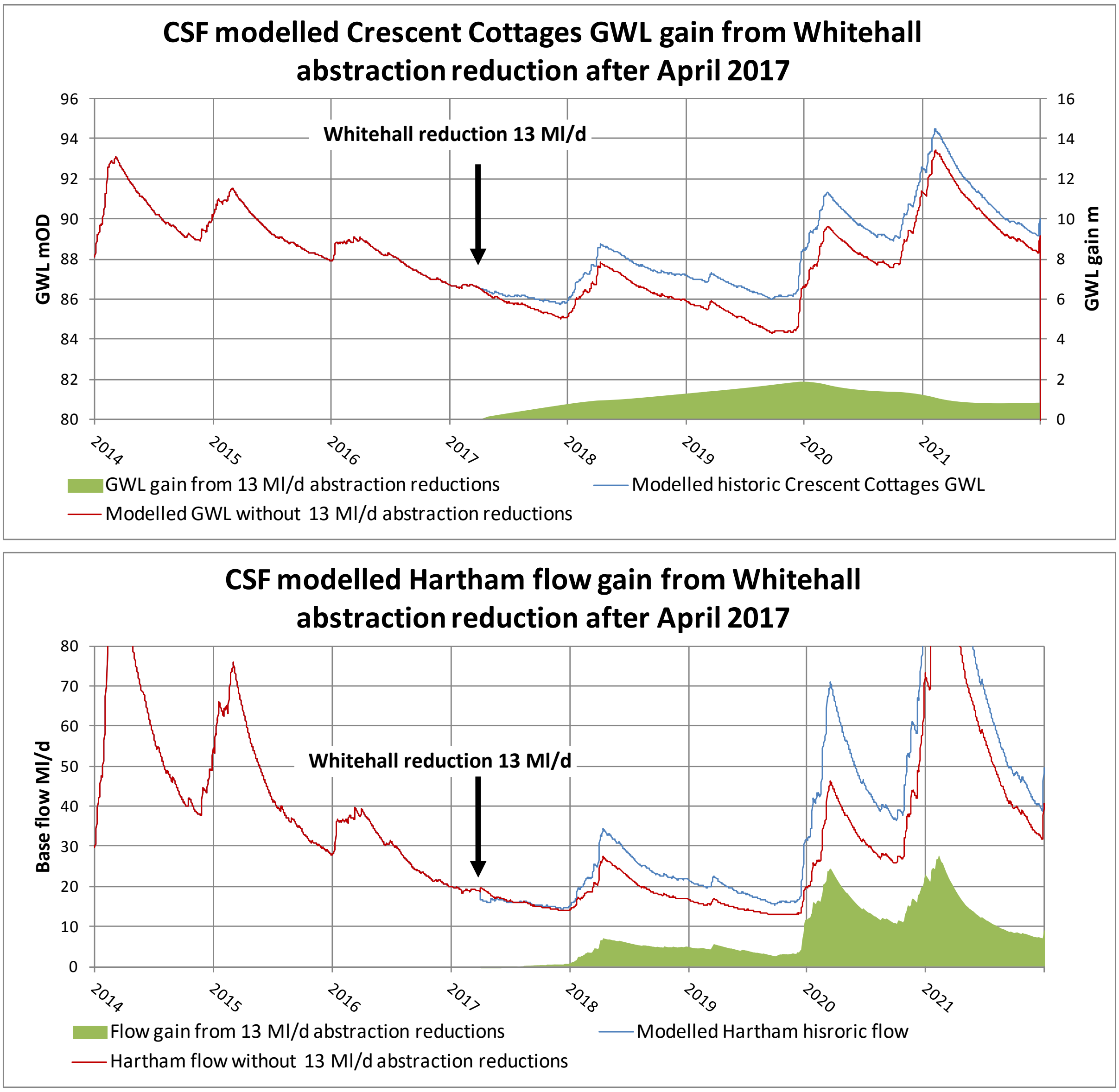
Figure C19 - Magnitude of relative Beane-Rib flow changes after abstraction changes

This shows that the 16.1 Ml/d relative change in abstraction generated relative flow changes of 9.6 Ml/d (59% recovery) to 14.6 Ml/d (91% recovery across the range of flows. The abstraction driven flow changes are also similar to those measured and modelled following the Friar's Wash abstraction reduction in the River Ver, as described in Appendix A.

Modelling of the Whitehall sustainability reduction

The available output from the HRGM model only extends to 2015, so it does not cover the Whitehall reduction in 2013.

The CSF modelling of the effect of the Whitehall reduction is shown on Figure C20:



Note: After April 2017, the modelled abstraction is the recorded historic abstraction + 13 Ml/d.

Figure C20 - CSF modelled flow increase following 13 Ml/d Whitehall reduction

When the Whitehall abstraction was reduced in April 2017, groundwater levels and river flows were unusually low after a dry winter. The drought continued for another 30 months until the winter of 2019/2020 when there was substantial recovery, followed by more normal conditions in 2020 and 2021. Data for 2022 are not currently available.

The CSF modelling shows that there would have been slow groundwater level recovery from April 2017 to the end of 2019, but virtually no flow recovery until the drought ended in winter 2019/20. At the time of the NEP report in 2020, it would have been impossible to separate the small recoveries up to that time from natural variations due to the weather. Even in 2022, there has not been sufficient time since the Whitehall reduction for a reliable comparison of measured ‘before-and-after’ flows, or for comparison with nearby chalk catchments where abstraction has not been reduced.

C5 Proposed abstraction reduction in the Beane catchment

Abstraction reduction targets

The two methodologies available for determining acceptable abstraction – using either EFIs or A%R – give broadly similar results for required abstraction reduction in the Beane catchment.

The EFI methodology gives a recent actual EFI low flow deficit of 11.0 Ml/d at Q95, assuming that the Beane is in the medium sensitivity band ASB2, and an allowed total Beane abstraction of 7.1 Ml/d, determined as in Table C1:

Calculated Natural Low Flow (Q95)	**Estimated % allowable abstraction (ASB%)**	**Estimated sustainable low flow (EFI)**	**Recent Actual Q95 Flow**	**Flow Deficit to EFI at low flow (Q95)**	Abstraction Sensitvity Band	Sustainable abstraction quantity at low flows	Cumulative Discharges	**Available to Abstract (Nat +Dis - EFI)**
42.7	15%	36.3	25.3	11.0	ASB2	6.4	0.7	**7.1 Ml/d**
	15% for ASB2	42.7 x 85%		36.3 - 25.3		Natural Q95 - EFI	Small STWs	6.4 + 0.7

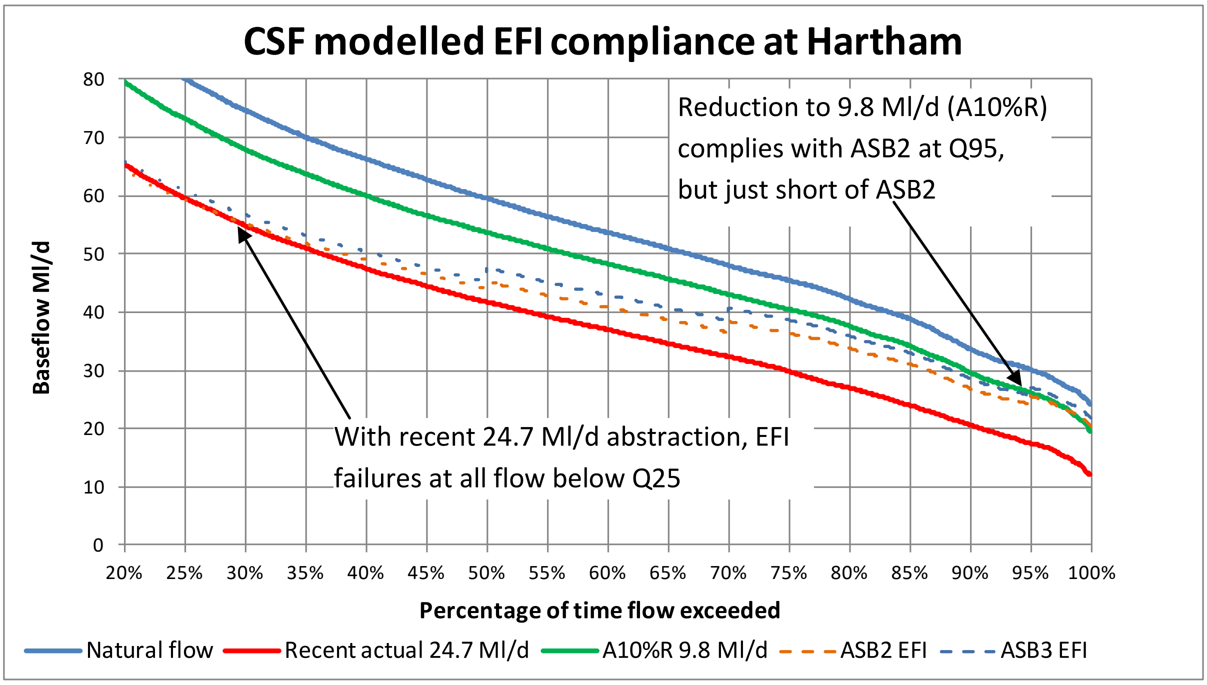
Notes: 1. Copied from EA worksheet 'Chilterns flow deficits 2020.xlxs' provided by EA email dated 9.12.2020

2. John Lawson comments in bottom row

Table C1 - EA allowable abstraction calculation for the lower River Beane

Effect of proposed reduction on flow durations and EFI compliance

Using the A%R methodology, the CSF modelling shows that the A10%R abstraction of 9.8 Ml/d (average recharge 98 Ml/d) complies with ASB2, although not quite ASB3 (see Figure C21). As the EA have categorised the Beane into the medium sensitivity band ASB2, it is suggested that total abstraction from the Beane should be limited to 9.8 Ml/d, a reduction of 14.9 Ml/d from the modelled 24.7 Ml/d recent actual abstraction. The CSF modelled flow duration compliance with EFIs at Hartham is shown on Figure C21:



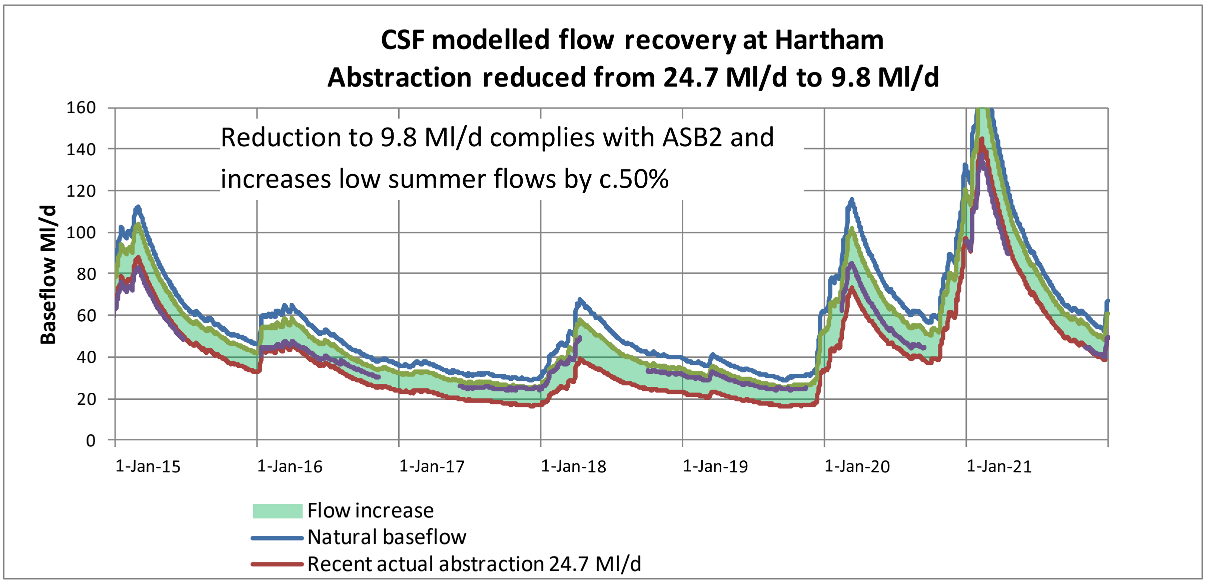
Note: Flow durations are calculated for the full 100 years of modelled flows 1920 to 2019

Figure C21 - CSF modelled flow compliance with abstraction cut to 9.8 Ml/d (A10%R)

As can be seen on Figure C21, reduction of total Beane abstraction to 9.8 Ml/d (A10%R) gives Hartham flow compliance with the ASB3 EFI target at all flows above Q95. Below Q95, reduction of abstraction to 9.8 Ml/d meets the ASB2 EFI target, but does not quite meet the ASB3 target. Summer flows at Hartham would be increased by about 30-60% compared with flows that have occurred with the recent abstraction of 24.7 Ml/d.

Improvement of flows in typical years

With total abstraction reduced to 9.8 Ml/d, the CSF modelled increases in flows at Hartham and Frogmore for the 5-year period 2015 to 2019, including the 2019 drought, are shown in Figure C22:



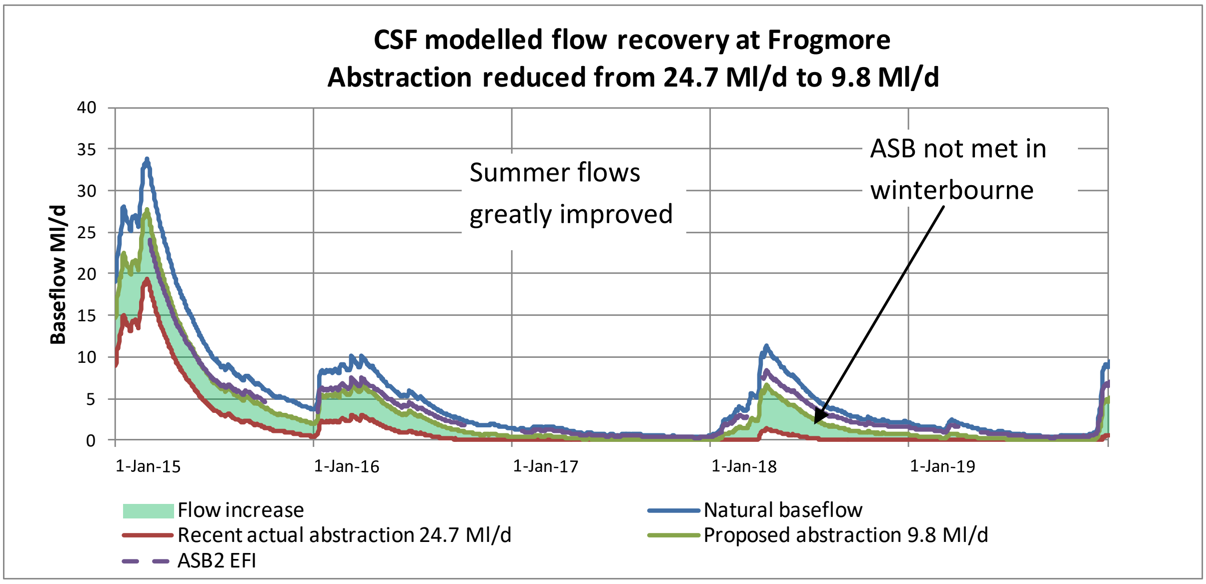


Figure C22 - CSF modelled Beane flow recovery at 9.8 Ml/d abstraction, 2015-2019

The plots shown in Figure C22 cover two ‘average’ years, 2015 and 2016, and the drought of 2018-19. It can be seen that the reduction of abstraction to 9.8 Ml/d gives a big improvement in flows, recovering to close to natural flows at Hartham and a big reduction in drying at Frogmore. ASB2 EFI flows at Hartham would be achieved at all times, including the drought of 2019.

It is suggested that the degree of compliance with ASB2 EFIs at Frogmore is acceptable, taking account of the great improvement in summer flows shown in the lower plot in Figure C22. Compliance with the ASB2 target at Frogmore would require the total abstraction to be reduced to around 1 Ml/d, but would give only a marginal overall improvement to summer flows.

C6 Benefit of Beane flow recovery for London's supplies

The GARD model of the London supply system has been linked to the CSF Beane model to assess the deployable output (DO) gain for London's supplies if Beane abstraction is reduced from 24.7 Ml/d to 9.8 Ml/d – a reduction of 14.9 Ml/d. Modelled flow recovery at Hartham in the droughts of 1921/22 and 1933/34, the most severe droughts of the last century for London's supplies, are shown in Figure C23:

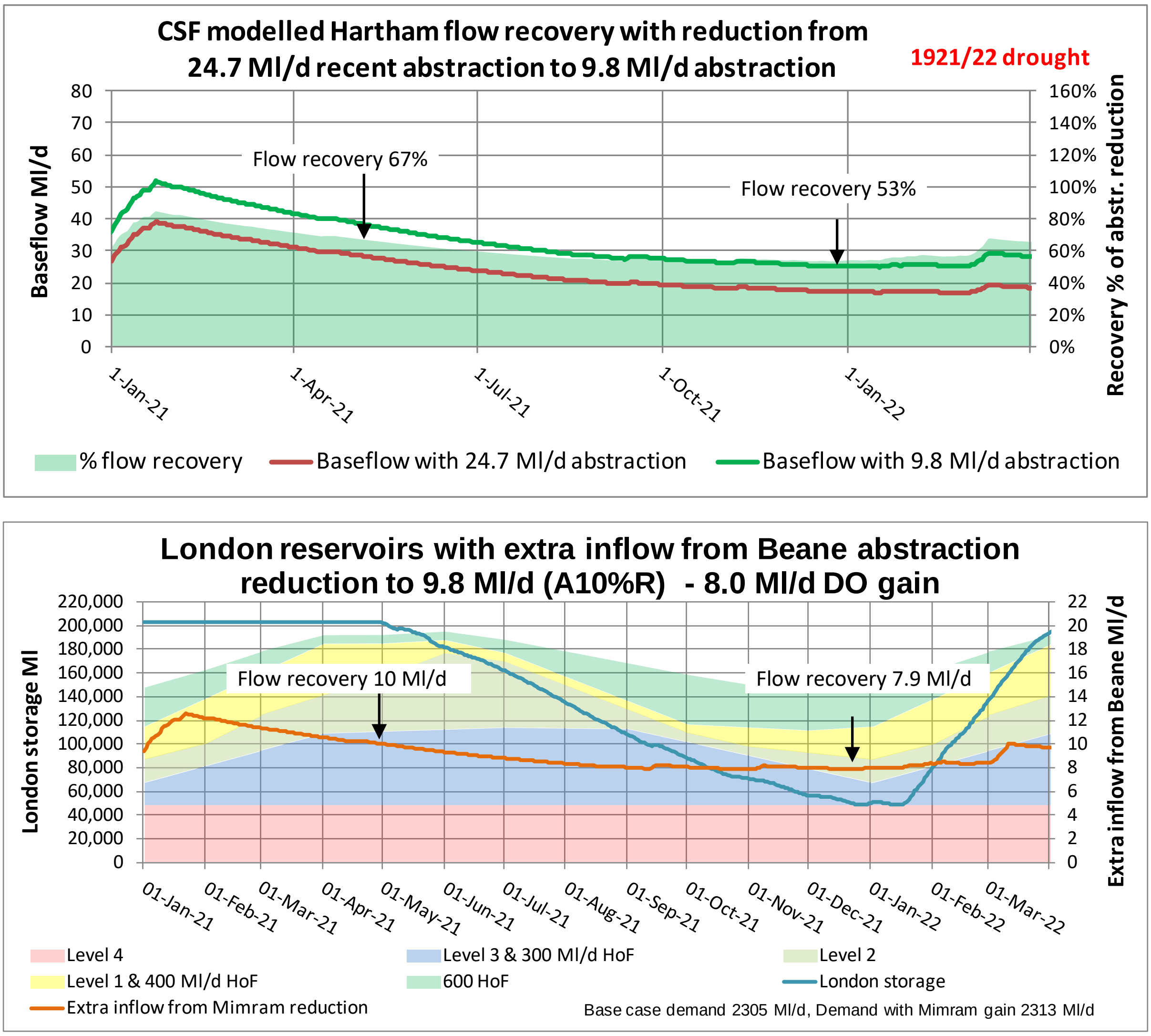


Figure C23 - Modelled river flow gain and DO gain for London in drought of 1921/22

The modelling shows a London deployable output gain of 8.0 Ml/d from the 14.9 Ml/d abstraction reduction – a recovery of 54%, substantially less than the modelled recovery for the Mimram, as described in Sections C8. The reason for the lower % recovery is the shape of the Hartham Flow vs GWL curve shown on Figure C13 which shows that when GWLs are low in droughts, gains in GWL result in very little flow gain.

