River Chess Catchment Perceptual Model

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Client Ref: OR/24/057

Issue number 1
12.12.2024

FDRI Floods & Droughts Research Infrastructure
UK Centre for Ecology & Hydrology
UKRI Natural Environment Research Council

Foreword

This report is the published product of a study by the British Geological Survey (BGS) into existing hydrogeological and hydrological understanding of the River Chess catchment, whilst highlighting any remaining uncertainties and knowledge gaps. This report results from work associated with the Floods and Droughts Research Infrastructure (FDRI) programme; a £38 million project which will advance understanding of how, when and where floods and droughts occur in the UK. As part of the FDRI programme, three sub-catchments across the UK have been selected for fixed infrastructure, these are the upper Severn, the upper Tweed and the Chess which this report focuses on.

Acknowledgements

A large number of individuals in BGS and UK Centre for Ecology and Hydrology (UKCEH) have contributed to the project. In addition to providing and sharing data, many individuals have freely given their advice, and provided the local knowledge important to improving the understanding of the River Chess catchment, and where to best focus efforts for preliminary surveys prior to locating monitoring infrastructure. In particular we would like to thank Gareth Old (UKCEH), Ilias Karapanos and Alessandro Marsili (Affinity Water), James Sorensen, Andrew Farrant, Alan MacDonald, Christopher Jackson, Mihai Cimpoiasu, Philip Meldrum, Jonathan Chambers, Oliver Kuras, Russell Swift (BGS).

Contents

1. Introduction

Natural Environment Research Council (NERC) are currently commissioning a large capital investment into floods and drought research infrastructure (FDRI, https://fdri.org.uk/) in the UK. Delivery of this investment is led by UKCEH with support from BGS, Imperial College London and the University of Bristol.

FDRI includes fixed flood and drought monitoring infrastructure in three catchments across the UK: the Chess, Upper Tweed, and Upper Severn. Previous scoping phases of FDRI included the development of perceptual models of the hydrological functioning of these catchments. However, to identify science needs and associated requirements for monitoring infrastructure, a detailed perceptual model of each catchment is required. This report builds on an initial perceptual model (see appendix) by highlighting key concepts, variables and assumptions within the catchment along with quantitative data.

This report details the perceptual model for the Chess catchment. Several studies have been undertaken in the Chess catchment in the past two decades, primarily to investigate the issue of low flows. This report synthesises the key findings from these various reports and other available information to detail the current understanding of the functioning and water balance of the Chess, and to identify the key knowledge gaps and uncertainties which remain.

1.1 Key previous reports

Some of the main reports used in this study are listed below.

- Environment Agency - Hertfordshire Chalk Conceptual Model (Stantec, 2024).
- The Geology Underlying the Lower Chess Valley (Bailey, 2024).
- Thames Water & Affinity Water AMP6 Low Flow Investigations – River Chess NEP Study (Mott MacDonald, 2018).
- British Geological Survey – Scientific and technical report to accompany the Chess catchment GSI3D geological model (Farrant et al., 2016).
- Restoring Sustainable Abstraction Investigation Stage 2 Plan: River Chess (Jacobs, 2008).
- Environment Agency Thames Region - Southwest Chilterns Model (Atkins, 2007).
- Environment Agency - Investigation of low flows and abstraction in the River Chess catchment – Desk Study (Kidney, 2006).

2. Geology and hydrogeology

2.1 Catchment overview

The River Chess catchment (Chess at Rickmansworth, NRFA 39088) is a north-west, south-east trending catchment that drains the dip slope of the Upper Cretaceous Chalk Group of the Chilterns to the north-west of London. The River Chess surface water catchment area is 105 km^2 and is 266 mAOD at its highest elevation and 47.7 mAOD at the gauge at Rickmansworth (Figure 1). It has a mixed land cover consisting of arable (35%), grassland (33%), woodland (18%), and urban (12%). The upper parts of the Chess catchment north of Chesham comprise grassland, woodland and arable land, whilst the perennial Chess begins near the urban area of Chesham before flowing south-east through mostly arable land and grassland to Rickmansworth where it flows into the River Colne. The urban areas of Amersham, Chalfont and Latimer, Chorleywood and Rickmansworth lie mostly outside of the catchment to the south.