C7 Comments on Affinity Water’s Beane NEP report

Affinity Water’s assessment of flow recovery from the Whitehall reduction

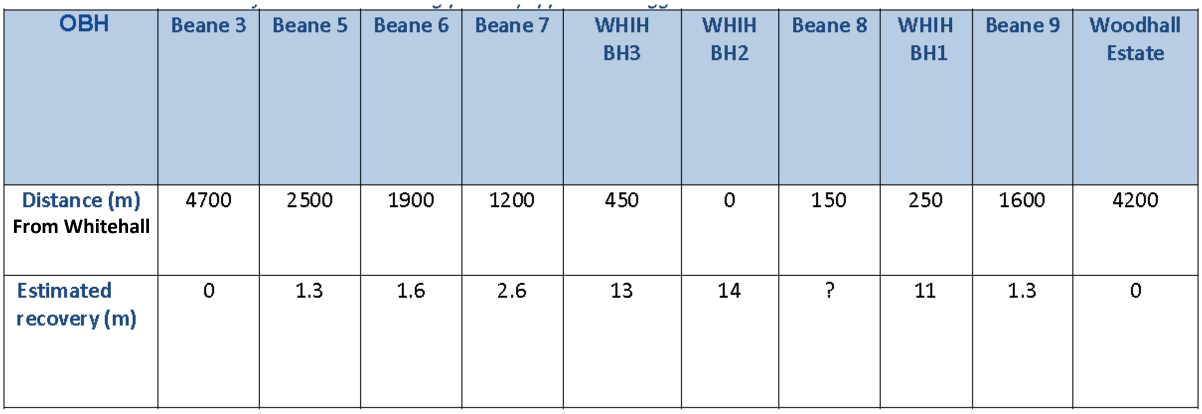
In the Summary of Affinity Water’s 2020 NEP report on the River Beane, the improvement in river flows following the Whitehall sustainability reduction was described as:

> *The inferred increase in baseflow during 2017-2019 observation periods could be in the order of 2 Ml/d. Large uncertainties remain about the potential flow improvement under average or above average groundwater conditions, as well as the groundwater and surface water interaction processes occurring at the top and middle catchment sections (page 14).*

In the NEP report conclusions, the improvement was described as:

> *No substantial change in river flow conditions has been observed as a result of the SR implementation (page 191).*
>
> *Data suggests a possible increase of baseflow of about 2 Ml/d, but it is subject to several uncertainties and it would refer to the groundwater and flow conditions experienced during the study period (page 191).*
>
> *Some potential response in terms of river flow could be inferred in the section between HEFT Site2 (DS Watton-at-Stone) and Waterford) and these are possibly in the order of 2-4 Ml/d (page 191).*

Section 8 of the Beane NEP report (pages 153 to 175) describes Affinity Water’s detailed assessment of measured flow and GWL changes arising from the Whitehall reduction. The recovery of GWLs in and around the Whitehall cone of depression is shown in Table C2:



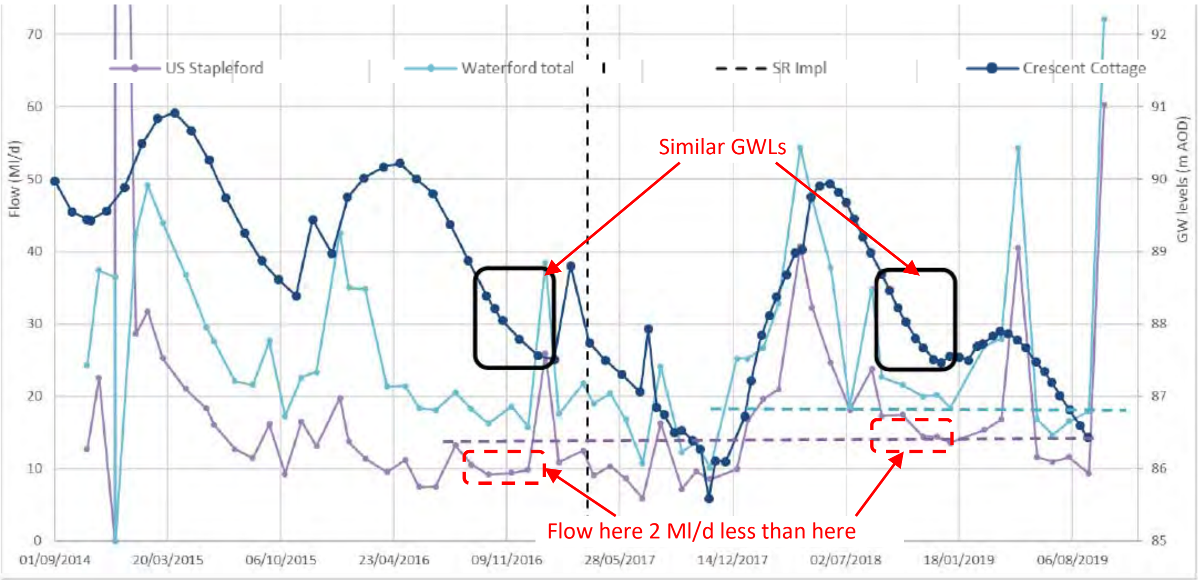
OBH	Beane 3	Beane 5	Beane 6	Beane 7	WHIH BH3	WHIH BH2	Beane 8	WHIH BH1	Beane 9	Woodhall Estate
Distance (m) **From Whitehall**	4700	2500	1900	1200	450	0	150	250	1600	4200
Estimated recovery (m)	0	1.3	1.6	2.6	13	14	?	11	1.3	0

Copied from Beane NEP report Table 27

Table C2 - Measured GWL recoveries after Whitehall reduction

The GWL recoveries shown in Table C2 were gained within about 9 months of the Whitehall reduction. However, these are only the recoveries within the cone of depression and they would have been superimposed on the recovery in regional groundwater levels. CSF modelling predicts regional GWLs would have risen by only 0.7 m within 9 months, as shown in Figure C20, and full recovery of regional GWLs would take at least 18 months.

The NEP report estimated 2 Ml/d flow gain from the Whitehall reduction was based on a comparison of spot gauged flows in two periods, before and after the reduction, when GWLs were almost the same – August to November 2015 and August to November 2018, as shown in Figure C24:



Plot copied from Beane NEP report Figure 160

Figure C24 - NEP report estimate of 2 Ml/d flow gain from Whitehall reduction

There appear to be some fundamental flaws in this estimate of only 2 Ml/d flow gain:

1. Based on the premise of a constant relationship between regional GWLs and flows, as explained in main report Section 2.1, if the GWLs are the same, the flows should be the same. Therefore, there should have been no expectation of any flow increase when comparing these two periods with similar GWLs.

2. CSF's modelling of the Whitehall reduction, as plotted on Figure C18, shows only a 4 Ml/d flow increase by late summer 2018, 18 months after the reduction. Groundwater levels were low throughout this period, so flow recovery would be expected to be low, as explained in main report Section 2.4.

3. The reliability of spot gauging in measuring such a small baseflow increase is also questionable, bearing in mind that the spot gaugings include surface run-off. Baseflow separation of the gauged daily Hartham flows shows significant surface flow contributions on the days of the spot gaugings in 2015, and lot less in 2018.

There was also a comparison of Beane and Misbourne flows, before and after the Whitehall reduction, which showed some Beane flow gains relative to the Misbourne, but without reaching any firm conclusions (pages 163-165).

The NEP report explained the perceived lack of flow recovery by arguing that the abstraction was taken from a separate chalk aquifer beneath impermeable layers (pages 173-175). However, the report recognises the lack of evidence to support this theory (page 175):

> *"The concept of a multi-layer aquifer system developed through the AMP6 investigation and therefore there are not many direct monitoring data to corroborate it."*

On the contrary, the observation borehole data show evidence that the shallow and deep aquifer levels at Whitehall are connected:

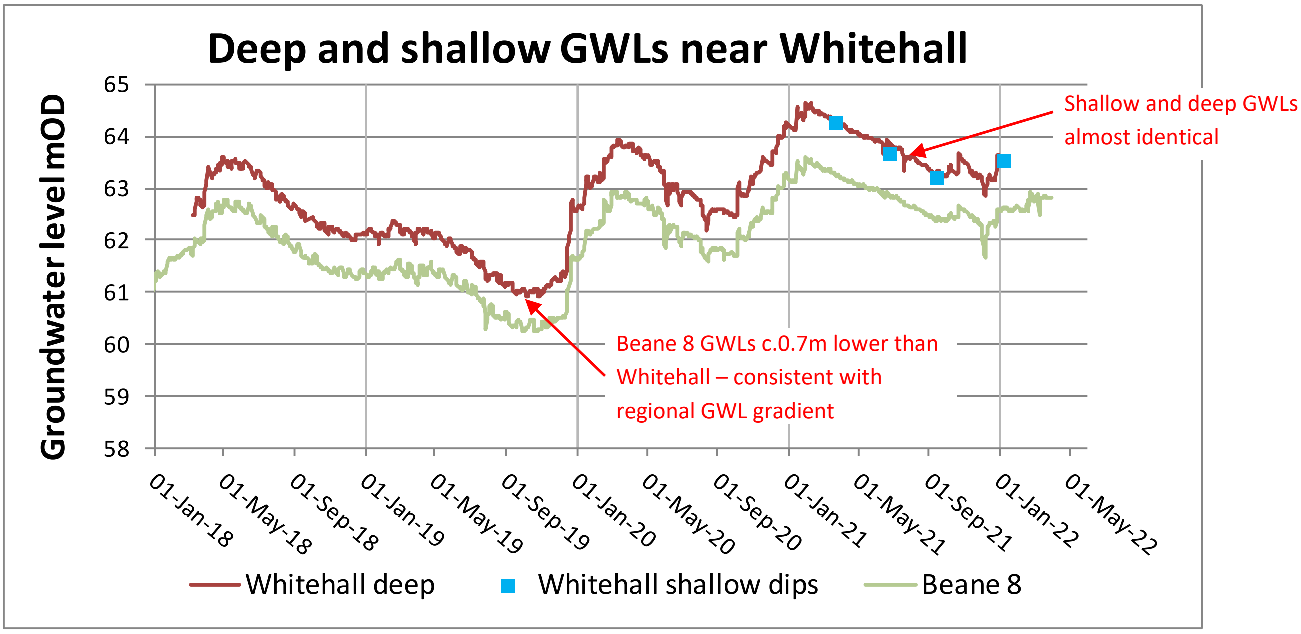


Figure C25 - Evidence of connection between deep and shallow aquifers at Whitehall

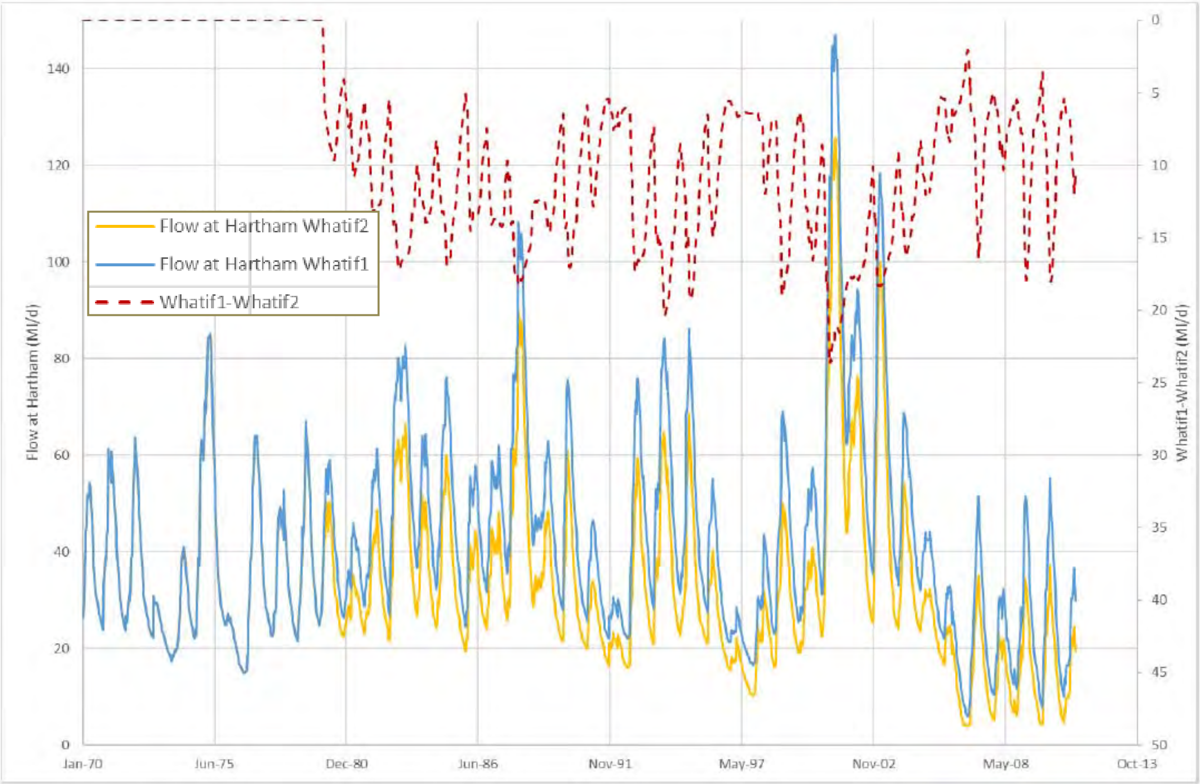
The shallow Whitehall GWLs are almost identical to the deep GWLs. The shallow Beane 8 OBH is located about 300m from Whitehall, down-gradient on the regional GWL contours. The Beane 8 GWLs are about 0.7m below the Whitehall GWLs, as would be expected from the approximately 0.004 gradient on the GWL contours. The seasonal fluctuations of the deep and shallow GWLs are a close match, as they are for all the catchment OBHs (see Figure C9). This all points to strong hydraulic connectivity between the deep and shallow chalk layers.

NEP report modelling of the Whitehall sustainability reduction

The HRGM model covering the post-2015 period was not available for the NEP report to simulate the actual Whitehall reduction. Therefore, 1980 was selected as being a similar year to 2017 and the model simulated the effect of a 15 Ml/d reduction in the Whitehall abstraction, starting in 1980 (NEP report page 176).

The modelling concluded that groundwater levels would rise by in the range 0.5 to 2.7m at OBH Beane 9, located about 1.6 km down-gradient of Whitehall (page 176).

The HRGM model predicted that flows at Hartham would increase as shown in Figure C26:



Copied from Beane NEP report Figure 162

Note: Whatif1 assumes 15 Ml/d abstraction reduction; Whatif1 assumes no reduction

Figure C 26 - HRGM modelling of 15 Ml/d abstraction reduction at Whitehall

The NEP states that modelled flows at Hartham increased by an average of 8 Ml/d, with a minimum rise of 2 Ml/d and a maximum rise of 23 Ml/d (page 177). Judging the flow increases in Figure C26 (red dotted line) by eye, the average increase of 8 Ml/d looks too low.

The modelled flow increases did not match the NEP report's perception that the flow gain was only 2 Ml/d, or the report's concept of impermeable layers over-lying the deep aquifer which would limit the flow gains from abstraction reduction. Therefore, the report concluded that the modelling must be at fault (page 177):

> *"the difference between the modelled and the observed GS flows suggests that the connectivity between the deep aquifer and the river is more complex than the simplified numerical representation in the model"*

The NEP report, dated May 2020, refers to model refinements intended to simulate the multi-layer concept (page 179):

> *"The EA is currently undertaking refinements and modifications of the groundwater model, particularly with the introduction of low permeability layers (marl bands) and multiple aquifer units, in line with the conceptualisation included in this report".*

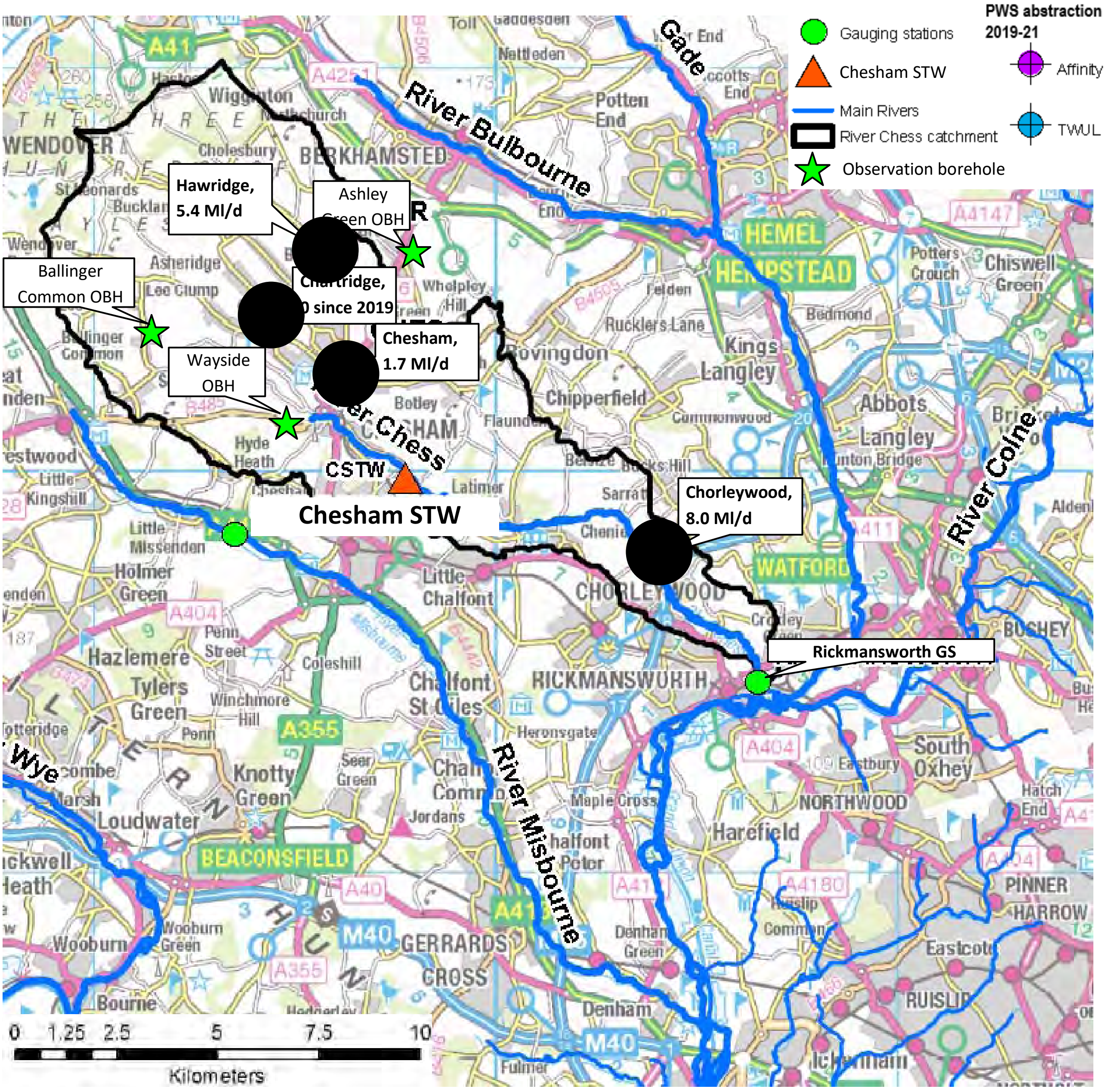
Outputs from the refined model have not yet been seen. However, the evidence of the observation boreholes as described above and illustrated in Figures C9 and C25, suggests that there is strong connectivity between the deep aquifer and the river, so the HRGM and CSF modelling is still valid and flow recoveries from the Whitehall reduction will be much more than the 2 Ml/d suggested in the NEP report.

Appendix D - Chess case study

Contents

D1 Chess location, geology and abstraction history

The approximate locations of public water supply abstractions from groundwater in the Chess catchment and nearby rivers are shown in Figure D1:

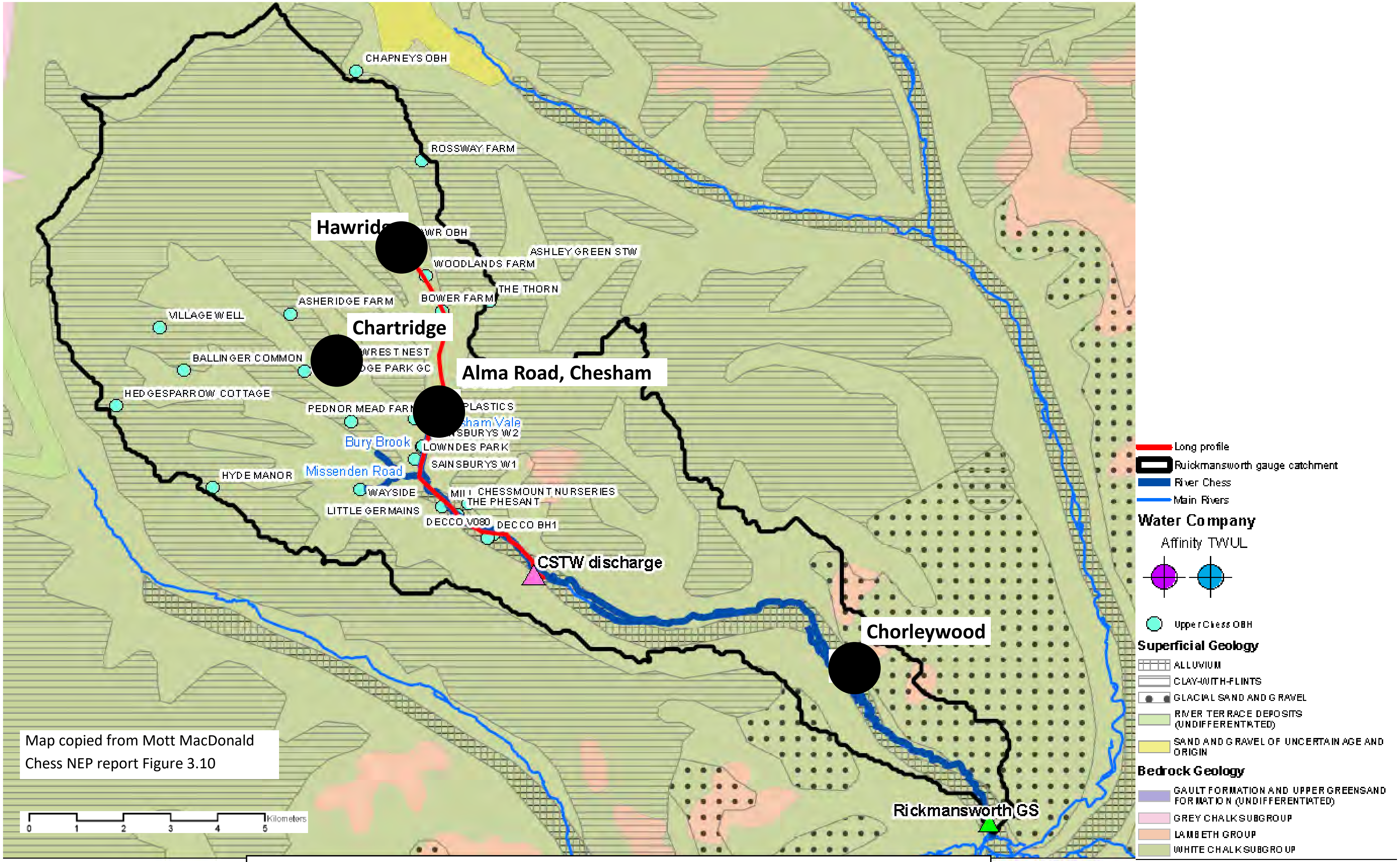


Base map copied from Chess NEP report Figure 1.1

Figure D1 - Chess catchment and abstraction locations

Much the largest Chess abstraction is at Chorleywood in the lower Chess catchment. Chesham sewage works has a dry weather flow of about 10 Ml/d, which supports river flows downstream of Chesham, providing almost all the flow at Rickmansworth in droughts (see later). The Chess NEP report focused only on the river upstream of the sewage works.

The bedrock and superficial geology of the Chess catchment are shown on Figure D2.