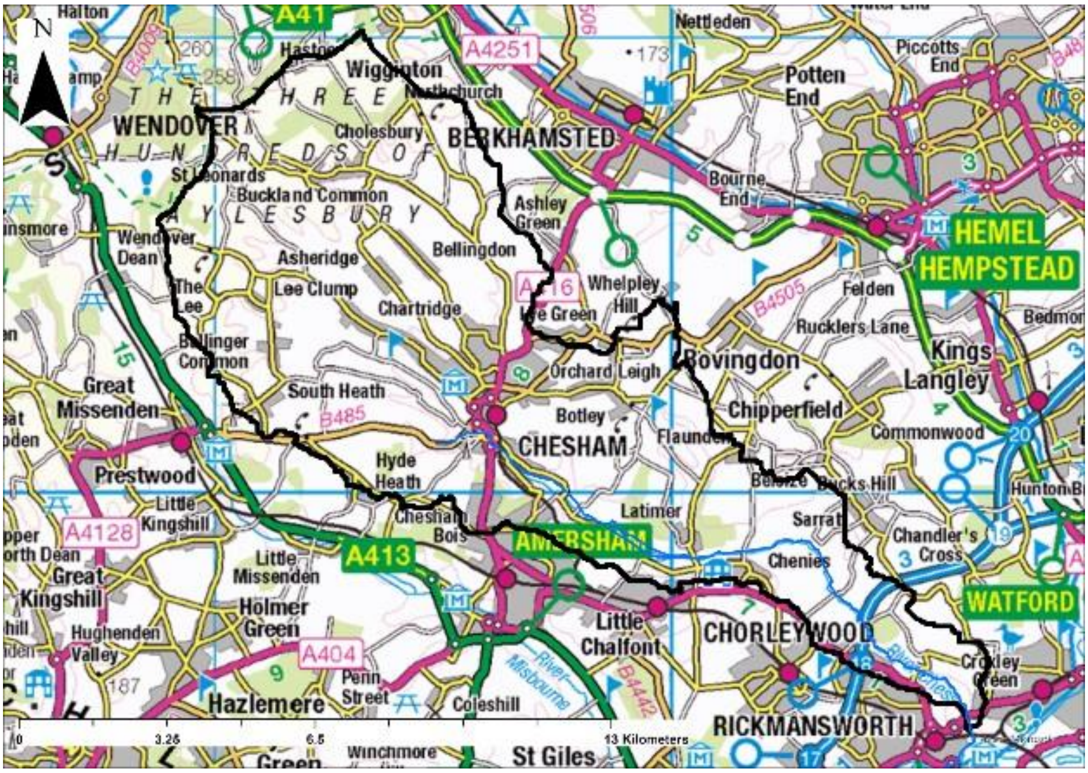

Figure 1: Map showing the River Chess surface water catchment (black) and its location in the Chilterns in relation to the Colne, Gade and Misbourne rivers. Contains Ordnance Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290.

2.2 Bedrock geology

Chiltern hills

The Chilterns are a range of chalk hills which run from Goring Gap north-eastward to Luton. The highest areas are along the north-west edge where they form an escarpment, whilst a series of north-west south-east trending dry valleys and valleys containing groundwater-fed rivers drain the Chilterns to the south-east.

The Chalk comprises the Upper Cretaceous Chalk Group which is sub-divided into the Grey Chalk Subgroup and the White Chalk Subgroup. Formations of the Grey Chalk Subgroup include the West Melbury Marly Chalk and ZigZag Chalk formations whilst the White Chalk Subgroup comprises the Holywell Nodular Chalk, New Pit Chalk, Lewes Nodular Chalk and Seaford Chalk formations.

The Lewes Nodular Chalk Formation and Seaford Chalk Formation outcrop over the majority of the Chilterns although the New Pit Chalk Formation is exposed in some of the deeply incised valleys. The West Melbury Marly Chalk, ZigZag Chalk and Hollywell Nodular Chalk formations of the Chalk Group and Upper Greensand and Gault formations underlying the Chalk Group outcrop towards the base of the scarp slope (Allen et al., 1997). Clay-with Flints superficial deposits cover much of the high ground whilst alluvium is found in the valleys and river terrace deposits are found along the south-east margin of the Chilterns.

The total thickness of the Chalk of the Chilterns is around 200-250 m thick (Allen et al., 1997). Karst features including swallow holes, sink holes and dissolution pipes are common across the Chilterns, although cave systems have not developed (Farrant et al., 2023). The Chalk of the Chilterns is also well fractured with a dominant regional fracture set trending north-west to south-east, mostly comprising of high angle conjugate fractures.

River Chess catchment

The bedrock geology underlying the Chess catchment is typical of the Chilterns, comprising Upper Cretaceous Chalk which gently dips south-east down valley (Figure 2, Figure 3) – with the southern interfluves overlain by Paleogene deposits.

The West Melbury Marly Chalk Formation is typically found at depths of >75 m below ground level (b.g.l.), while the overlying ZigZag Chalk Formation is found at depths of ~50-75 m b.g.l. – both of these formations are only intercepted by the deepest boreholes (e.g. HAW and CHE abstraction boreholes). Above this is the Holywell Nodular Chalk Formation which is not exposed in the catchment but is close to the surface in parts of the Upper Chess.

The Holywell Nodular Chalk Formation is overlain by the New Pit Chalk Formation which is exposed in much of the Chess valley but is buried 40-50 m below the surface in the interfluves (high ground). Because the Chess flows over the New Pit Chalk Formation, it is highly important for groundwater - surface water interactions (Figure 3). In the upper catchment, the Chess intersects the lower-mid part of the New Pit Formation, whereas further downstream the Chess intersects the upper part of the New Pit Formation.

The Lewes Nodular Chalk Formation overlies the New Pit Chalk Formation forming the surface bedrock across much of the catchment, especially the high ground (interfluves) away from the south-east. However, the Lewes Nodular Chalk Formation is frequently overlain by superficial deposits of Clay-with-Flints which cover much of the higher ground. In the lowermost catchment from Loudwater to Rickmansworth, the Chess overlies the Lewes Nodular Chalk Formation. Towards the base of this formation lies the Chalk Rock member, which is a 1-3 m thick, particularly hard, compacted and mineralised Chalk which is highly fractured and fissured. Above the Chalk Rock member, the formation becomes less nodular and less hard.

In the south-east of the catchment the lower part of the Seaford Chalk Formation comprising the Belle Tout marls overlies the Lewes Nodular Chalk Formation. The upper part of the Seaford Chalk Formation has been removed by Palaeogene erosion. Minor deposits of the Lambeth Group (Palaeogene silts, sands and clays) are found overlying the Lewes Nodular Chalk and Seaford Formation in the south-east of the catchment.