Map copied from Mott MacDonald Chess NEP report Figure 3.10

Figure D2 - Solid and drift geology of River Chess, with PWS borehole locations

The growths in abstraction in the Chess catchment and Colne chalk are shown in Figure D3:

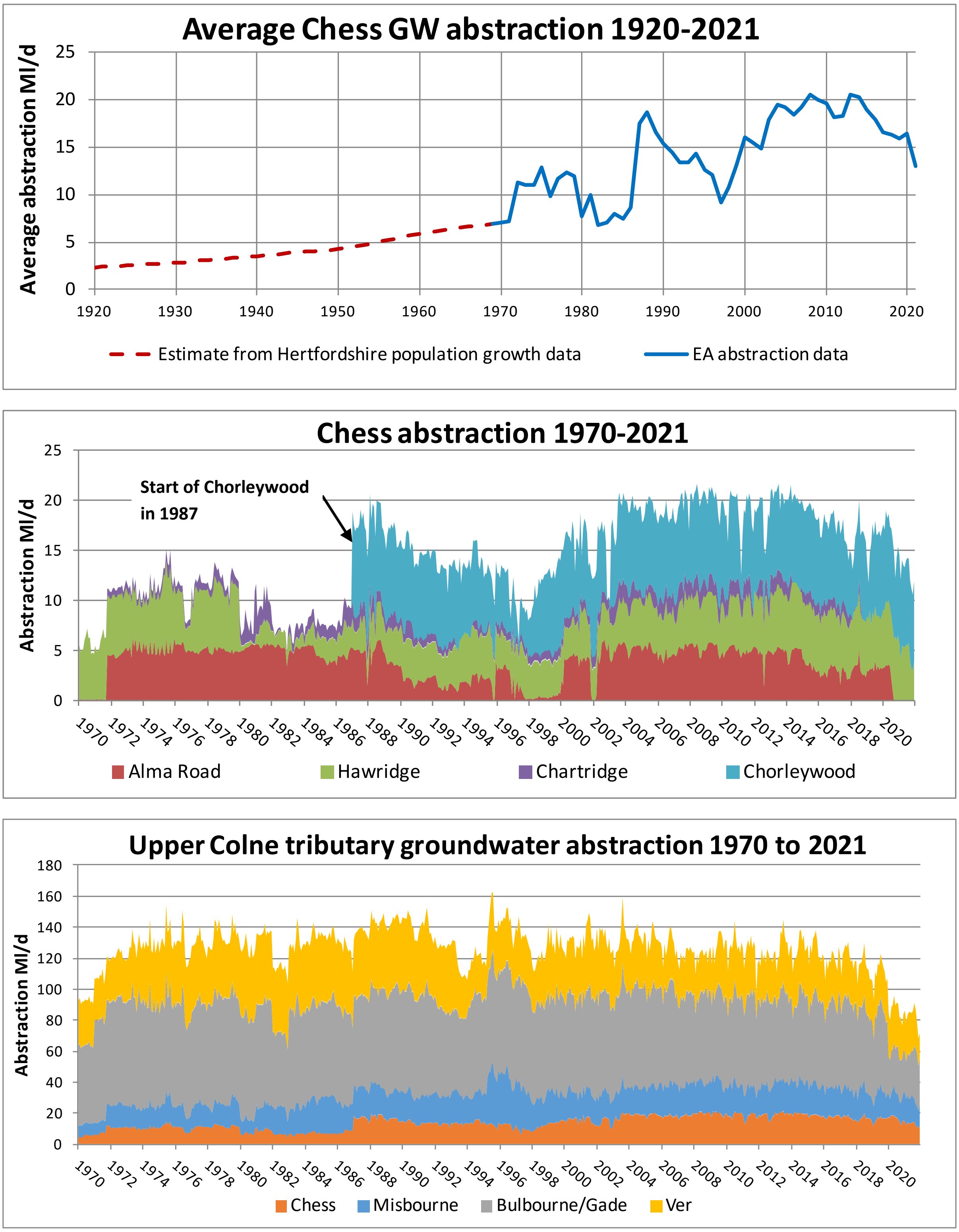


Figure D3 - Abstraction growth in Chess and upper Colne tributaries

Figure D3 shows that abstraction in the Chess catchment doubled when Thames Water's Chorley wood abstraction started in 1987. The small abstraction at Chartridge stopped in December 2018 and the abstraction at Alma Road Chesham stopped in September 2020.

D2 Measured flow changes arising from abstraction changes

As mentioned in Appendix A when considering the measured effect of abstraction changes in the Ver catchment, flow changes from abstraction reductions can only be reliably measured by comparing flow duration curves if there are:

- Similarly lengthy periods, at least 10 years each, containing comparable droughts
- Substantial and sustained differences in abstraction between the two periods

Neither of these criteria is met by the abstraction changes in the Chess catchment shown on Figure D3. However, comparison of relative flows and abstractions in the Ver and Chess catchments shows substantial relative flow changes arising from the relative abstraction changes as shown in Figure D4:

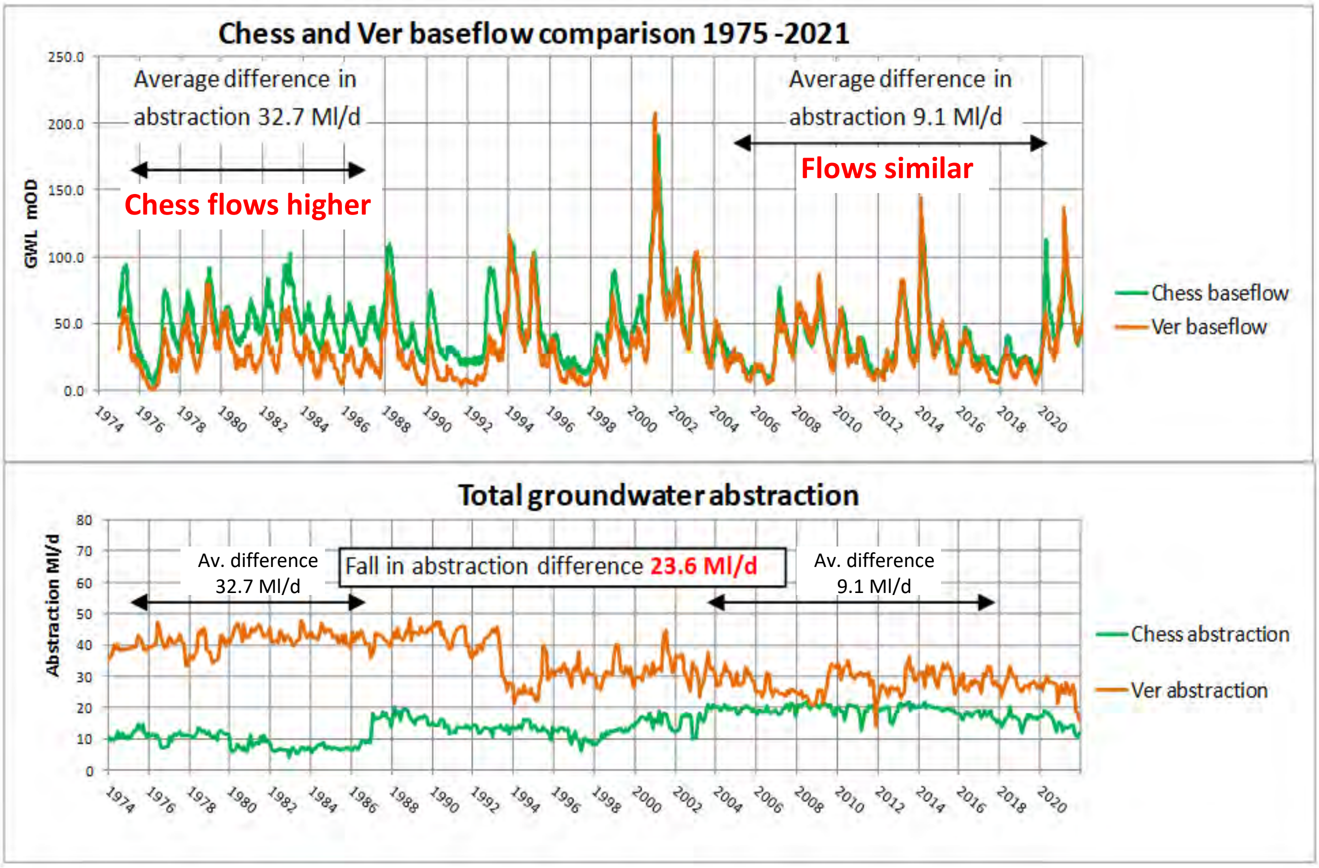
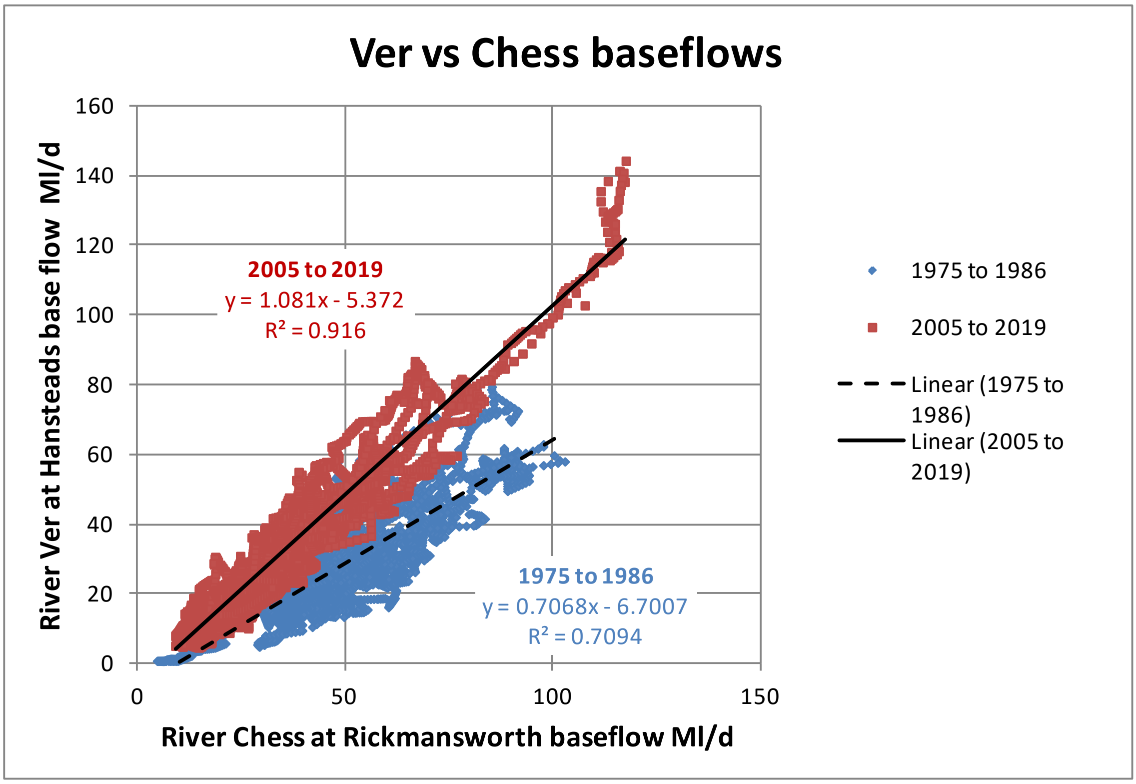


Figure D4 – Relative changes in Chess vs Ver abstractions and flows

This shows that flows in the Chess at Rickmansworth were clearly more than Ver flows at Hanstead before the start of the Chorley wood abstraction in 1987. The magnitude of the relative flow impacts from the relative abstraction changes are shown by plotting Ver vs Chess baseflows in Figure D5, comparing the relationship prior to the start of the Chorleywood abstraction (1975-86) with the relationship after various abstraction reductions (2005-2019):



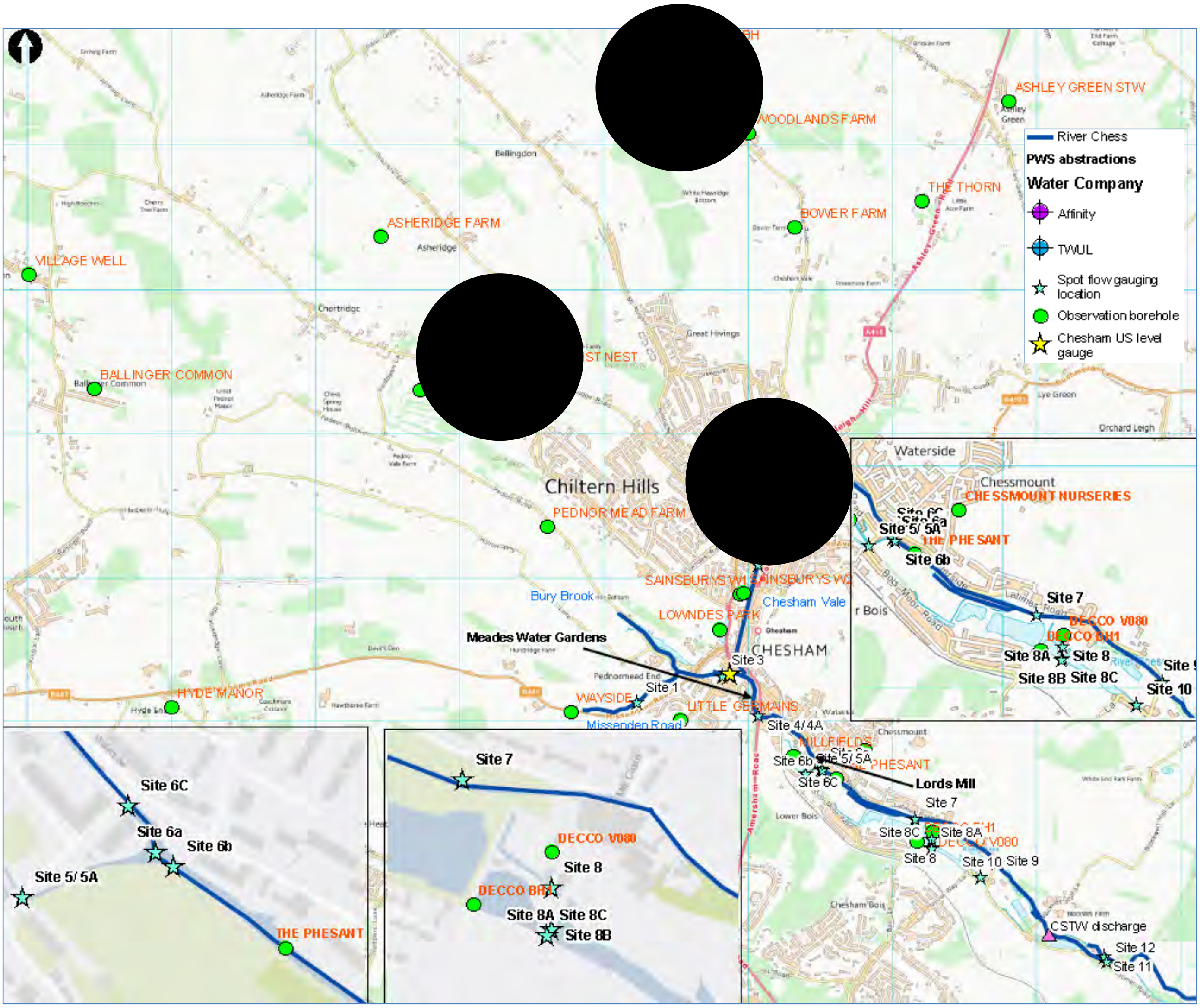
	Chess flow Ml/d	Relative Ver flow gain 1975-86 vs 2005-18 Ml/d	Gain as % of 23.7 Ml/d relative change in abstraction
Q99	10.3	5.2	22%
Q95	14.0	6.6	28%
Q50	39.7	16.2	69%
Q20	61.8	24.4	104%
Q5	89.9	34.9	148%

Figure D5 - Magnitude of relative Chess-Ver flow changes after abstraction changes

This shows that the 23.7 Ml/d relative change in abstraction generated relative flow changes of 5.2 Ml/d (22%) at Chess Q99 flows, rising to 16.2 Ml/d (69%) change at median flows and 34.9 Ml/d (148%) at Q5 flows. The magnitude and pattern of the abstraction-driven flow changes are similar to those derived using the same methodology, comparing flows in the Rivers Beane and Rib, as described in Appendix C. The abstraction driven flow changes are also similar to those measured and modelled following the Friar’s Wash abstraction reduction in the River Ver, as described in Appendix A.

D3 Relationship between Chess flows and GWLs

In addition to the EA’s Ballinger Common, Ashley Green and Wayside observation boreholes shown on Figure D1, as part of the NEP investigation Affinity Water have collected data at a number of OBHs and spot flow gauging sites in the upper catchment as shown on Figure D6:



Map copied from Figure 3.2 in Mott MacDonald Chess NEP report

Figure D6 – Observation borehole and spot gauging sites in the upper Chess catchment

Groundwater levels and river flows in the Chess catchment are closely linked in the manner described in main report Section 2.2. This can be seen in the plot of GWLs and river baseflows shown in Figure D7:

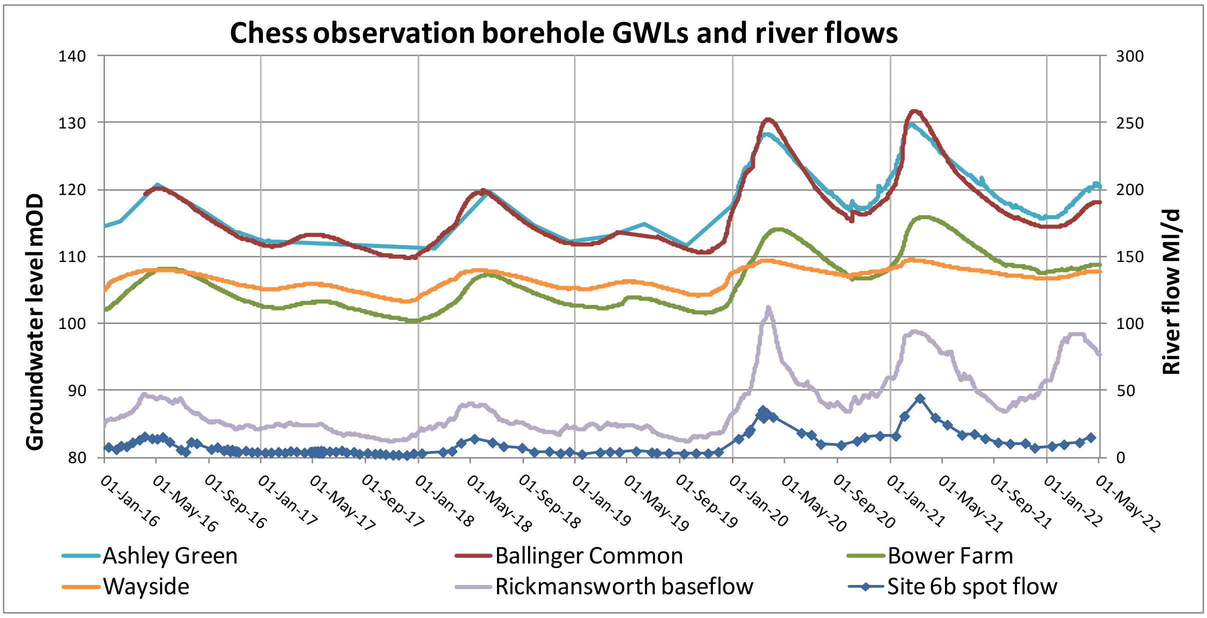
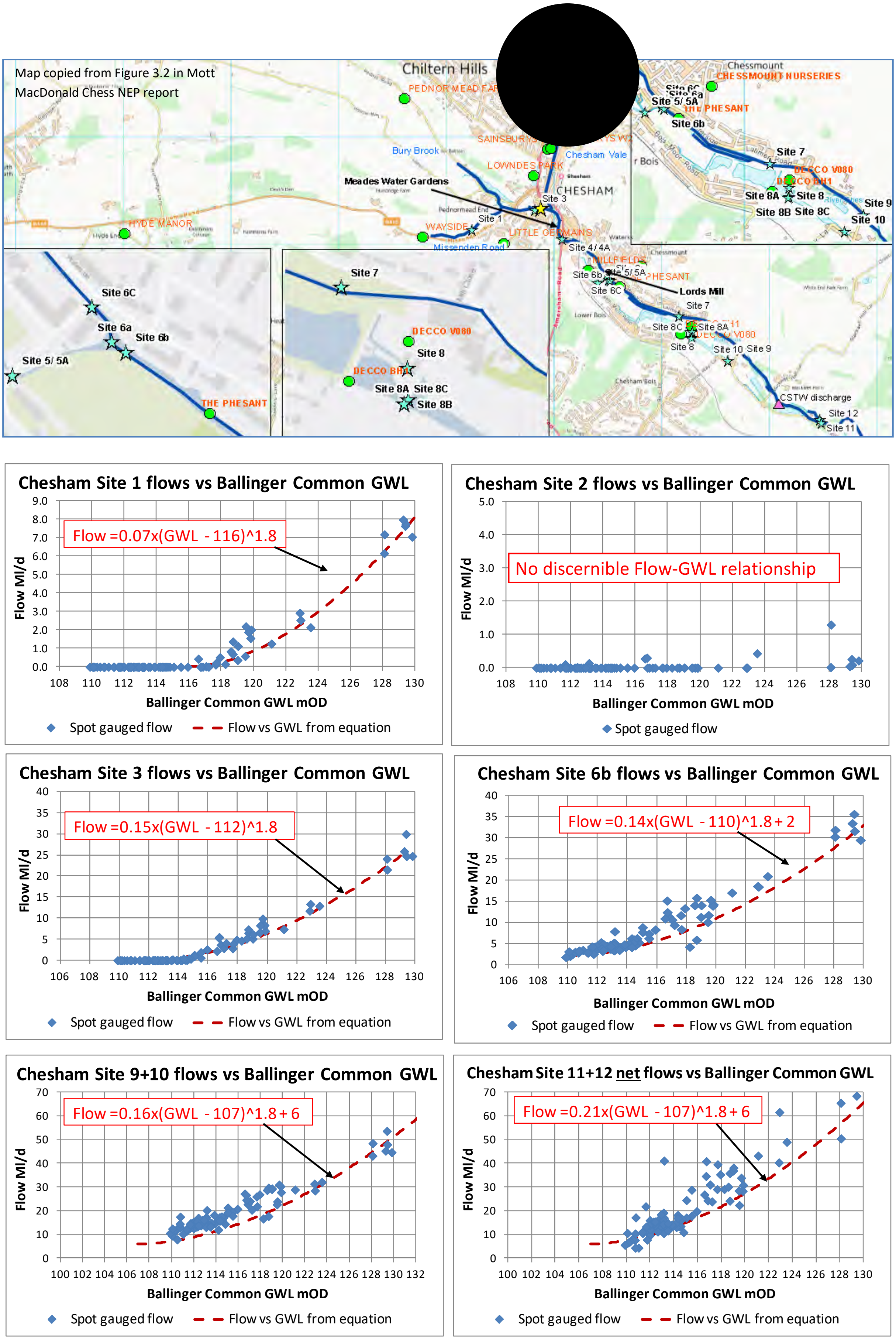


Figure D7 - Chess GWLs and flows 2016-22

Commenting on the relationships between GWLs and flows that can be seen in Figure D7:

1. All the GWLs follow a similar pattern, suggesting they are all part of the regional water table with its seasonal fluctuations.
2. The Ballinger Common and Ashley Green GWLs, although about 7 km apart, are each about 3 km from the valley bottom and have very similar amplitude of fluctuations.
3. The Bower Farm and Wayside GWLs are progressively closer to the valley bottom and have correspondingly smaller amplitudes of seasonal fluctuations.
4. The river flows in the lower Colne at Rickmansworth and in Chesham upstream of the sewage works (Site 6b) rise and fall in unison with the GWLs.