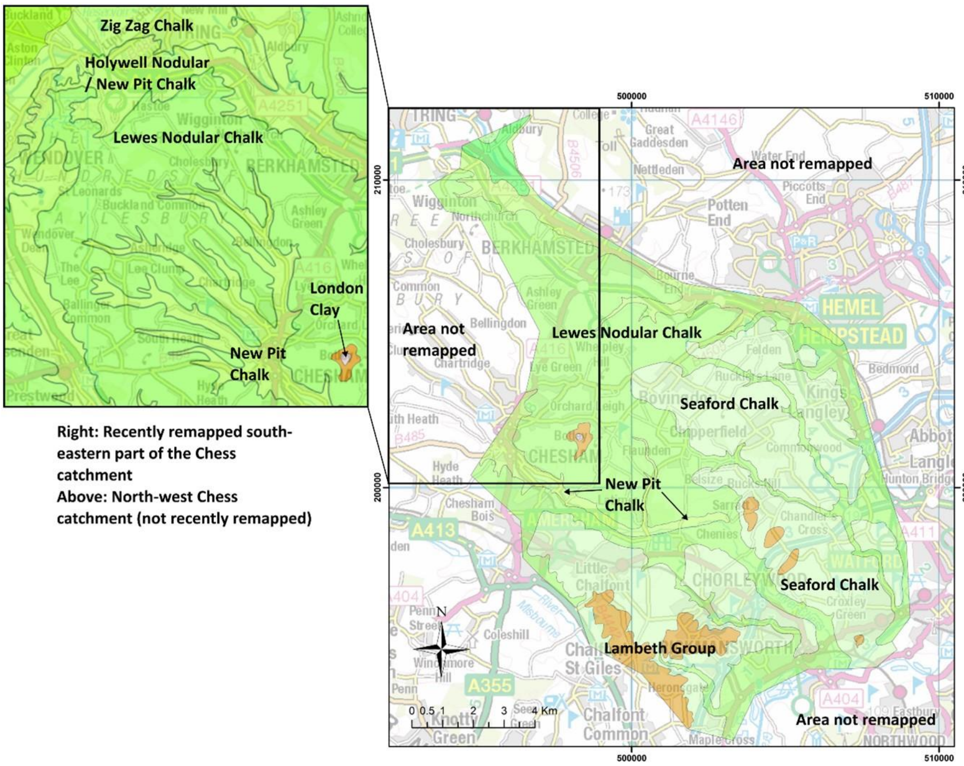

Figure 2: Bedrock geology for the Chess catchment. The map on the right is from the most recent available data (modified from Farrant et al., 2019) and does not extend to the north-west of the catchment. The map on the left is the 1:50000 BGS bedrock map showing the rest of the catchment (11.5 km by 12.5 km area) north-west of Chesham. Contains Ordnance Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290. Contains BGS materials © UKRI. All rights reserved.

Although the Chess largely flows over the New Pit Chalk Formation, this formation contains several largely continuous marl bands including the New Pit Marls (Figures 1 & 2) situated approximately in the lower-middle part of the formation (Figure 3, Figure 8), and the Glynde Marl situated near the top of the formation. There are also hardgrounds and flint layers (of varying continuity) within the Chalk. Additionally, there are notable marl bands within the Lewes Nodular Chalk Formation including the Caburn Marl Bed and Southerham Marl Bed.

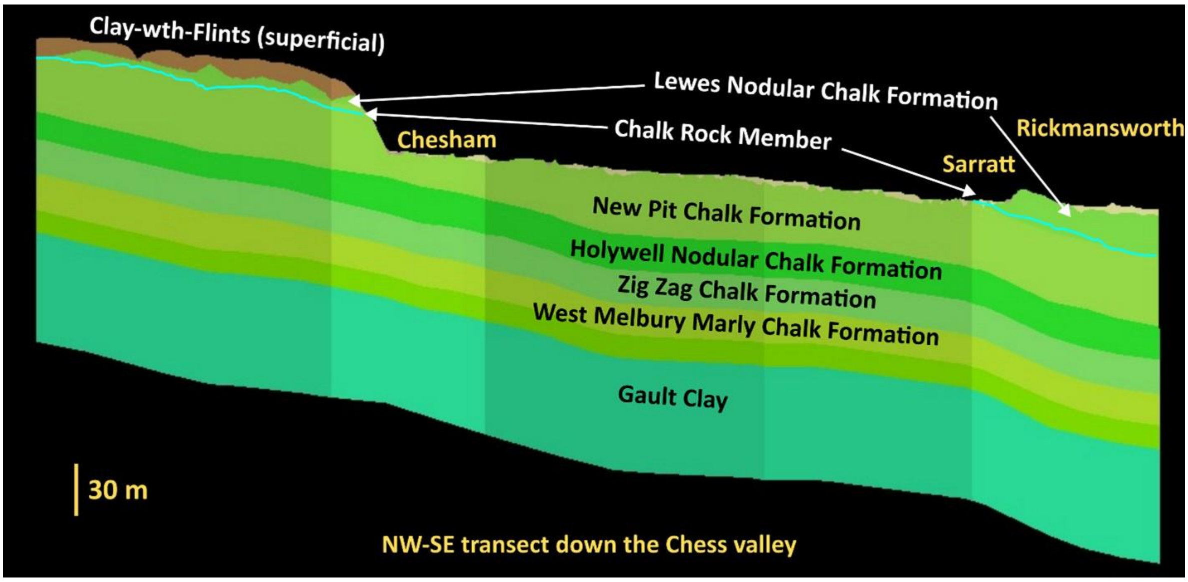

Figure 3: Simplified geological cross-section down the Chess valley showing the Chalk formations. From Farrant et al., 2016.