The relationship between GWLs and spot gauged flows in the vicinity of Chesham is shown for several of the spot flow locations in Figure D8:


[redacted]

Notes: 1. Spot flows may include surface run-off so are not true baseflows

2. Spot flows plotted for Sites 11+12 are net flows after deducting EA monthly recorded STW outflows

Figure D8 - Spot flow vs GWL relationships around Chesham

With the exception of Site 2, the recorded spot flows (which may include some surface flows) exhibit a strong relationship with the Ballinger Common GWLs. The stream bed at Site 2 could be too high above the water table to benefit from groundwater fed spring flows.

There are signs of artesian flows influencing the spot flows from Site 6b downwards, as evidenced by the continuous flow at the very low groundwater levels in 2019.

As with the Ver, Mimram and Beane catchments, the close relationships between GWLs and flows at all locations shows that the water table in the Chess valley behaves as a single aquifer, with river flows strongly linked to GWLs.

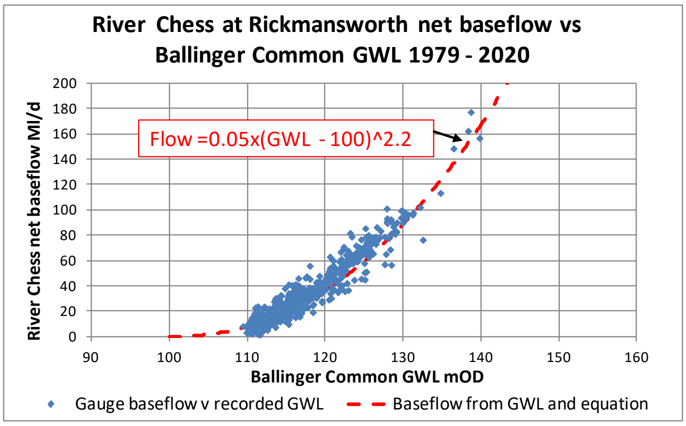
D4 Validation of CSF and HRGM models for the River Chess

CSF lumped parameter model for the River Chess

The CSF modelling methodology described in Main Report Section 2.3 has been used in a lumped parameter model for the River Chess. The model features are:

- Covers 102-year period 1920 to 2021, including droughts of 1921, 1934 and 1944
- Effective rain since 1920 taken from EA daily data for East Colne 6140TH
- Abstraction data from latest EA records and data used in HRGM model
- Chesham STW flow data from EA records
- Daily GWLs simulated at the Ballinger Common observation borehole site
- River flows simulated for the Rickmansworth gauge site and the spot flow gauging Sites 1, 3, 6b and 9+10 (locations shown on Figure D6)
- Effective catchment area for recharge 85 km^2 (ie less than the 105 km^2 catchment to Rickmansworth gauging station – adjusted through model calibration)

In daily calculation of the aquifer water balance, the model uses the strong relationship between river flows and GWLs shown in Figure D18:



Note: the plotted Rickmansworth baseflows are net of Chesham STW flows

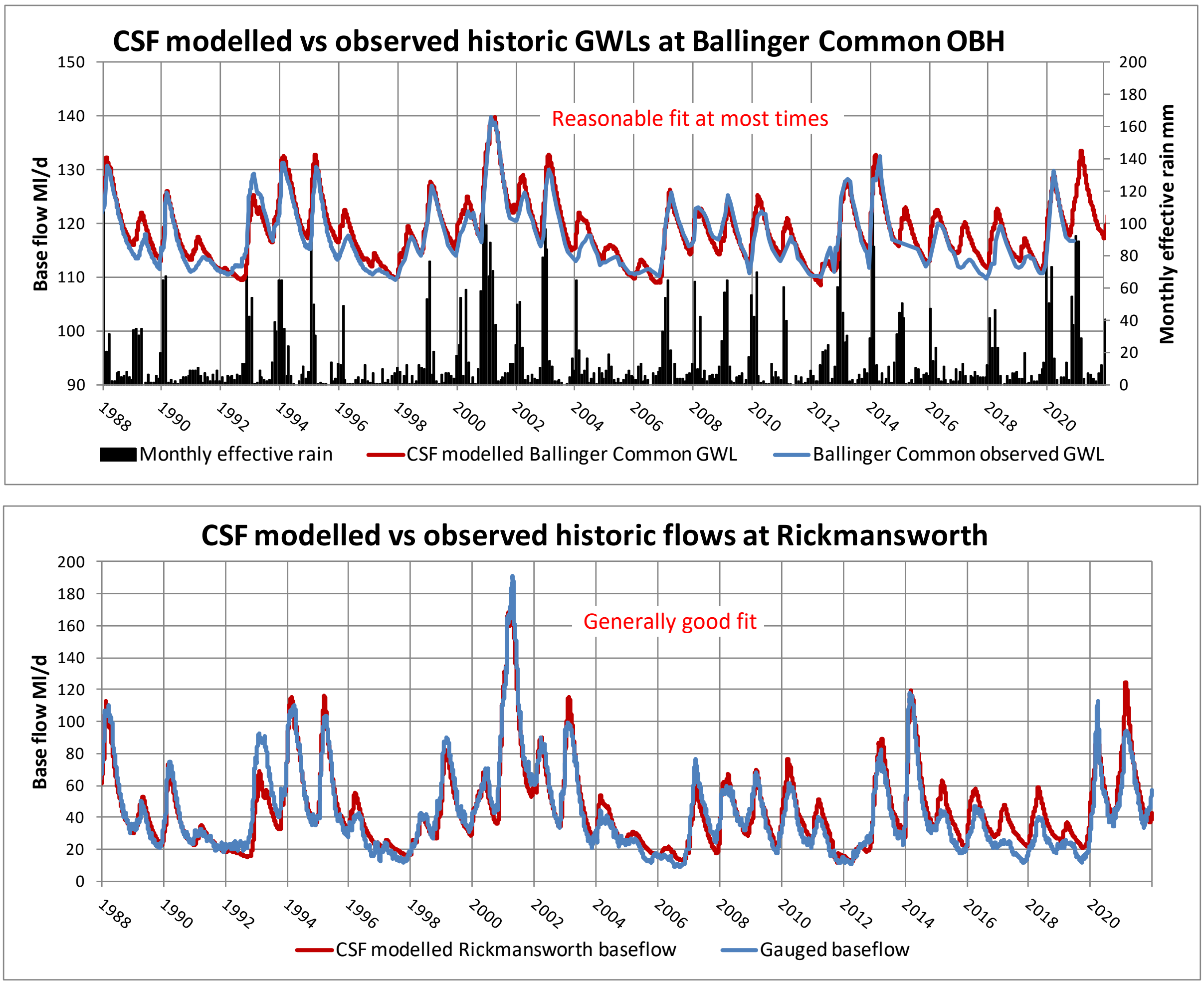
Figure D9 – Measured River Chess outflow vs GWLs used in CSF Chesham model

For simulating the flows at spot flow gauging locations, the model uses the relationships between gauged spot flows and Ballingdon Common OBH shown in Figure D8.

For modelling of the recent actual abstraction scenario of 16.5 Ml/d, starting in 1920 and ending in 2020 on a date when the modelled storage is the same as the modelled starting storage, the water balance over the 100 year period is:

Inputs	Ml/d
• Average aquifer recharge	62.9
• Average leakage from supplies to aquifer	1.5
Total inputs	64.4
Outputs	
• Average net baseflow at Rickmansworth	33.7
• Average underflow from catchment	14.2
• Average abstraction	16.5
Total outputs	64.4

The CSF model was calibrated to give best fits to recorded groundwater and river flow records in the period 1988 to 2021 (the Ballinger Common GWL record started in 1987):


CSF modelled vs observed historic GWLs at Ballinger Common OBH

Reasonable fit at most times

CSF modelled vs observed historic flows at Rickmansworth

Generally good fit

Figure D10 - Validation of CSF River Chess modelled GWLs and flows 1988-2021

As can be seen in Figure D10, the CSF model gives a close fit between modelled and historic measured Ballinger Common GWLs and Rickmansworth baseflows throughout the 30-year period, 1988 to 2020, for which the model was calibrated. More validation evidence of good fit between observed and modelled flows for the CSF model can be seen by comparing modelled and historic baseflows at Rickmansworth between 1974 and 1987, ie before the period for which the model was calibrated:

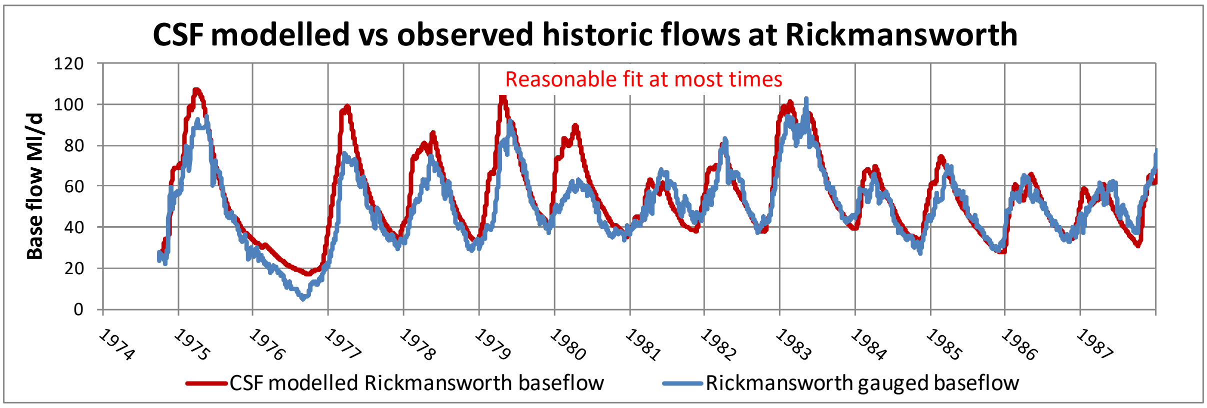


Figure D11 - CSF Chess model validation: Rickmansworth flow 1956-1990

The CSF model provides good fits between modelled baseflows and observed spot flows at the various locations around Chesham:

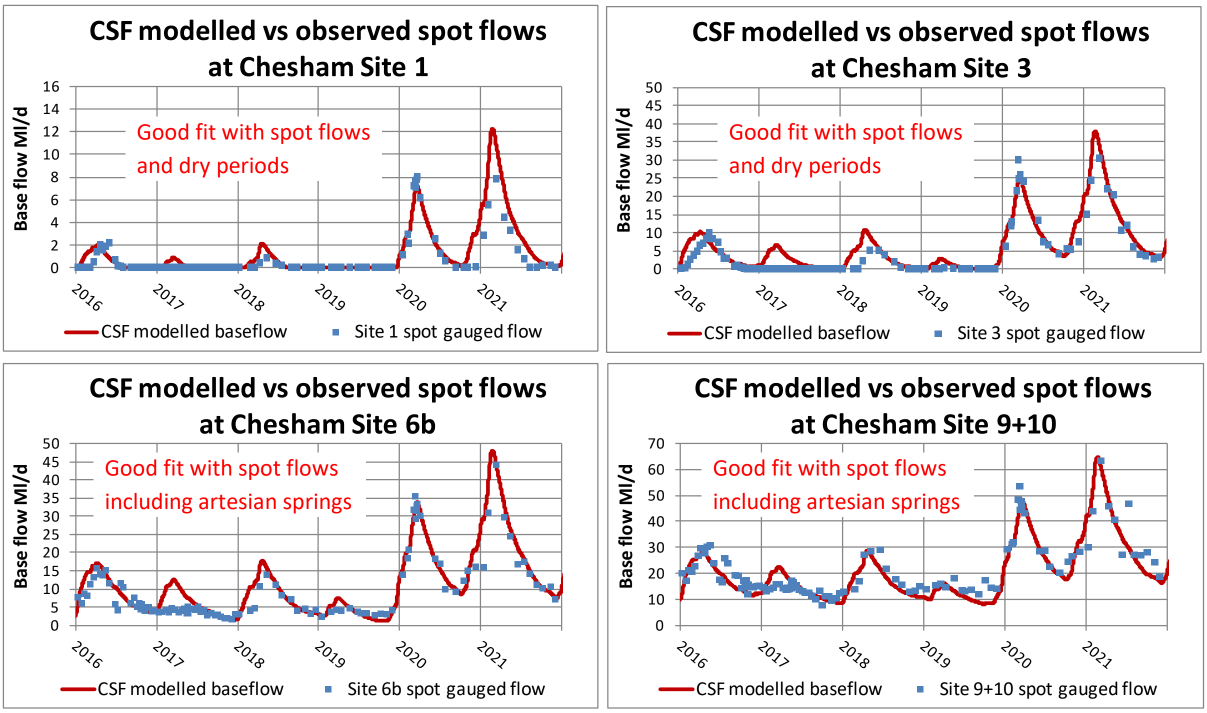


Figure D12 - Validation of CSF modelling of flows at spot flow locations around Chesham

Comparison of validation of the HRGM and CSF models

A comparison of validation plots for the HRGM and CSF models is shown in Figure D13 (the HRGM model output was only available up to 2015):

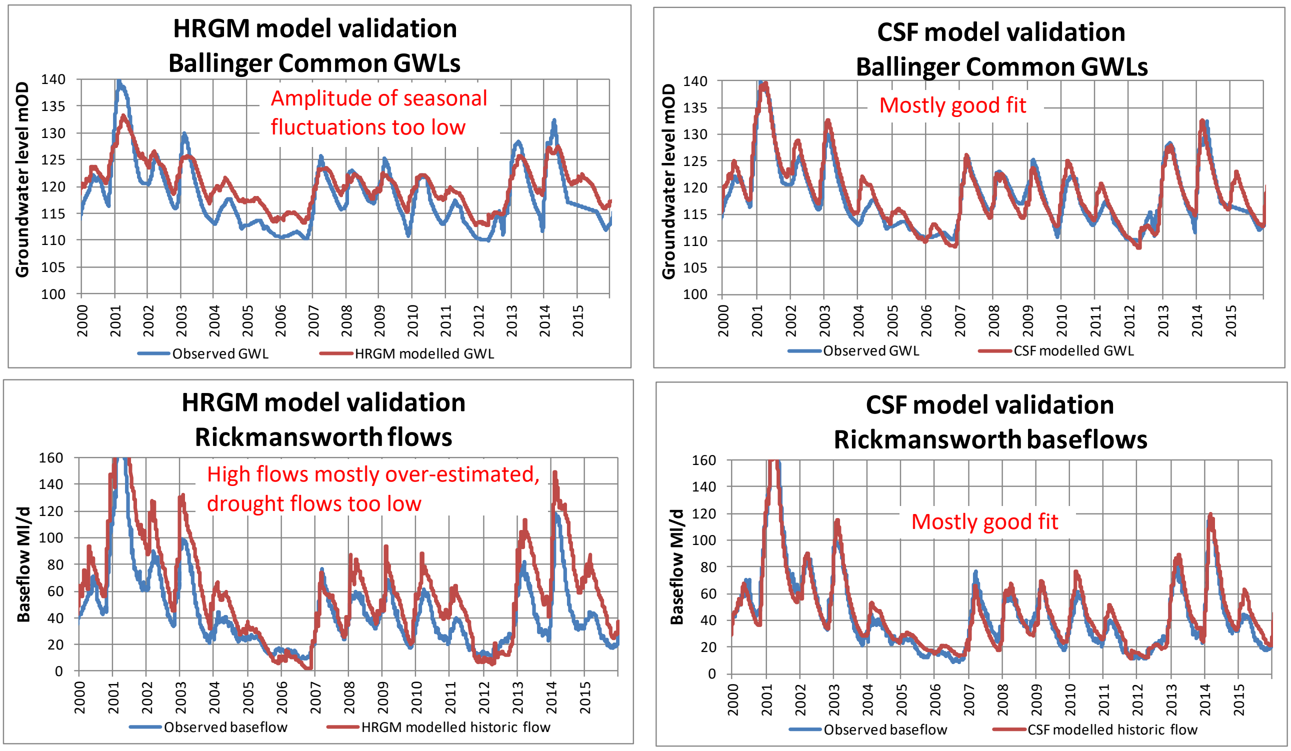


Figure D13 - Comparison of validation fits for HRGM and CSF Chess models

The amplitudes of the seasonal GWL fluctuations are too low in the HRGM model. The HRGM flows generally over-estimates high flows and under-estimates low flows in droughts. The CSF has mostly good fits for both GWLs and baseflows, so appears to match the historic data markedly better than the HRGM model.

At present, HRGM modelled flow data is not available at the locations of spot flow gaugings in the Chess catchment around Chesham (additional model output for spot flow gauging locations was requested on 6.12.2022). However, the NEP report suggests that the HRGM model does not effectively simulate flows around Chesham, for example on page 130:

> *The model does not represent the Bury Brook, and only partially represented the Missenden Road Stream ephemeral sources of the River Chess. As a result, the finer detail of flow in these reaches, where drying is known to occur, will not be represented. This may also cause small variations in groundwater levels in the dry valleys of the River Chess where stream cells are not represented.*

In contrast, the CSF model simulates flows around Chesham very effectively, including the contributions of the artesian springs at Sites 6b and 9+10, as shown on Figure D12.

The HRGM model does not replicate the measured relationship between Rickmansworth baseflows and Ballinger common GWLs, as shown in Figure D12:

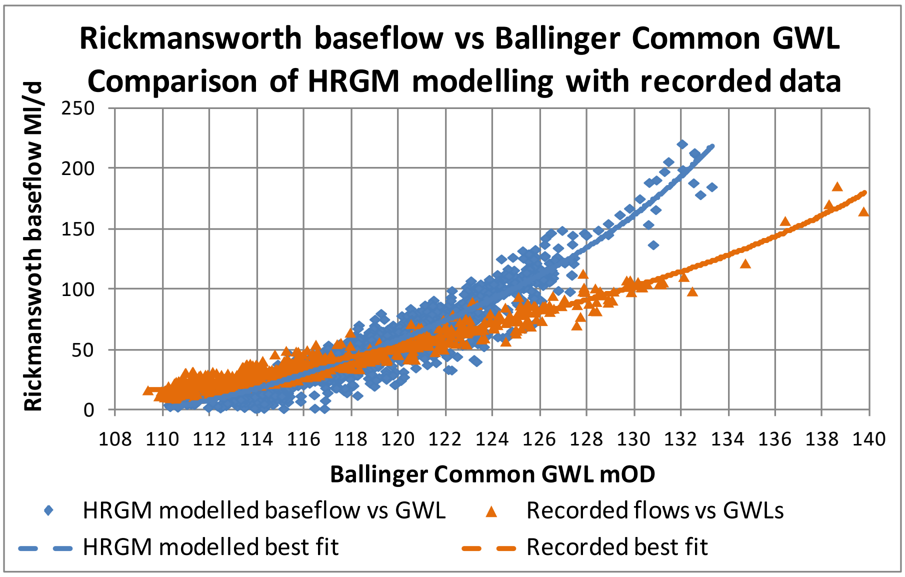


Figure D14 - HRGM Chess model validation comparing Flow vs GWL relationships

This poor fit to the measured 'Flow vs GWL' relationship is similar to that found in the HRGM Ver modelling in Figure A14 in Appendix A.

D5 Modelling of 'recent actual' abstraction impacts on the Chess

Modelling of abstraction impacts and EFI compliance for the Chess at Rickmansworth is complicated by the influence of effluent from Chesham sewage works, with a recent dry weather flow of about 11 Ml/d. An example of the influence of the Chesham STW effluent on flows at Rickmansworth in the drought of 2005-06 is shown in Figure D15:

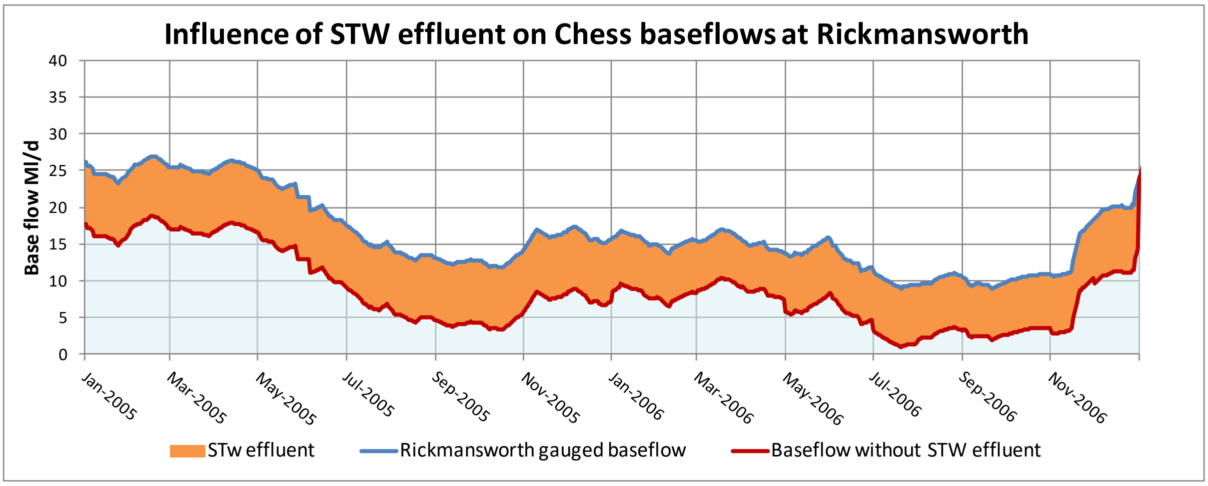
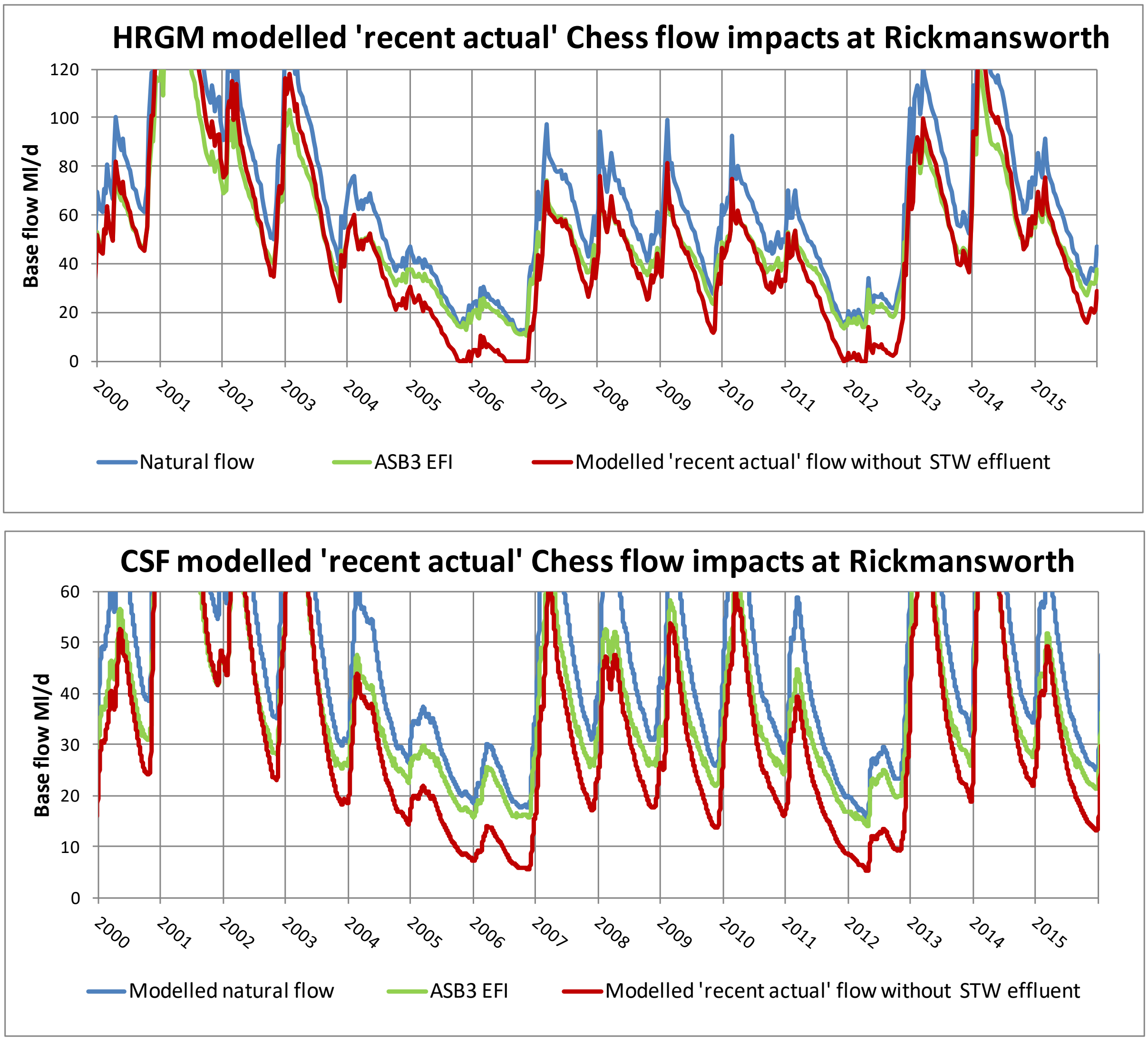


Figure D15 – Effect of STW effluent on Chess baseflow in 2005-06 drought

In the 2005-06 drought, the STW effluent of about 8.5 Ml/d comprised almost all the River Chess flow and the river would have been virtually dry at Rickmansworth without it. Therefore, in assessing the impact of recent actual abstraction and compliance with EFIs, it is better to model baseflows net of the STW effluents, rather than baseflows artificially raised by the STW effluents.

The available HRGM modelling of 'recent actual' abstraction is understood to have assumed a total Chess abstraction of 19.3 Ml/d and total STW effluent return of 10.9 Ml/d, as per the EA file *'HERTS Artificial Influences Overview_Red.xlsx'*. These values are assumed to be averages for 2013-15. HRGM and CSF modelling of these 'recent actual' baseflows net of STW effluents are compared in Figure D16:



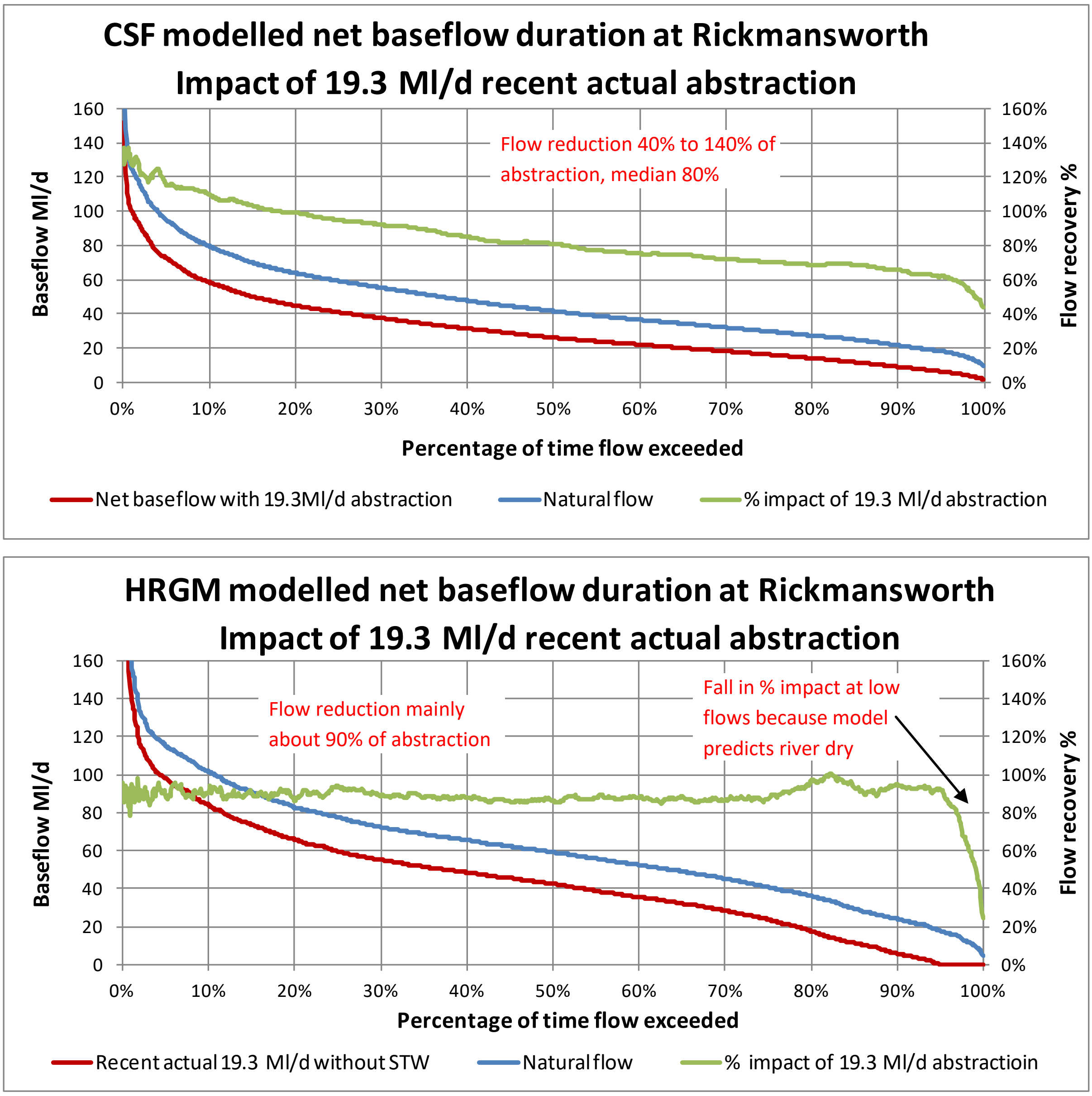
Notes:

1. The modelled flows are net of STW effluents.
2. The 'recent actual' abstraction of 19.3 Ml/d is as used in HRGM modelling in 2015.

Figure D 16 – Modelled impacts of 'recent actual' 19.3 Ml/d abstraction at Rickmansworth

Both models show that, with abstraction of 19.3 Ml/d there is substantial non-compliance with the ASB3 EFI at most times.

The impact of recent actual abstraction of 19.3 Ml/d on 'without STW effluent' baseflow durations at Rickmansworth is shown on Figure D17, which also shows the flow reduction from natural as a percentage of the 19.3 Ml/d abstraction:



Note: ‘net baseflows’ exclude contributions from STW effluents

Figure D17 - Modelled flow duration impacts at Rickmansworth of 19.3 Ml/d recent abstraction

The CSF model shows that flow reduction as a % of abstraction rises from around 40% at low flows to 140% at high flows, with a median of about 80% recovery. This pattern of recovery is as explained in main report Section 2.4. The HRGM modelling shows flow reduction of mostly around 90% of abstraction. The HRGM predicted sharp fall in % reduction at low flows is the consequence of the HRGM model’s prediction of zero net baseflows at flows less than Q95.

Since 2015, total Chess abstraction has fallen slightly to an average of 15.1 Ml/d in 2019-21. CSF modelling of flow impacts at Site 6b in Chesham with the recent total Chess abstraction of 15.1 Ml/d is shown in Figure D18:

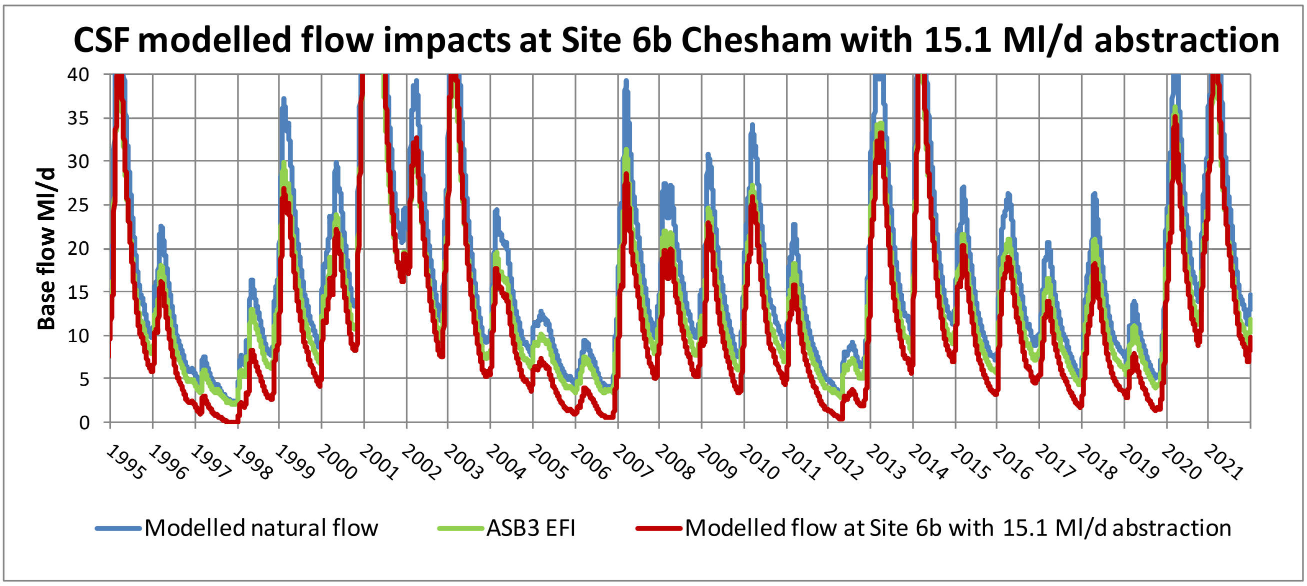


Figure D18 - Flow impacts and EFI compliance at Site 6b Chesham with 15.1 Ml/d abstraction

This shows that recent amounts of abstraction would caused flows to fall well below the EFI at most times and cause the river to dry completely in severe droughts like 1997.

D6 Required abstraction reduction in the Chess catchment

The two methodologies available for determining acceptable abstraction – using either EFIs or A%R – give somewhat different results for required abstraction reduction in the Chess catchment.

The EFI methodology gives a recent actual EFI low flow deficit of 12.9 Ml/d at Q95, assuming that the Chess is in the medium sensitivity band ASB2. The EFI methodology allows for STW effluent to give an acceptable total Chess abstraction of 9.8 Ml/d, determined as in Table D1:

River Assessment Point	**Calculated Natural Low Flow (Q95)**	**Estimated % allowable abstraction (ASB%)**	**Estimated sustainable low flow (EFI)**	**Recent Actual Q95 Flow**	**Flow Deficit to EFI at low flow (Q95)**	Abstraction Sensitvity Band	Sustainable abstraction quantity at low flows	Cumulative Discharges	**Available to Abstract (Nat +Dis - EFI)**	Groundwater Abstraction impact on Flow
Lower Chess	19.6	15%	16.7	11.5	5.2	ASB2	2.9	6.9	**9.8 Ml/d**	15
Comments	HRGM shows 18.0 Ml/d	CaBA proposes ASB3, so 10%	16.2 with 18.0 Q95 and ASB3	HRGM shows 11.0	ie 16.7-5.2	CaBA proposes ASB3	ie 19.6-16.7	EA records show about 12 Ml/d	**Would be higher with recent dwf**	

Notes: 1. Copied from EA worksheet ‘Chilterns flow deficits 2020.xlxs’ provided by EA email dated 9.12.2020
2. John Lawson comments in bottom row

Table D1 - EA allowable abstraction calculation for the lower River Chess

There are some questionable aspects to the calculation shown in Table D1:

- Assessment downstream of the STW discharges doesn’t consider the acceptability of river flows at and above Chesham, upstream of the STWs.
- The natural and recent actual Q95 flows in Table D1 don’t match the available HRGM model output (see comments in bottom row).

- Inclusion of the STW effluents in determining acceptable flows means that river flows comprising 100% sewage effluent are considered acceptable.
- The assumed cumulative discharges of 6.9 Ml/d is a lot less than the EA's file *'HERTS Artificial Influences Overview_Red.xlsx'*, which shows an average STW discharge of 10.9 Ml/d.
- The CaBA strategy suggests ASB3 for the Chess rather than ASB2.

Using the A%R methodology, the allowable abstraction to achieve A10%R abstraction would be 6.3 Ml/d (the CSF model allows average recharge 63 Ml/d). The modelled compliance with EFIs at Rickmansworth, net of the STW effluents, and at Chesham Site 6b is shown in Figure D19:

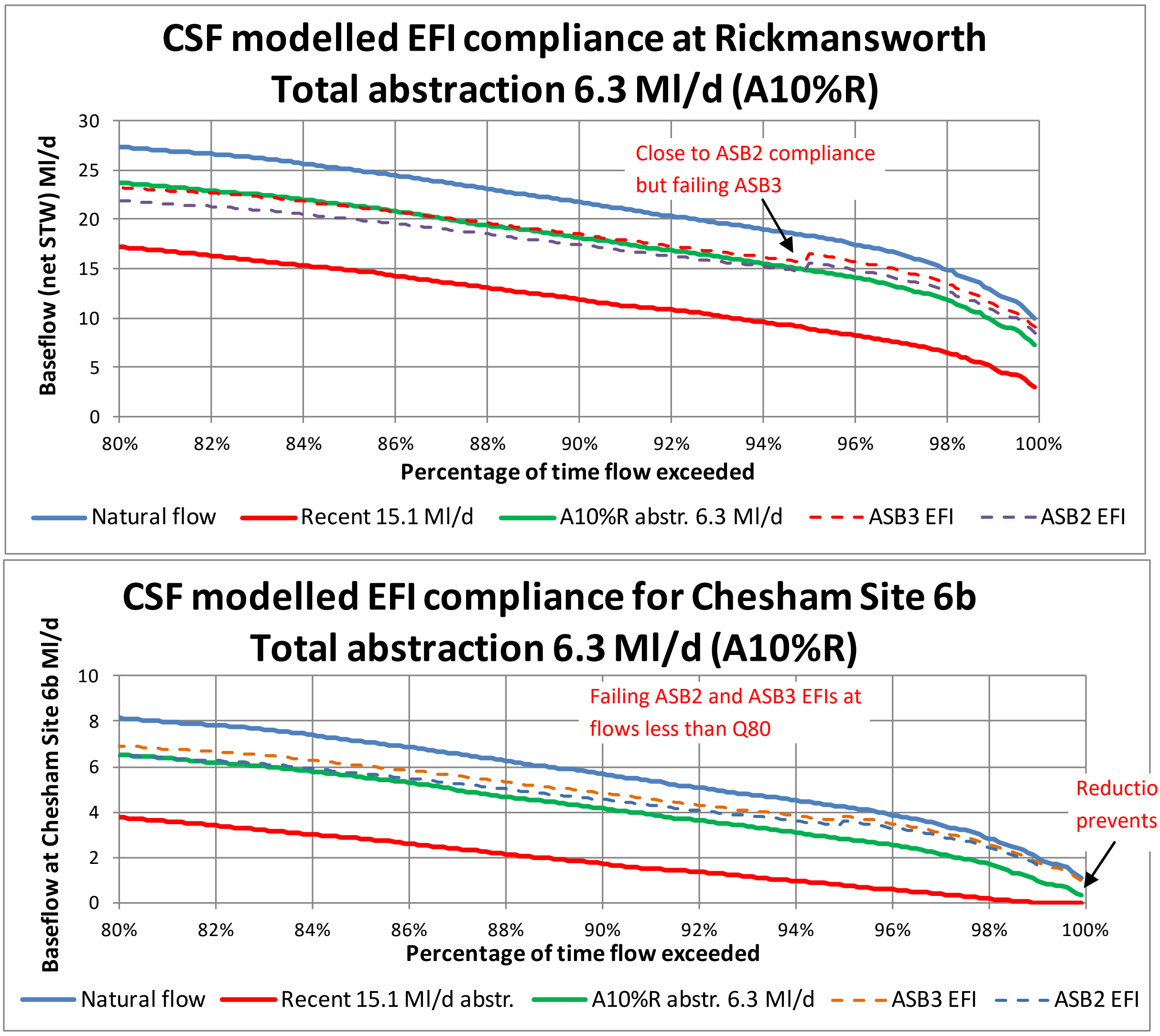


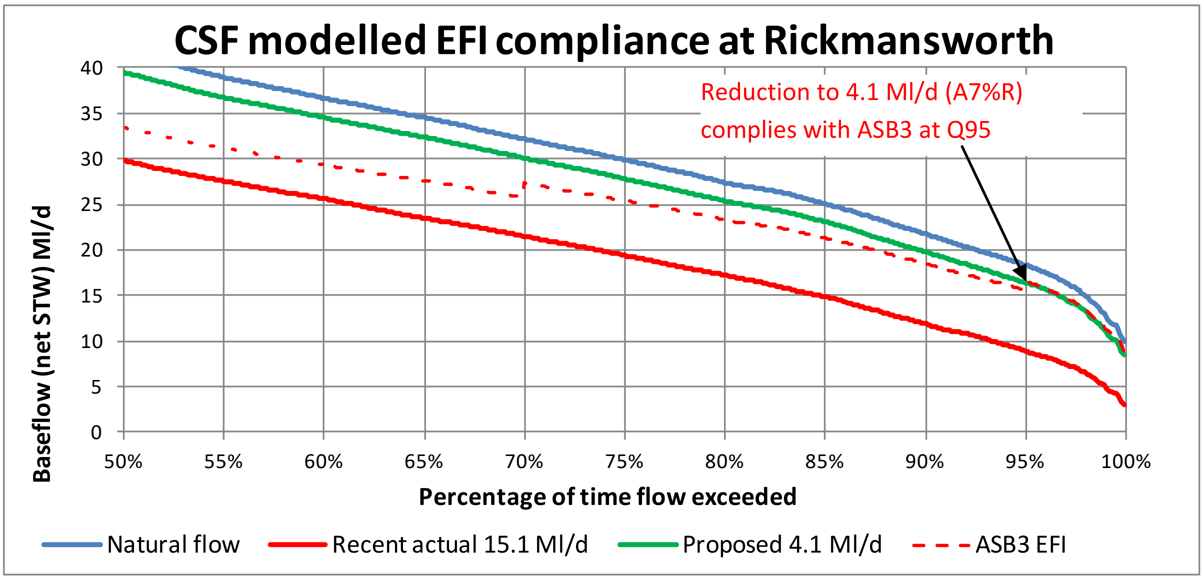
Figure D19 - CSF modelled Chess flow compliance with abstraction 10% of recharge (A10%R)

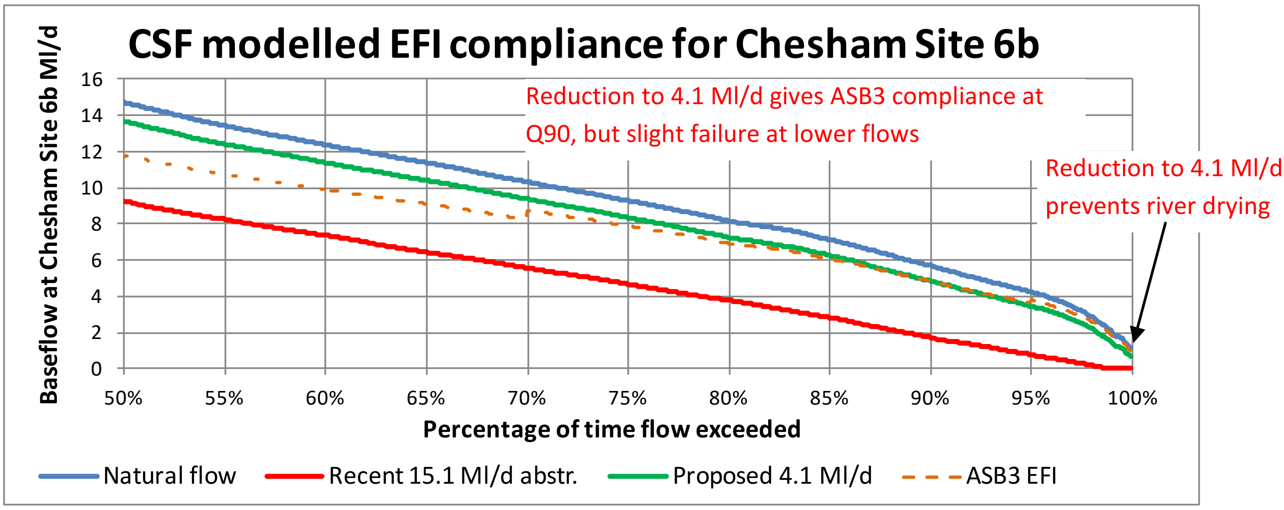
This shows that a total Chess abstraction of 6.3 Ml/d (A10%R) would almost comply with the ASB2 EFI, but not the ASB3 EFI. CSF modelling shows that compliance with ASB3, limiting flow reduction to 10% of natural flows at Q95, requires a reduction in total abstraction to 4.1 Ml/d, which is equivalent to A7%R.