There are also small outcrops of the Woolwich and Reading Beds of the Lambeth Group located to the east of Chesham and around Sarratt (Figure 2). These comprise of clays, silts and sands.

2.3 Superficial geology

Superficial deposits cover the White Chalk Subgroup across much of the catchment. The Clay-with-Flints Formation is the predominant superficial deposit in the catchment (Figure 4). It primarily results from the modification of the original Palaeogene cover through in-situ weathering, decalcification and cryoturbation, coupled with the dissolution, of the underlying chalk (Klinck et al., 1998). This unit is interpreted as the oldest superficial unit in the study area. It is found across much of the Chess catchment, resting on bedrock of the White Chalk Subgroup.

The formation has been modelled to have a mean thickness of about 8-10 m and a maximum of about 15 m (Figure 5), with the greater thicknesses occurring on the interfluves, whilst it is typically thinner or absent from the valleys. The rockhead is likely to be highly irregular, with the potential for deep dissolution pipes, particularly close to the Palaeogene margin, so the modelled thickness should be treated with caution (Williamson & Terrington, 2020). Some very large dissolution pipes are known from borehole data to occur along the route of the M25, containing sediment derived from the Clay-with-Flints and the Palaeogene. These can be up to 20 m deep.

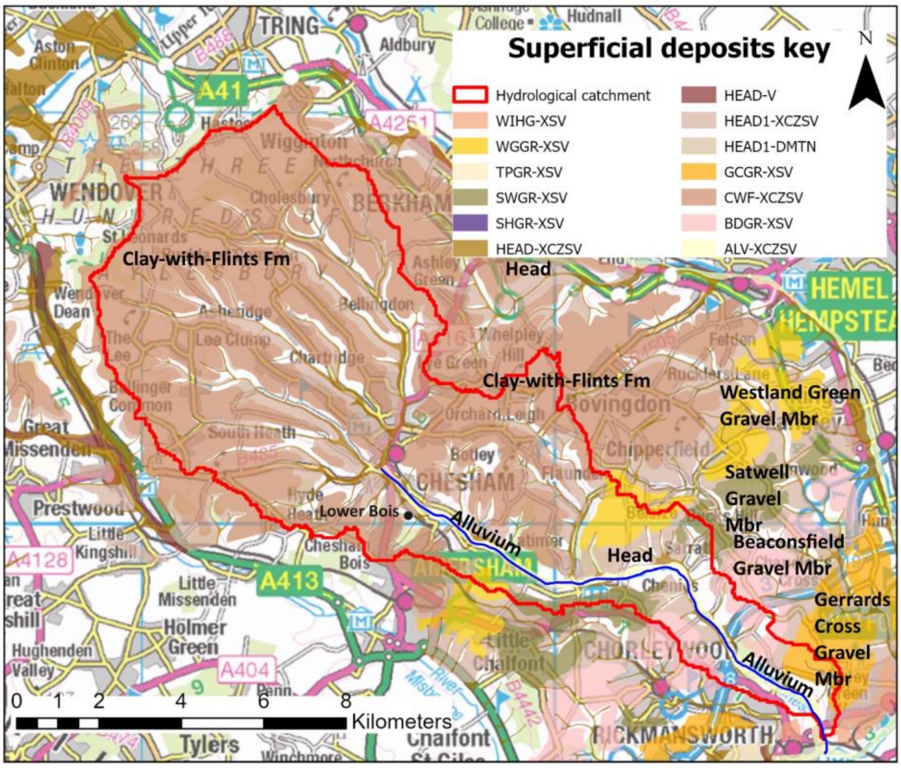

Figure 4: Map of superficial deposits in and around the Chess catchment. Note that the extent of the mapped area shown is from the most recent available data which does not extend to the south-west and north-east areas of the figure. Modified from Farrant et al., 2016. Contains Ordnance Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290. Contains BGS materials © UKRI. All rights reserved.