D7 Modelled benefits of total Chess abstraction reduction to 4.1 Ml/d

Compliance with Environmental Flow Indicators

The CSF model has been used to assess the flow benefits from reducing abstraction to 4.1 Ml/d (A7%R). The modelled flow duration compliance with EFIs at Rickmansworth and Chesham Site 6b is shown on Figure D20:





Note: Flow durations are calculated for the full 100 years of modelled flows 1920 to 2020

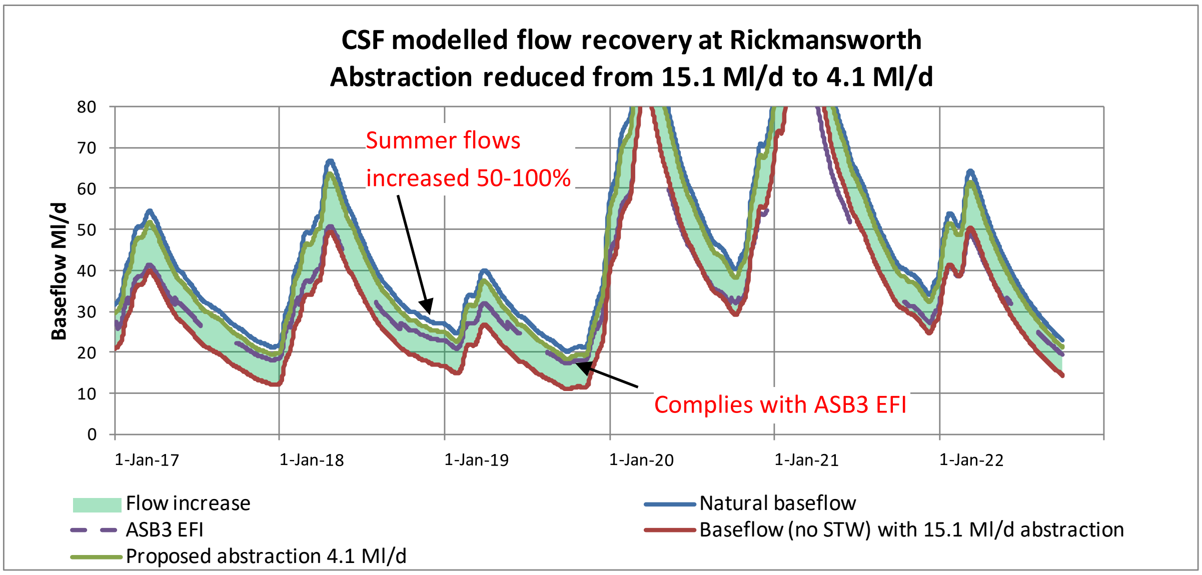
Figure D20 - CSF modelled flow compliance with abstraction cut to 4.1 Ml/d (A7%R)

As can be seen on Figure D20, reduction of total Chess abstraction to 4.1 Ml/d (equivalent to A7%R) gives Rickmansworth flow compliance with the ASB3 EFI target, without any contribution from the STW effluents.

Reduction of total abstraction to 4.1 Ml/d would prevent the river from drying at Chesham Site 6b as it probably would without the STW effluents in 1976, 1997 and 2011/12. Summer flows would be greatly increased, but would still fail the ASB3 EFI at flows below about Q90. Meeting the ASB3 EFI at Q95 at Site 6b would require the abstraction to be reduced to 3 Ml/d.

Improvement of flows in typical years

With total abstraction reduced to 4.1 Ml/d, the CSF modelled increases in flows at Rickmansworth and Chesham Site 6b for the 5-year period 2017 to summer 2022, including the 2019 drought, are shown in Figure D21:



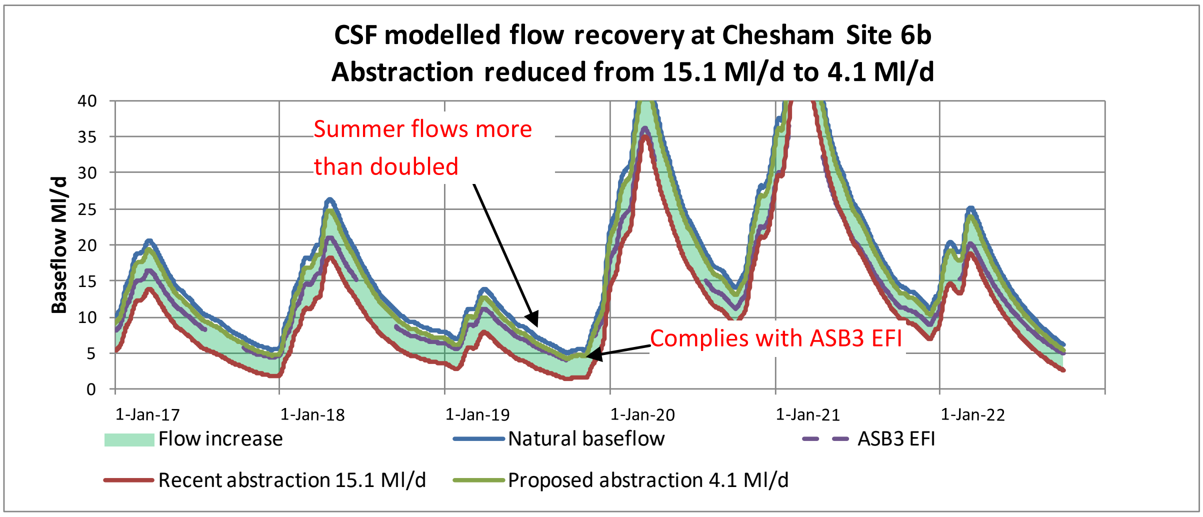


Figure D21 - CSF modelled Chess flow recovery at 4.1 Ml/d abstraction, 2017-2022

The plots shown in Figure D21 cover two ‘average’ years, 2020 and 2021, and the droughts of 2017-19. It can be seen that reduction of abstraction to 4.1 Ml/d gives a big improvement in flows, exceeding ASB3 EFI flows considerably at most times and recovering to close to natural flows at both Rickmansworth and Chesham.

Bearing in mind that actual flows at Rickmansworth would be about 10 Ml/d more than shown in Figure D21 because of the STW effluents, arguably reducing abstraction to 4.1 Ml/d for strict compliance with ASB3 is unnecessarily restrictive.

D8 Benefit of Chess flow recovery for London’s supplies

The GARD model of the London supply system has been linked to the CSF Chess model to assess the deployable output (DO) gain for London’s supplies if Chess abstraction is reduced from 15.1 Ml/d to 4.1 Ml/d – a reduction of 11.0 Ml/d. Modelled flow recovery at Rickmansworth in 1921/22, the most severe drought of the last century for London’s supplies, is shown in Figure D22:

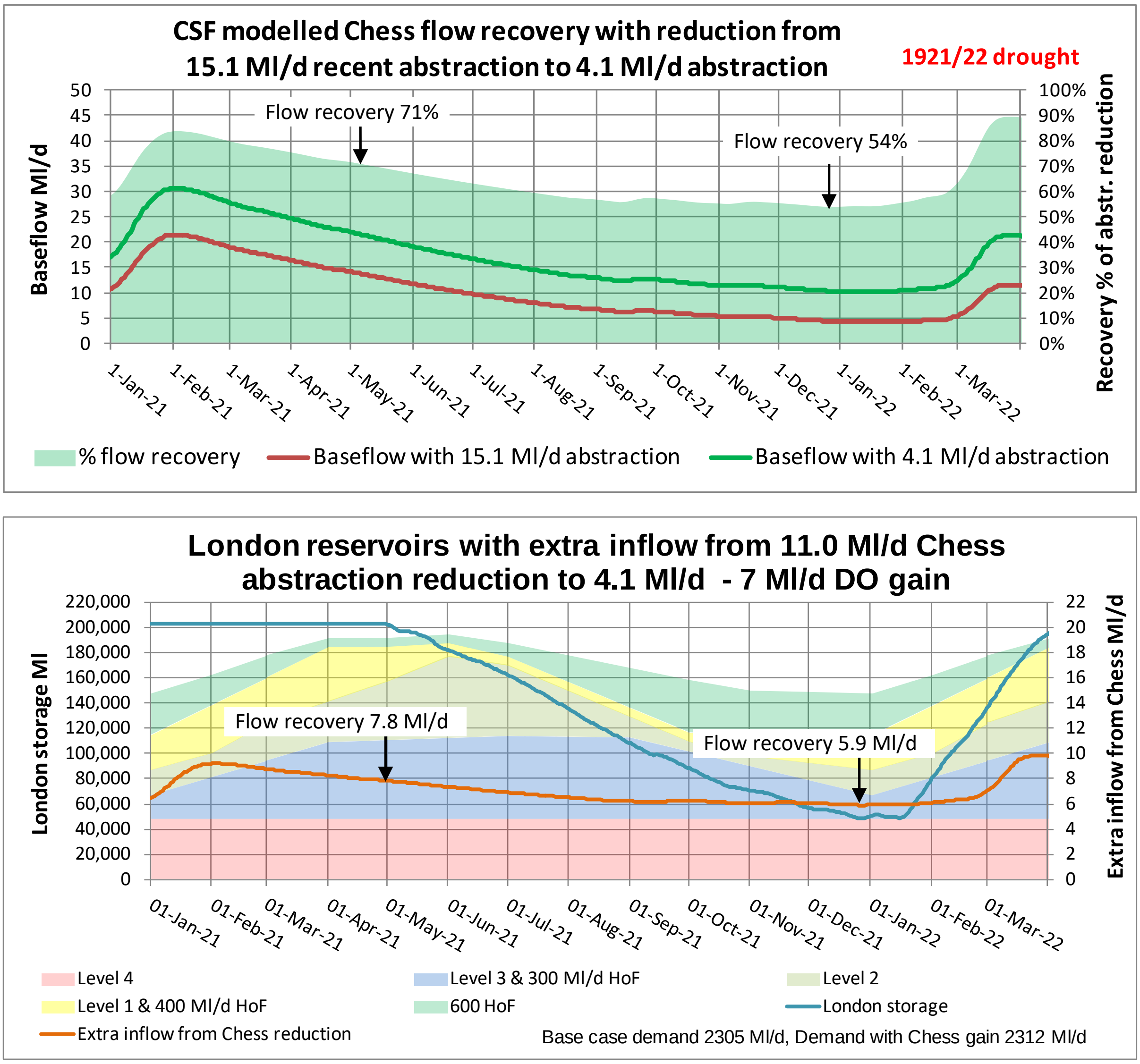


Figure D22 - Modelled river flow gain and DO gain for London in drought of 1921/22

The modelling shows a London deployable output gain of 7.0 Ml/d from the 11.0 Ml/d abstraction reduction – a recovery of 64% of the 11 Ml/d abstraction reduction.

For London’s supplies, the drought of 1933/34 is marginally less severe than the 1921 drought, but is of a longer duration. The modelled flow recovery and benefit to London’s supplies is shown in Figure D23:

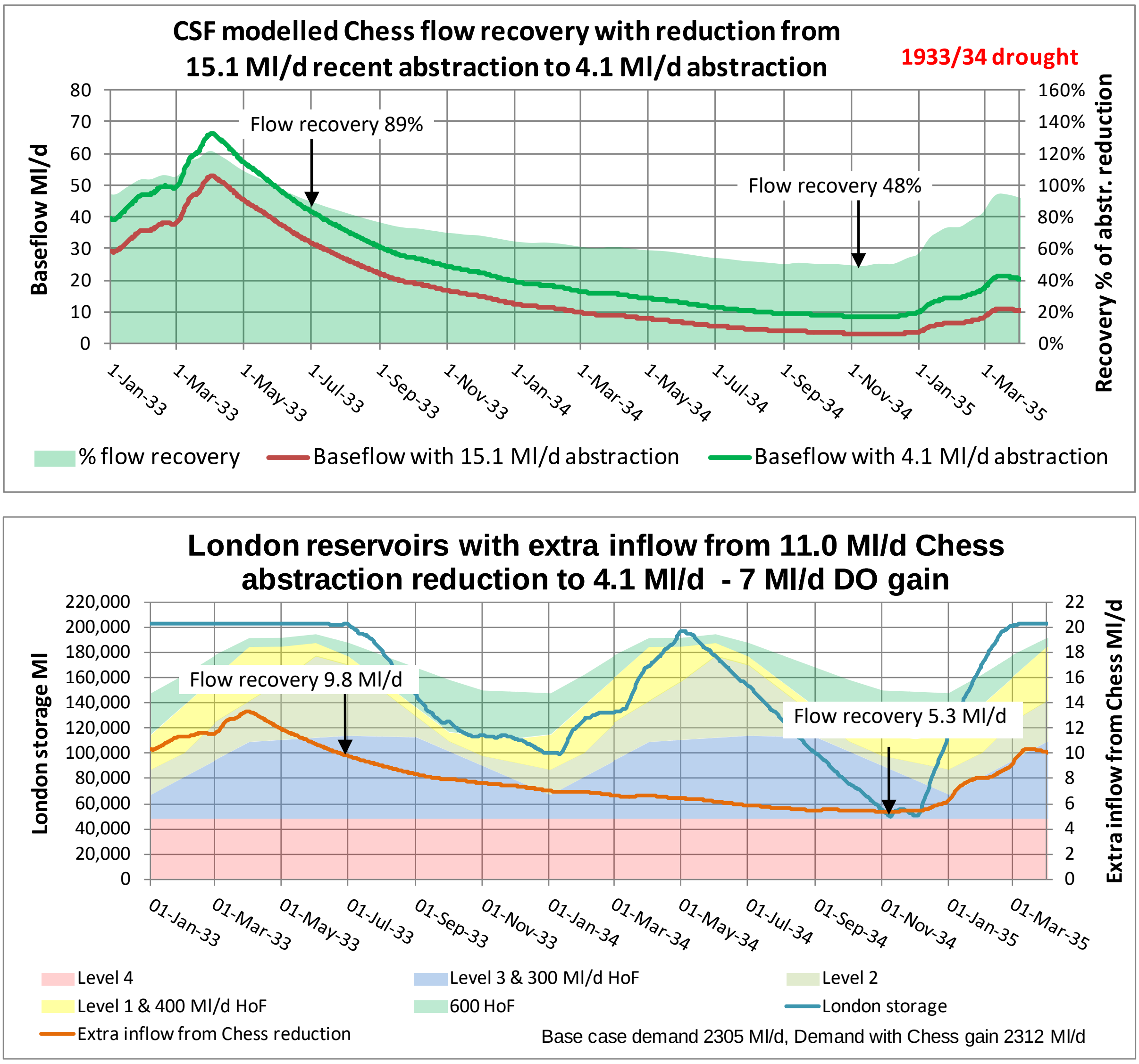


Figure D23 - Modelled river flow gain and DO gain for London in drought of 1933/34

The deployable output gain of 7.0 Ml/d, 64% recovery of the 11 Ml/d abstraction reduction, is less than the 80%-90% recovery assumed in the Chalk Streams First proposal for improvement to the Lea and Colne chalk streams (based on other water company groundwater modelling[33]), but still would allow major chalk stream flow improvement with relatively little loss of regional supply.

D9 Comments on Chess NEP report

Scope of the Chess NEP investigation

The AMP6 NEP report for the Chess, dated August 2018, was written by consultants Mott MacDonald. It pre-dates the NEP reports for the Rivers Ver, Mimram and Beane, which were written by Affinity Water and dated 2020.

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[33] Chalk Streams First, page 16 https://chalkstreams.org/chalk-streams-first/

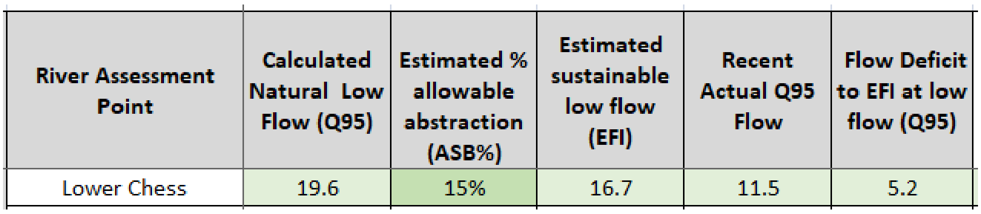
The Summary of the Chess NEP report on page 1 states the objectives as:

> *The objectives of the investigation are to assess the available hydrogeology, hydrology, and ecology information for the upper Chess catchment to define the extent (if any) and nature of impacts of identified abstractions on the flow and the ecology of the River Chess upstream of CSTW [Chesham sewage treatment works].*

The limitation of the investigation to impacts of upstream of Chesham STW is explained in the Summary, page 2:

> *Flow in the River Chess is augmented by discharge from CSTW, approximately 3km downstream of the convergence between the three river sources. The discharge makes a major contribution to flows and therefore impact of abstraction on hydroecology downstream of this point is not of concern. The discharge location forms the downstream limit to the area for this investigation.*

It seems difficult to justify the exclusion of assessment of abstraction impacts in the 15 km of river between Chesham STW and the confluence with the River Colne. The Environment Agency's assessment of flow deficits in the River Chess, as shown in Table D1, gives a Q95 flow deficit of 5.2 Ml/d at the confluence with the Colne – see the extract from Table D1 below:



River Assessment Point	Calculated Natural Low Flow (Q95)	Estimated % allowable abstraction (ASB%)	Estimated sustainable low flow (EFI)	Recent Actual Q95 Flow	Flow Deficit to EFI at low flow (Q95)
Lower Chess	19.6	15%	16.7	11.5	5.2

The 5.2 Ml/d deficit at Q95 is calculated after inclusion of the effluent from the Chesham STW, so, with a dry weather STW effluent of 10 Ml/d, the deficit in the natural baseflow would have been about 15 Ml/d – about 75% of the natural Q95. The exclusion of the river below Chesham from the Chess NEP investigation would seem in retrospect to have been a mistake.

Evaluation of signal tests

Signal tests were carried out at the two Affinity Water PWS sources in the upper Chess in 2016/17. A recovery test at the Chartridge source was carried out in October 2016 (for 15 days). Prior to the test, abstraction had been continuous and constant at a rate of about 1.2 Ml/d. A recovery test at the Chesham source was carried out in May 2017 (for 13 days). Prior to the test, abstraction had been almost constant at about 3.1 Ml/d.

These tests were, therefore, of short duration and undertaken during times of low river flows (see the hydrographs of spot flow data on Figure D12). Although the shutdowns would have been expected to have led to local GWL increases within the cones of depression, they are not of sufficient duration to have a material effect on the overall aquifer storage and the regional GWLs, which mainly govern spring and river flows, as per the CSF interpretation of chalk stream behaviour described in Section 2 of the main report. The low GWLs at the times of the tests, with some ephemeral river reaches dry, mean that, even with much longer duration shutdowns, flow increases would probably have been too small to be realistically detectable, for the reasons given in Section 2.4 of the main report.

The Chess NEP report on page 87 summarises the effect of the Chartridge signal test on river flows as follows:

> *The abstraction at CHAR might also, therefore, have an impact on groundwater flow in any Chalk fissures at a shallow depth which support flows in the River Chess just upstream of Chesham. The test did not, however, provide any direct evidence of impact of change in abstraction at CHAR on flows in the River Chess. This was a result of the relatively small abstraction rate from the source and low river flows during the shutdown period, combined with the variability in river flows and flow monitoring.*

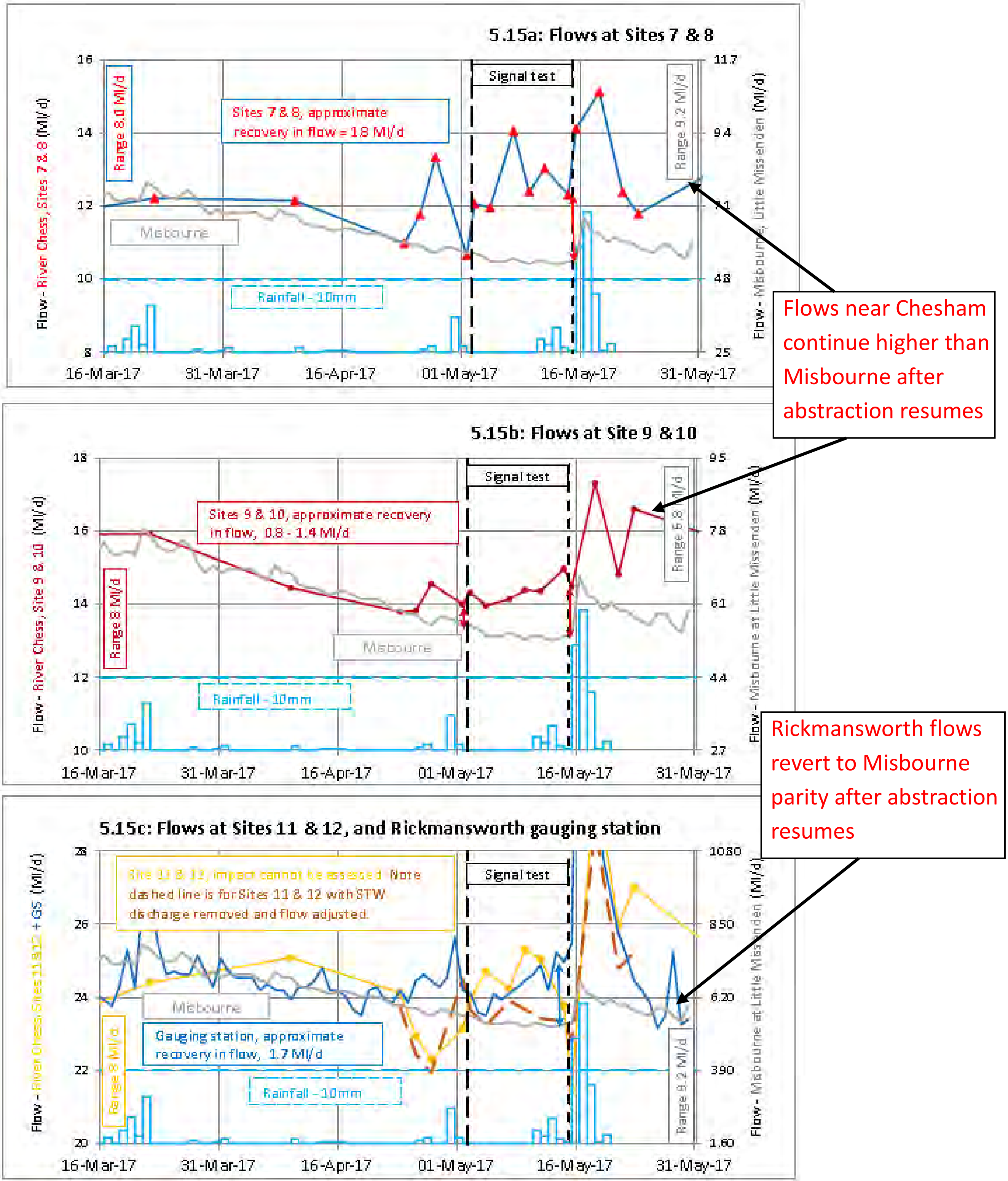
And on page 88:

> *Based on the analysis of flow monitoring data, flow in the River Chess between Meades Water Gardens and Lords Mill could be affected by abstraction changes at the CHES PWS source. At Site 4 (downstream of Meades Water Gardens), given the inaccuracies in the data and the method of assessment, possible impacts might vary between no impact and an impact of about 0.15Ml/d. There was no indication of a recovery in flow upstream of Site 4, where the river was dry during testing. However, the shutdown was conducted at a time of relatively low flow in the River Chess. Evidence of the effect of abstraction on shallow groundwater level suggests that impacts on flow upstream of Meades Water Gardens could occur due to abstraction from all three sources under higher groundwater level conditions and for long term abstraction variations*.

This assessment appears to support the view that the signal test shutdowns needed to be of longer duration and at higher GWLs for the river flow increases to be detectable in the Chesham area. Downstream of Chesham, some flow increases were detected during the Chesham signal test, as described on page 88 of the NEP report:

> *A recovery in flows was evident at several sites from Lords Mill (site 6b) downstream to Rickmansworth gauging station during the shutdown at CHES. The recovery is assessed as varying between about 0.8 and 1.8 Ml/d, equivalent to 26 to 58% of the average daily abstraction occurring at the CHES source prior to the start of the signal test. These reaches of the river are known to be heavily influenced by artesian flow. Therefore, changes in abstraction are expected to have an impact on the flow in the river downstream of Lords Mill where flow is supported by artesian discharges.*

The flow recovery downstream of Chesham is shown on Figure 5.15 of the NEP report:



Copied from Figure 5.15 in Mott MacDonald Chess NEP report

Figure D24 - Flow recovery downstream of Chesham after 3.1 Ml/d shutdown at Chesham

Figure D24 illustrates the difficulty of separating flow changes from the shutdowns from natural flow variations and fluctuations in the output from Chesham STW. In this case, comparison with gauged flows in the adjacent River Misbourne appears to have been the main method of detecting flow increases. During the shutdown, steadily rising flows relative to the Misbourne are clearly visible in all the lower river locations shown on Figure D24. However, after the c.3.1 Ml/d abstraction resumed on 17th May, the flow increases were maintained in the sites just below Chesham, when they might be expected to drop back to their previous parity with Misbourne flows. On the other hand, when abstraction resumes, flows at Rickmansworth do appear to fall back quickly to their previous parity with Misbourne flows. This confusing and inconsistent picture shows the difficulty of interpreting the signal tests and the potential unreliability of their conclusions.

The magnitude of the flow increases measured in the lower river, up to 1.8 Ml/d for a 3.1 Ml/d shutdown, are a lot more than the 0.12 Ml/d flow increase predicted by the CSF model at the end of the 16-day shutdown. If the measured 1.8 Ml/d flow increase is correct, it suggests that recovery of GWLs within the cone of depression makes a significant contribution to spring and river flow recovery. If so, the CSF model concept would tend to under-estimate the speed of flow recovery, but not the ultimate flow recovery which would still depend on the eventual gain in aquifer storage and the overall regional GWLs.

Evaluation of modelled abstraction impacts

Page 129 of the NEP report states that the South West Chilterns Groundwater Model (now understood to be incorporated in the HRGM) was used to a) model the impact of the signal tests and compare results with observed impacts; and b) simulate the impacts of long-term historic abstraction.

On page 145, the NEP report summarises the modelled abstraction impacts of the three sources upstream of Chesham as follows:

> *On average, the model indicates that the decline in river flow accounts for the following proportions of the licensed abstraction at the three PWS sources:*
>
> - *50% upstream of the STW discharge; and,*
> - *81% at the Rickmansworth gauging station.*

Flow hydrographs and flow duration curves demonstrating modelled abstraction impacts are not presented in the NEP report. However, Figures D16 and D17 of this report show HRGM modelled hydrographs and flow duration curves for the Chess at Rickmansworth, which suggest flow impacts of about 90% of recent actual abstraction at most flows down to Q95, but falling to just 20% at extreme low flows – this may be because the HRGM appears to overestimate the frequency of drying up of the net baseflows at Rickmansworth.

In conclusion, modelling analysis in the NEP report in 2018 suggested flow recoveries significantly higher than the 50% understood to be the assumption used in the assessment of the Chalk Streams First proposal in the Gate 2 report on the Thames to Affinity transfer[34].

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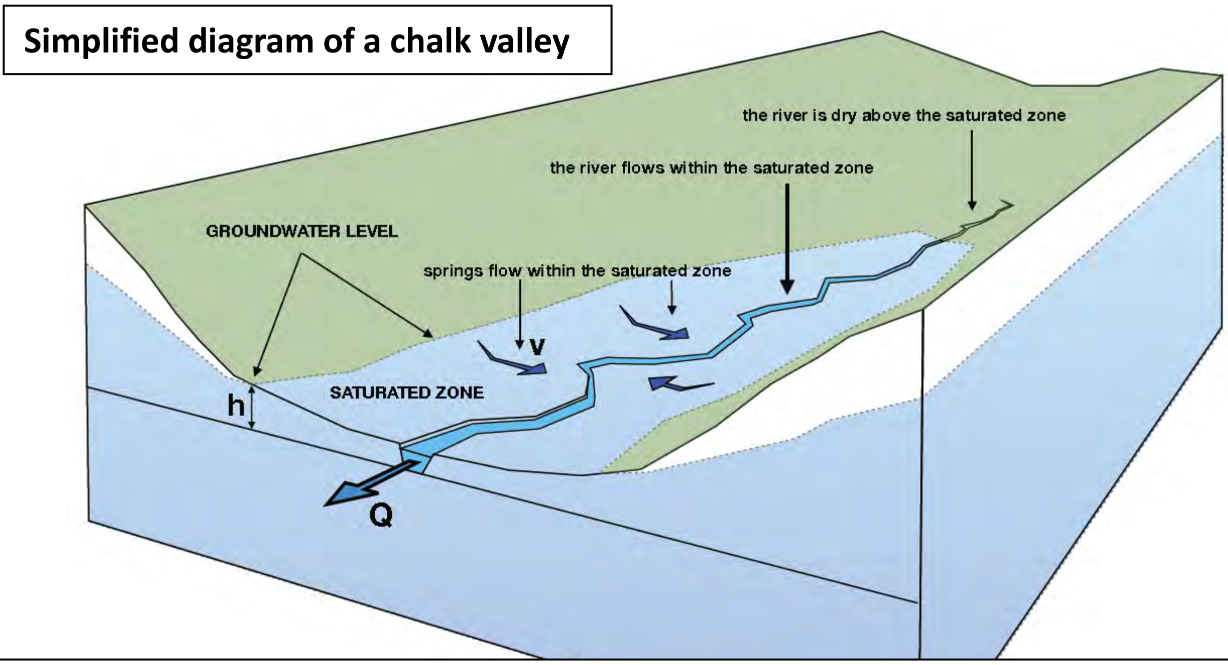
[34] Thames to Affinity transfer Gate 2 report, Section 4.2.2 page 15
https://affinitywater.uk.engagementhq.com/strategic-resource-options

Appendix E – Description of the CSF model

Hydrological and hydraulic principles

Chalk stream flows and groundwater levels respond to rainfall, as illustrated conceptually in Figure E1:


Simplified diagram of a chalk valley

Principle underlying the CSF model:
In theory, the river flow (Q) is related to the height (h) of the groundwater level above the river bed, so that **$Q = ah^b$**, where (a) and (b) are constants determined by the shape of the valley and properties of the chalk. For a V-shaped valley with a constant river bed gradient:

If (h) is the average head of the groundwater table above river bed, elementary fluid mechanic shows the velocity flow (v) from the spring sources is proportional to $h^{0.5}$

Assuming a V-shaped valley, the area of the exposed fissures is proportional to h^2, so the baseflow (Q) in the river from the springs upstream is proportional to $h^{2.5}$ (ie $h^{0.5}$ x h^2), so **$Q = ah^{2.5}$**.

If the valley is U-shaped, as usually the case for chalk streams, the area of exposed fissures is less than for a V-shaped valley, so the equation becomes **$Q = ah^b$**, where b is typically between 2 and 2.5.

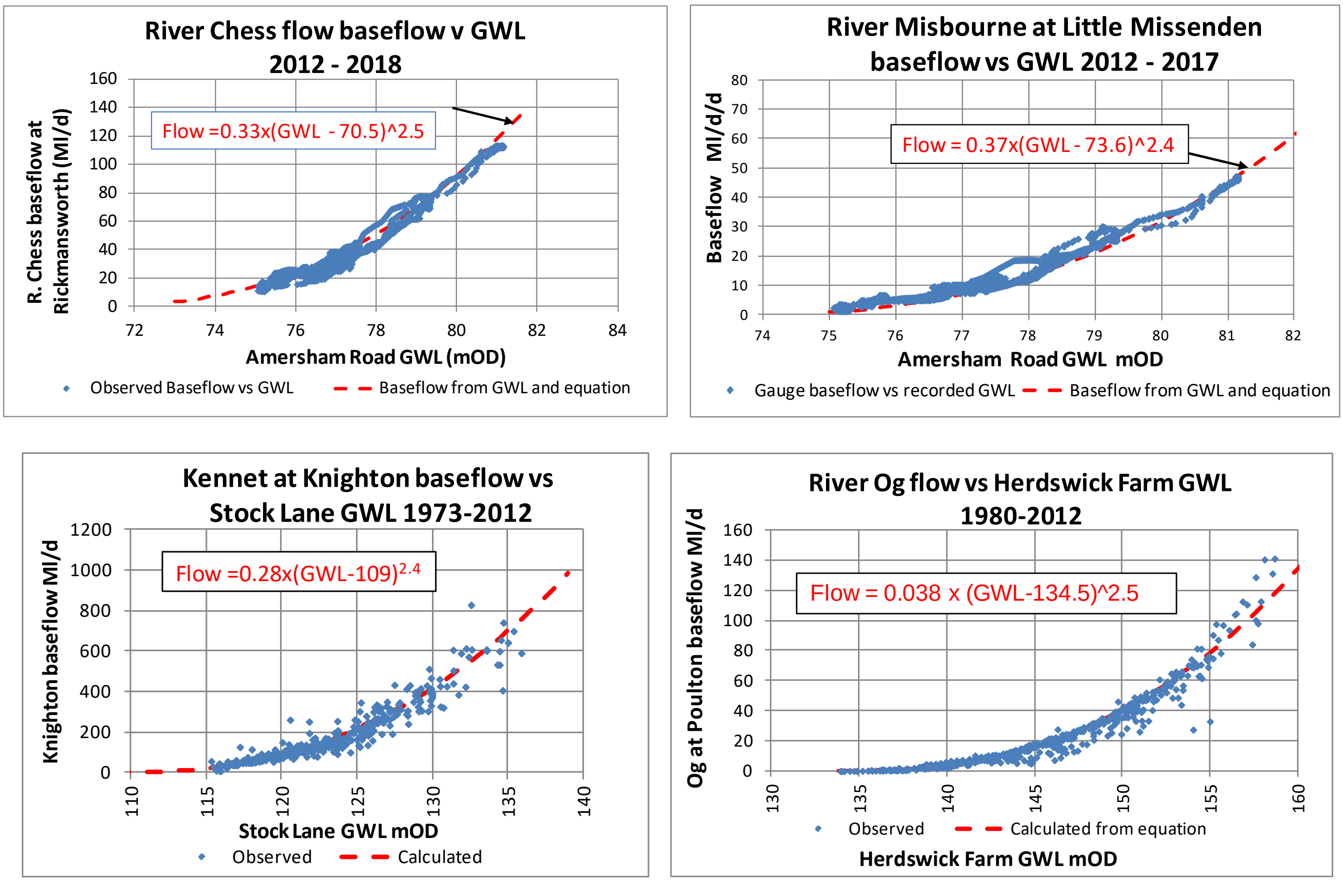
Figure E1 – Concept of how groundwater level drives river flow in a chalk valley

The diagram represents a simplified 'typical' chalk-stream valley, and shows how a chalk stream flows within the saturated zone of the valley floor. The upper boundary of that zone, commonly called the "spring-line", moves up and down the valley according to groundwater levels – the level to which the ground is saturated with water. Simply put, above the groundwater level the valley is dry and the river does not flow; below it, the valley is saturated and the river flows.

The level of the groundwater, therefore, determines both the length of the river (the saturated zone extends higher up the valley as the groundwater height increases) and the gathering intensity of the flow (Q). This principle is used in the CSF lumped parameter model.

Relationship between observed groundwater levels and river flows

With all chalkstreams, there appears to be a strong relationship between observed groundwater levels and river flows, in the form of $Q=ah^b$, where a and b are constants and h is the water table level over a datum. The relationship applies to the perennial and ephemeral reaches of the Rivers Ver, Mimram and Beane as shown on Figures E4, E6 and E7. Some examples from other rivers are illustrated in Figure E2.



Note: 1. Base flows separated from gauged river flows using IoH method software

Figure E2 - Relationship between observed river flows and groundwater levels

Generally, the changes in measured flow lead the changes in measured GWLs. In the examples above, the lead times are 5 days for the Chess, 7 days for the Misbourne, 6 days for the Kennet and zero for the Og (lead times have been determined by optimising the R^2 value for a polynomial trendline fitted for the observed Q-h plot). Some of the measured lead times for the Ver, Mimram and Beane are considerably larger (see comments on Figures E4, E6 and E7). However, these lead times are not built into the models – the computed flows on each day are calculated using the modelled GWLs on that day.

Computation process in the CSF lumped parameter model

The CSF model is an Excel spreadsheet of about 80 Mb, including all the graph plotting and analysis routines. The model uses the Environment Agency daily data for effective rain to simulate daily groundwater levels and river flows at various locations in the catchments. The models simulate daily river flows and groundwater levels in the 103-year period 1920 to 2022, which includes the major droughts of 1920/21, 1933/34, 1943/44 and 1975/76. These are the four most severe droughts of the past century for London's supplies.

For each day, the model calculates GWLs and river flows as follows:

Step 1: Calculate daily aquifer recharge

Recharge = Daily effective rain (Er) x effective catchment area (A_R)

The effective catchment area is the topographic catchment to the lowest available flow gauging location, less the area draining as surface flow (determined by the NRFA base flow index), less an allowance for surface water drained from built-up areas and leaving the catchment via sewerage.

The effective rainfall is assumed to take up to 30 days to reach the aquifer, with the proportion of each day's rainfall arbitrarily distributed in ten 3-day blocks over the next 30 days, with an example shown in Figure E3:

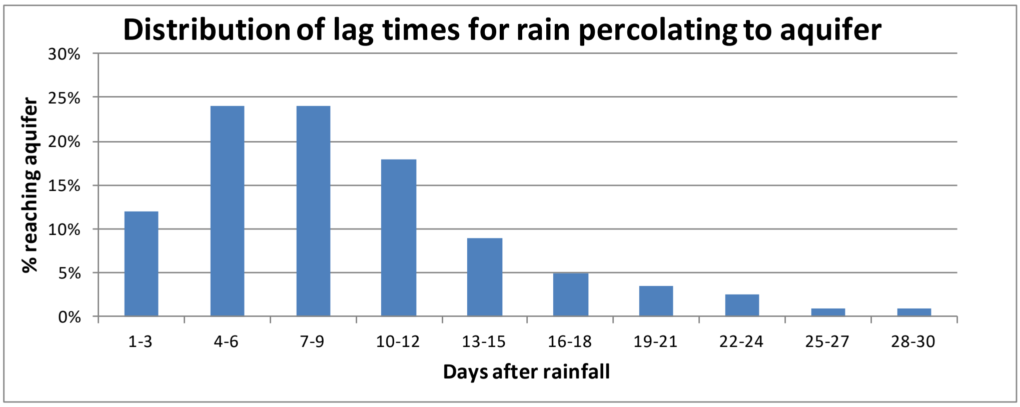


Figure E3 – Example distribution of percolation time lags

Step 2: Change in aquifer storage = (Er x A_R) – Q_R – Q_A – Q_U

Where Er is effective rainfall, A_R is effective catchment area, Q_R is river flow, Q_A is abstraction and Q_U is underflow within the aquifer to outside of the catchment.

The river flow, Qr, is calculated from the groundwater level the previous day and using the relationships between groundwater level and river flow of the type shown on Figure E2.

The underflow, Q_U, is calculated by the empirical formula $Q_U = a \times (GWL - b)^c$

where a, b and c are constants obtained by trial and error as part of the process of calibrating the model. If c=1, the linear relationship between flow and excess head is equivalent to Darcy's equation for subsurface flow.

Step 3: Change in groundwater level = Change in aquifer storage ÷A ÷ S

Where A is the topographic catchment area and S is the average specific yield for the catchment. The specific yield appropriate to each catchment at the location of the modelled GWL was found by trial and error to give best fit to recorded groundwater levels and river flows when modelled with historic abstraction.

Step 4: Calculate new groundwater level and river flows

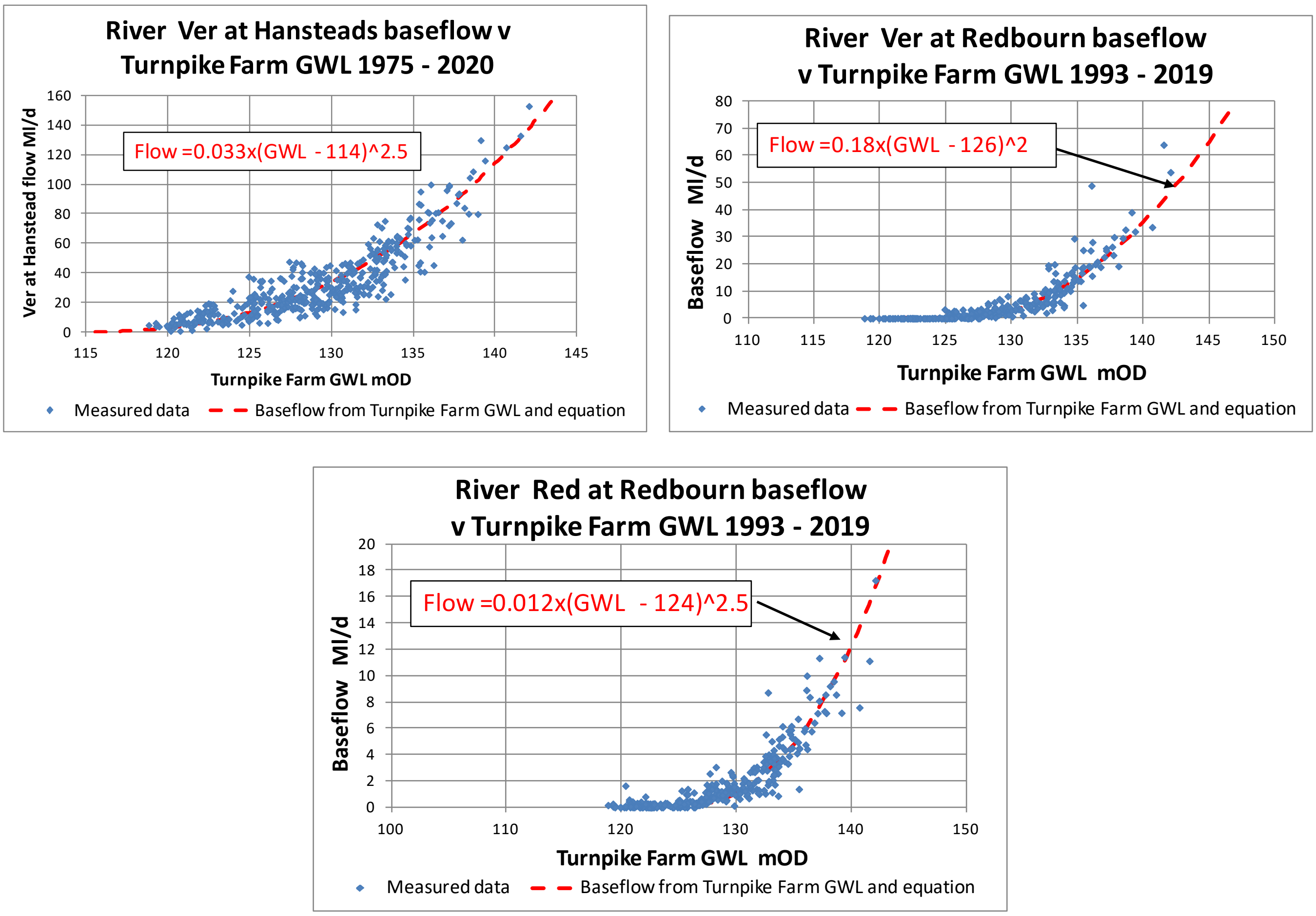
The new groundwater level for the day is the previous day's level plus the increment from Step 3.The new river flow for the day is calculated from the new groundwater level using a formula similar to those shown in Figure E2.

More details specific to the individual models are given below.

River Ver lumped parameter model

The CSF model simulates GWLs at the Turnpike Farm OBH and river flows at the Hansteads, Ver at Redbourn and Red at Redbourn gauge sites. The formulae linking the river flows to the Turnpike Farm GWLs are shown on Figure E4, with the measured data as blue dots and the formulae plotted as the dashed red lines.

The optimised lead times for the flows relative to the GWLs are 20 days for the Hansteads flows, and zero each for the Ver at Redbourn and the River Red.