Other superficial deposits present across the Chess valley floor include Late Quaternary periglacial mass movement deposits on the valley floors. These typically consist of sandy, flinty, gravelly clay or clayey gravel and are typically less than a few metres thick (Williamson & Terrington, 2020). In the lower Chess catchment south-east of Latimer there are gravel deposits including the Westland Green Gravel (1-5 m thick), Satwell Gravel (1-5 m thick), Beaconsfield Gravel (1-7 m thick), Gerrards Cross Gravel (1-10 m thick) and Winter Hill Gravel (1-8 m thick) of the Kesgrave Catchment Subgroup. These gravel members are river terrace deposits associated with the proto-Thames which flowed north-eastwards prior to the Anglian glaciation (Bailey, 2024). The Westland

Green Gravel is the oldest whilst deposits become younger further south-eastwards as the river shifted further south-east (Farrant et al., 2016).

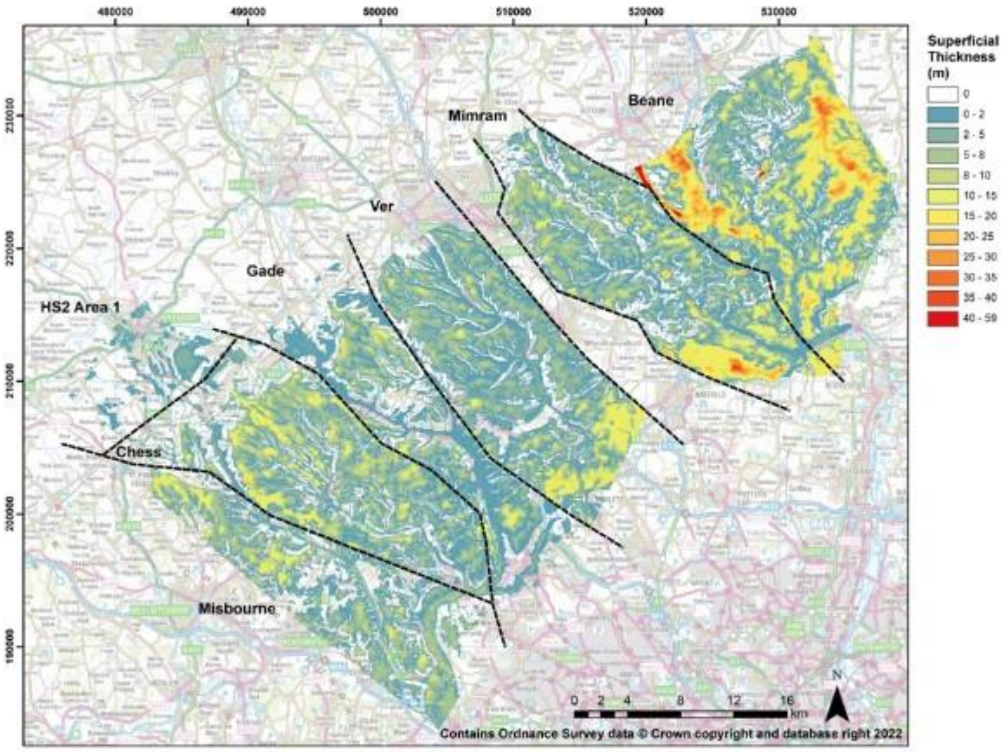

Figure 5: Mean superficial thicknesses modelled across the Chilterns including the Chess catchment showing the spatial extent of deposits. From: Williamson & Terrington, 2020. Contains BGS materials © UKRI. All rights reserved.

In the interfluve areas of the Thames Valley, Putty Chalk has been observed at the top of the Chalk, especially where the Chalk is overlain by the Proto-Thames river terrace gravels (Younger, 1989). Putty Chalk is a soft clayey chalk which formed from the breakdown of fresh Chalk during freeze-thaw cycles. It has a low permeability and therefore may impede recharge or confine aquifer below (Allen et al., 1997). However, Putty Chalk is not widely observed in the Chess catchment (Farrant, 2024).

2.4 Structural geology

The Chalk anticline forms the Chilterns. This anticline has a general south-west, north-east strike and in the catchment the Chalk dips gently to the south-east at an angle of ~0.5 degrees (Williamson & Terrington, 2020). This results in younger formations such as the Seaford Chalk Formation being exposed in the lower River Chess catchment but not in the upper catchment.

Faulting has been identified in the neighbouring catchments such as the Misbourne (Bailey, 2024) but is not visibly extensive within the Chess. There is no evidence of any major faults in the Chess catchment, however, small scale faulting and associated fracturing is likely to occur, particularly just south-east of Chesham around Lower Bois, and further downstream, primarily as extensions of the west-east orientated faults mapped across the Misbourne catchment (Farrant, 2024). There are also north-west, south-east trending faults in the neighbouring Misbourne catchment through the Wendover Gap (Farrant, 2024) which lie close to or possibly within the far north-west of the River Chess groundwater catchment.

The River Chess largely flows along the dip of the Chalk but then flows nearly perpendicular to dip for around 3.5 km from Latimer towards Sarratt, before flowing back along dip to Rickmansworth (e.g. Figure 4). This section of the Chess valley may have formed when the Proto-Thames (or other previous glacial meltwater channels) incised as it flowed north-eastwards towards East Anglia, rather than because of structural geology (Farrant, 2024). During three phases of pre-Anglian glaciation, the Proto-Thames deposited successive gravel terraces comprising glacially derived material across what is now the south-eastern part of the Chess catchment as its course gradually migrated further south-eastwards (Green et al., 1982).

2.5 Hydrogeology

Chalk hydrogeology

The Chalk effective porosity in the saturated zone is primarily through macro-pores, fractures and karst features. All of the Chalk formations described form a principal aquifer. Specific yield in the Chalk is low (typically 1-3%), highlighting the importance of fractures. Although matrix porosity is ~30%, the movement of water in and out of the matrix is dependent on the pore throat size (MacDonald & Allen, 2001; Price, 1987). Where the pore throat size is large enough, matrix storage may occur during high groundwater levels, with subsequent slow release when groundwater levels are low (Taylor et al., 2023). However, groundwater storage is primarily within the fracture network and macropores (MacDonald & Allen, 2001).

Transmissivity and borehole yields in the Chalk are typically higher in the river valleys compared to the interfluves (MacDonald & Allen, 2001). Hydraulic conductivity within the Chalk tends to decrease with depth due to compaction by overburden, and a reduction in chemical/pressure solution (Allen et al., 1997). Fractures and karstic features are responsible for preferential flows paths within the Chalk. Inclined conjugate fracture systems (~60-degree angles) are key to the permeability of the New Pit Chalk Formation, allowing the vertical movement of water (e.g. percolation) through the unsaturated zone (Mortimore, 2021; Bailey, 2024). Meanwhile, low permeability marl bands, flint bands and hard grounds play a crucial role in groundwater flow (see: Hydrogeological significance of marls, flint bands and hardgrounds section for further details). Table 1 summarises the formations present in the Chess catchment and their hydrogeological characteristics.

Table 1: Summary of geological formations in the catchment, their distribution and hydrogeological properties.

Formation (in the Chess catchment)	Formation thickness & distribution	Hydrogeological characteristics	Formation (in the Chess catchment)	Formation thickness & distribution	Hydrogeological characteristics	Formation (in the Chess catchment)
London Clay	Thin, only exposed at one location east of Chesham	Low permeability	London Clay	Thin, only exposed at one location east of Chesham	Low permeability	London Clay
Woolwich & Reading Beds	Thin? Locally exposed east of Chesham & near Sarratt	Low permeability but focused recharge may occur around periphery	Woolwich & Reading Beds	Thin? Locally exposed east of Chesham & near Sarratt	Low permeability but focused recharge may occur around periphery	Woolwich & Reading Beds
Seaford Chalk	Present in south-east of catchment. Top of formation absent (eroded)	Probably unsaturated but important for unsaturated processes and recharge where present. Contains Belle Tout marls	Seaford Chalk	Present in south-east of catchment. Top of formation absent (eroded)	Probably unsaturated but important for unsaturated processes and recharge where present. Contains Belle Tout marls	Seaford Chalk