River Ver at Hansteads baseflow v Turnpike Farm GWL 1975 - 2020

River Ver at Redbourn baseflow v Turnpike Farm GWL 1993 - 2019

River Red at Redbourn baseflow v Turnpike Farm GWL 1993 - 2019

Figure E4 Flow-GWL relationships used in Ver model

The relationships shown by the red dashed lines in Figure E4 have been used in the CSF model to simulate river flows from modelled groundwater levels. The values for the constants in the equations were fixed by trial and error to fit the recorded GWL-flow data.

The effective catchment area for recharge was reduced by 20% from the topographic catchment of 132 km^2 to allow for drainage of built-up areas via surface sewerage out of the catchment and the large amount of clayey drift in the catchment which reduces recharge. The 20% reduction in effective catchment for recharge can be justified as 12% allowance for surface run-off (the Baseflow Index is 0.88) and a nominal 8% for export via sewerage from built-up areas, primarily in St Albans and Hemel Hempstead.

The specific yield used to convert modelled groundwater storage changes to GWL changes was 1.1%. This value was determined by trial and error to optimise the amount of seasonal GWL fluctuations when calibrating the model.

The 1.1% specific yield is less than the specific yield of 2% for the Ver shown on Map 31 of the recent Mott MacDonald modelling report[35]. However, an earlier version of the CSF Ver model, which modelled the Kinsbourne GWLs, adopted a specific yield of 4.5% to achieve a

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[35] Hertfordshire Groundwater Model – numerical model report, Mott MacDonald, March 2019

similar fit between measured and modelled Kinsbourne Green GWLs (the amplitude of seasonal GWL fluctuations at Kinsboune Green is much less than the amplitude of fluctuations at Turnpike Farm). This shows that specific yield varies considerably across the catchment and is a lot less uniform than suggested on Mott MacDonald's Map 31 which is reproduced below in Figure E5.

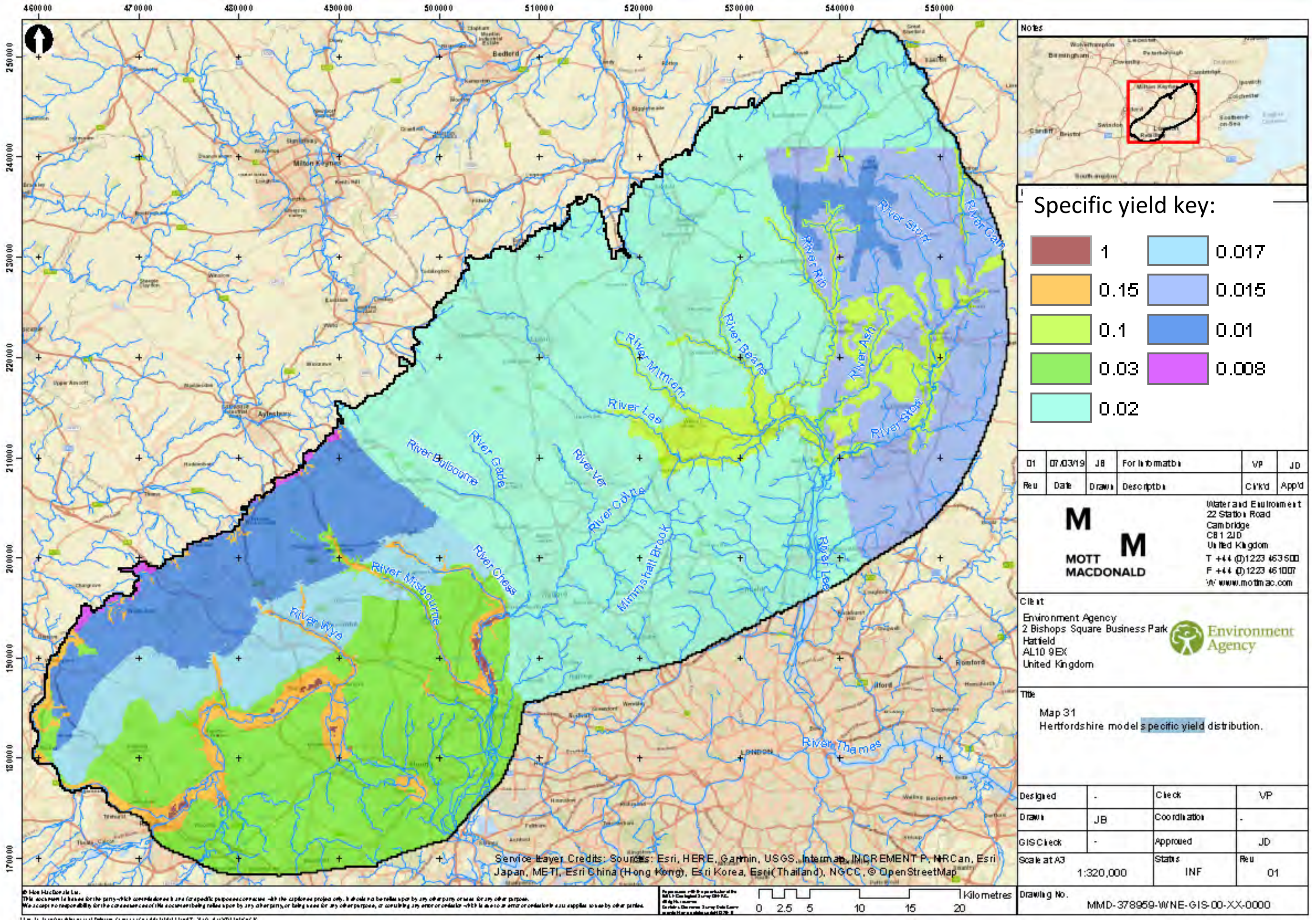


Figure E5 Mott MacDonald specific yield values in HRGM model

The modelled underflow in the format $Q_U = a\ x\ (GWL- b)^c$ was set by trial and error to the equation: Underflow = 4.9 x (GWL – 119.0)$^{0.5}$. The power factor of 0.5 (as would be used in the fluid mechanics term $\surd(2gh)$, gave a better fit to measured data than a power factor of 1.0, which would apply to the pressure gradient in the Darcy equation for sub-surface flow.

The modelled water balance makes allowance for effluent from the Caddington, Markyate and Studham STWs in the upper Ver catchment, using EA STW output data. The model assumes that the STWs, which are all located close to the winterbourne well upstream of Redbourn, discharge into the aquifer via soak-aways or river bed leakage.

For modelling of the recent actual abstraction scenario of 16.4 Ml/d, starting in 1920 and ending in 2020 on a date when the modelled storage is the same as the modelled starting storage, the water balance over the 100 year period is:

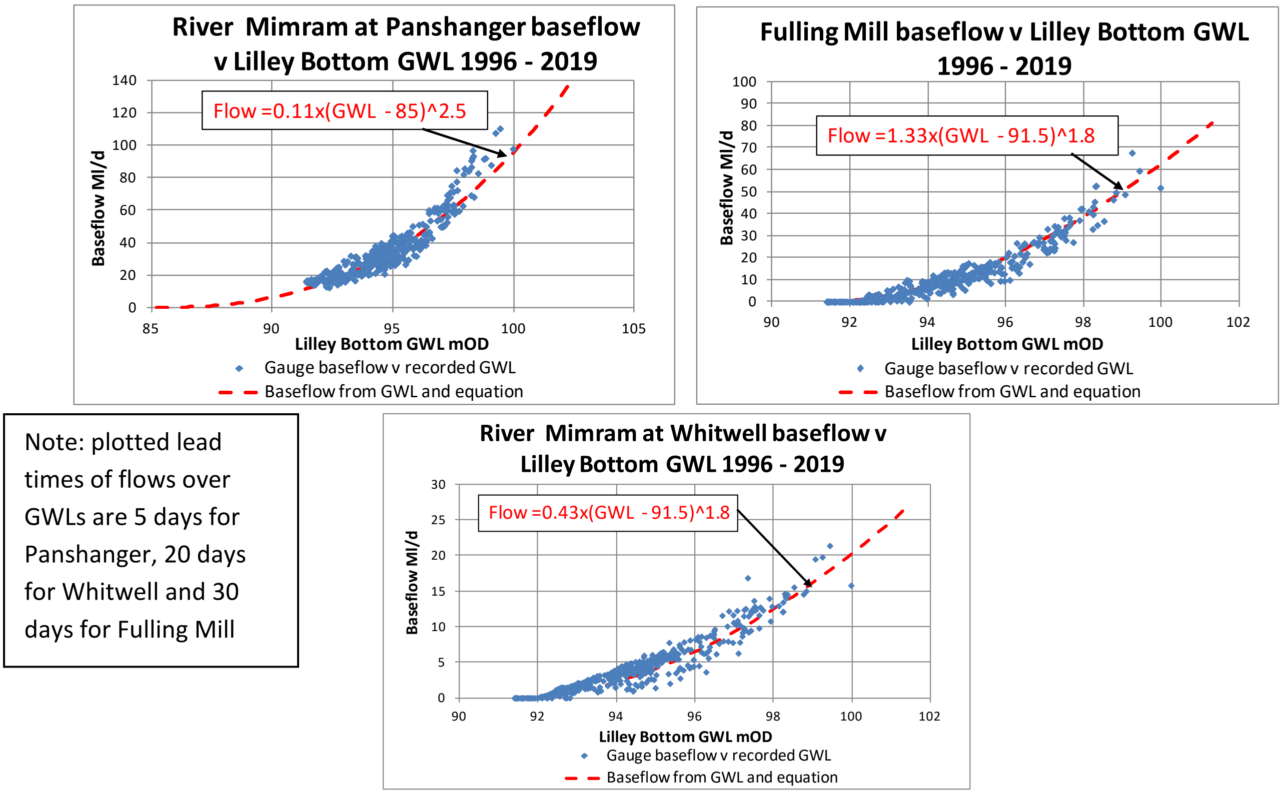
Inputs	Ml/d
- Average aquifer recharge	78.2
- Average STW discharge to aquifer	2.5
Total inputs	80.7
Outputs	
- Average river outflow at Hansteads	37.6
- Average underflow from catchment	15.5
- Average abstraction	27.6
Total outputs	80.7

The current Ver model does not allow for leakage from supplies into the aquifer, as is done for the Mimram model. Leakage will be included in the next version of the model.

Validation plots for the CSF Ver model are shown in Figures 14 and 15 of the main report.

The River Mimram lumped parameter model

The CSF Mimram model simulates GWLs at the Lilley Bottom OBH and river flows at the Panshanger, Fulling Mill and Whitwell gauge sites. The formulae linking the river flows to the Lilley Bottom GWLs are shown on Figure E6, with the measured data as blue dots and the equations plotted as the dashed red lines:


River Mimram at Panshanger baseflow v Lilley Bottom GWL 1996 - 2019

Fulling Mill baseflow v Lilley Bottom GWL 1996 - 2019

River Mimram at Whitwell baseflow v Lilley Bottom GWL 1996 - 2019

Note: plotted lead times of flows over GWLs are 5 days for Panshanger, 20 days for Whitwell and 30 days for Fulling Mill

Figure E6 Flow-GWL relationships used in Mimram model

The relationships shown by the red dashed lines in Figure E6 have been used in the CSF model to simulate river flows from modelled groundwater levels. The values for the constants in the equations were calibrated to fit the recorded flow-GWL data.

The effective catchment area for recharge was reduced by 10% from the topographic catchment of 134 km^2 to allow for drainage of built-up areas via surface sewerage out of the catchment and the large amount of clayey drift in the catchment which reduces recharge. The 10% reduction in effective catchment for recharge can be justified as 7% allowance for surface run-off (the Baseflow Index is 0.93) and a nominal 3% for export via sewerage from built-up areas.

The specific yield used to convert modelled groundwater storage changes to GWL changes was 2.5%. This value optimised the amount of seasonal GWL fluctuations when calibrating the model against recorded GWL data. The 2.5% specific yield is consistent with the values shown on Map 31 of the recent Mott MacDonald modelling report which is reproduced above as Figure E5. This shows specific yield of 2% for much of the Mimram catchment, but up to 10% in the lower valley.

The modelled underflow in the format $Q_U = a\ x\ (GWL - b)^c$ was set by trial and error to the equation: Underflow = 2.0 x (GWL – 119.0). This is consistent with the Darcy equation for sub-surface flow, which assumes a linear relationship between flow and pressure gradient.

The modelled water balance makes allowance for effluent from the small STWs in the upper Mimram catchment, using EA STW output data. The model assumes that the STWs, which are all located close to the winterbourne river section, discharge into the aquifer via soak-aways or river bed leakage when Lilley Bottom GWLs are less than 93 mOD, but otherwise add to river flows.

Leakage from supplies to the aquifer is allowed at a nominal 5% of abstraction, which assumes that the majority of leakage is taken up by evapo-transpiration or exported out of the catchment either via sewerage or to supplies outside the catchment.

For modelling of the recent actual abstraction scenario of 16.4 Ml/d, starting in 1920 and ending in 2020 on a date when the modelled storage is the same as the modelled starting storage, the water balance over the 100 year period is:

Inputs	Ml/d
• Average aquifer recharge	67.4
• Average leakage from supplies to aquifer	0.8
• Average STW discharge to aquifer	0.1
Total inputs	68.3
Outputs	
• Average river outflow at Panshanger	44.6
• Average underflow from catchment	7.3
• Average abstraction	16.4
Total outputs	68.3

Validation plots for the CSF Mimram model are shown in Figures 45 and 46 of the main report.

The River Beane lumped parameter model

The CSF Beane model simulates GWLs at the Crescent Cottages OBH and river flows at the Hartham gauging station and the Frogmore spot gauging site. The formulae linking the river flows to the Crescent Cottages GWLs are shown on Figure E7, with the measured data as blue dots and the equations plotted as the dashed red lines:

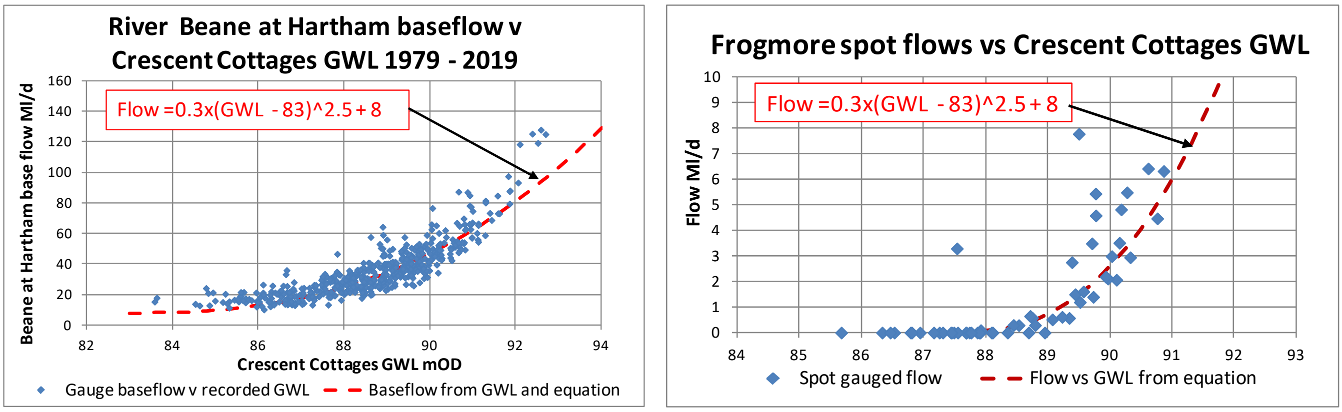


Figure E7 Flow-GWL relationships used in Beane model

The Flow-GWL relationship for Hartham is less strong than the equivalent relationships for the lower Ver and lower Mimram (R^2 is 0.83 for a polynomial fitted trend line). The flows on the Hartham plot lead the GWLs by 40 days. This could be a reflection of the lower baseflow index for the Beane at Hartham (BFI 0.76) and possibly connected to the amount and variability of the drift in the valley bottom or to location of the Crescent Cottages borehole in the upper valley, about 16 km from Hartham.

The scatter plot for Frogmore shows spot gauged flows, with no allowance for surface run-off. Similar degrees of it to the Q=ahb relation are found at most other spot gauging sites. The scatter plot for the Stevenage Brook gauging station has a poor fit to the Q=ahb relationship, which is consistent with the high urbanisation and low baseflow index (0.23).

The relationships shown by the red dashed lines in Figure E7 have been used in the CSF model to simulate river flows from modelled groundwater levels. The values for the constants in the equations were calibrated to fit the recorded flow-GWL data.

The effective catchment area for recharge was reduced to 134 km^2 to allow for drainage of built-up areas via surface sewerage out of the catchment and the large amount of clayey drift in the catchment which reduces recharge. The reduction in effective catchment for recharge is 76% of the topographic catchment, ie equivalent to the baseflow index.

The specific yield used to convert modelled groundwater storage changes to GWL changes was 3.5%, optimised to match the amount of seasonal GWL fluctuations when calibrating the model. The 3.5% specific yield is consistent with the values shown on Map 31 of the recent Mott MacDonald modelling report in Figure E5, which shows specific yield of 2% for much of the catchment, but up to 10% in the lower valley.

The modelled underflow in the format $Q_U = a\ x\ (GWL- b)^c$ was set by trial and error to the equation: Underflow = 2.9 x (GWL – 88.0), equivalent to a linear relationship between flow and pressure gradient, as per Darcy's Law.

Leakage from supplies to the aquifer is allowed at a nominal 10% of abstraction Higher than the Mimram assumption of 5% in recognition of the large population in the upper part of the catchment (Stevenage).

For modelling of the recent actual abstraction scenario of 27.4 Ml/d, starting in 1920 and ending in 2020 on a date when the modelled storage is the same as the modelled starting storage, the water balance over the 100 year period is:

Inputs	Ml/d
• Average aquifer recharge	75.4
• Average leakage from supplies to aquifer	2.0
Total inputs	77.4
Outputs	
• Average river outflow at Hartham	47.9
• Average underflow from catchment	4.9
• Average abstraction	24.7
Total outputs	77.5

Validation plots for the CSF Beane model are shown in Figures 74 and 75 of the main report.

Appendix F – GARD’s model of Thames Water’s supply system

GARD’s model of Thames Water supply system is a daily flow simulation of supplies in London and the Thames valley since 1920, developed to assist GARD’s work in resisting Thames Water’s plans for a new reservoir near Abingdon. The model includes:

- Daily inflows and outflows to TW’s lower Thames and lower Lea reservoirs
- Reservoir control rules as per the Lower Thames Control Diagram
- Daily operation of Gateway desalination to match TW operating rules
- Aquifer recharge schemes, West Berkshire GW scheme and other drought sources
- Daily inflows and outflows to Farmoor reservoir

The model has been validated by comparison with output from Thames Water’s WARMS2 modelling of London’s supplies delivering the WRMP19 deployable output of 2305 Ml/d, providing a virtually exact match as shown below:

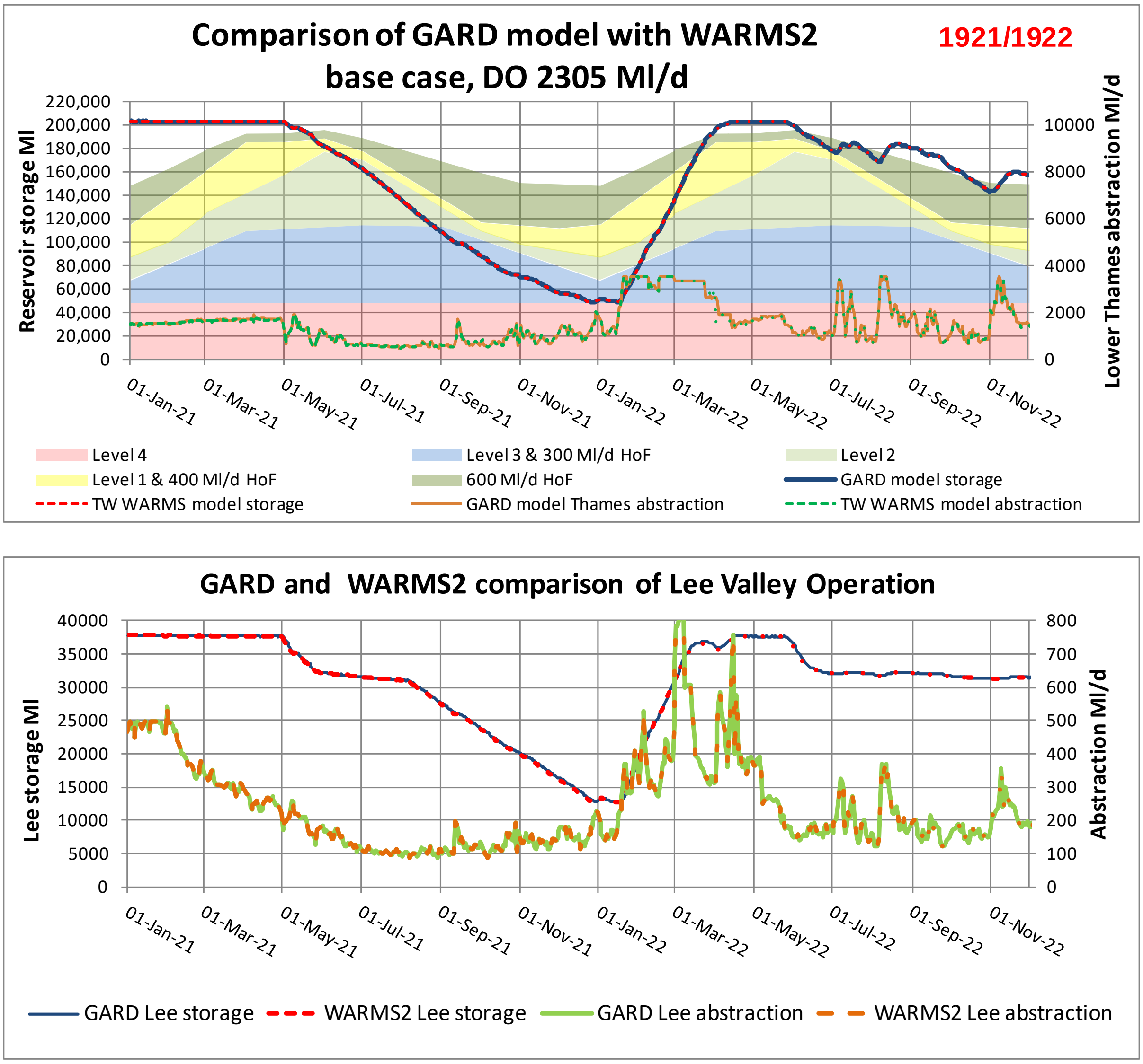


Figure F-1: Validation of GARD model against WARMS2 model output