Groundwater catchment area

The groundwater catchment area of the Chess differs to the surface water catchment area and can vary substantially both seasonally and interannually. Atkins (2007) estimated the size and variable extent of the groundwater catchment from borehole data and additional control points whereby groundwater levels were estimated based on average water levels, seasonal fluctuations and average water levels relative to groundwater fluctuation. They showed that the catchment area contracts following wet periods with high groundwater levels and expands following dry periods when groundwater levels are low (Figure 6). This is partly due to the anisotropic nature of the water table slope on either side of the groundwater divide in relation to the scarp and dip slope (Parker et al., 2016). However, the catchment area variation is not that well constrained due to a low density of observation boreholes in interfluve settings, particularly in the north and west.

The Colne catchment abstraction management system (CAMS) resource assessment calculated the groundwater catchment area as being 102.4 km^2 (Kidney, 2006). Atkins (2007) estimated the groundwater catchment area at different groundwater levels: Typical low = 104 km^2, average = 105 km^2, high = 83 km^2 and maximum = 81 km^2. During wet periods the groundwater catchment area decreases by up to 25% as the Misbourne catchment increases to the north-east (Atkins, 2007).

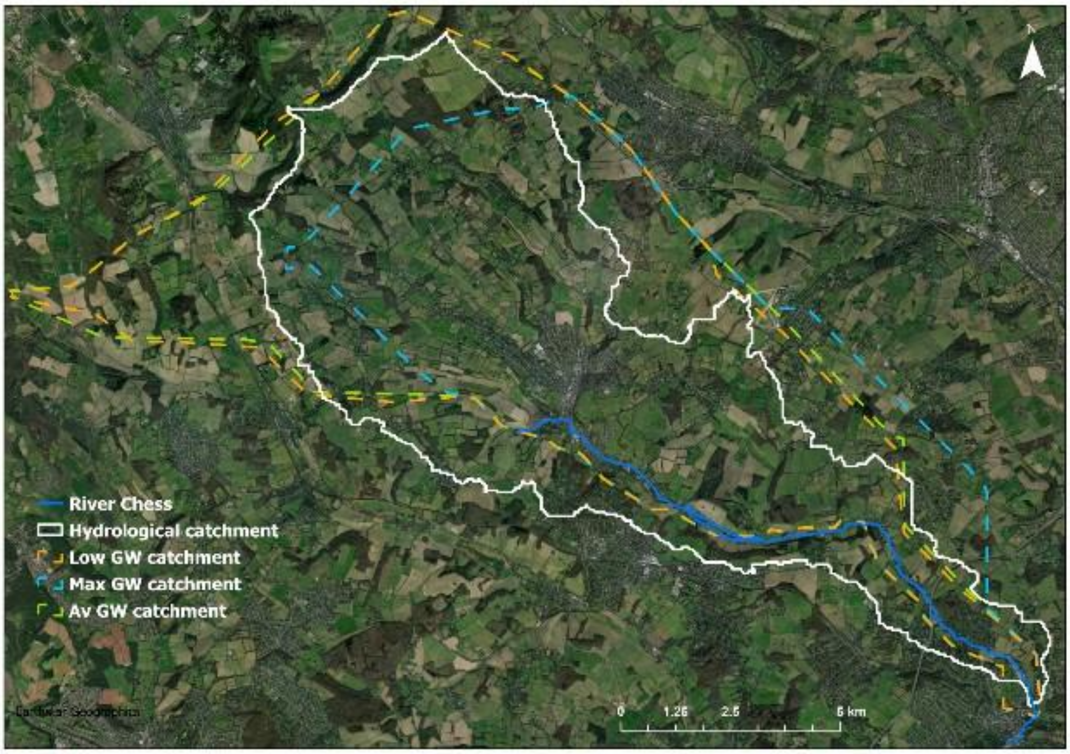

Figure 6: Groundwater catchment area of the Chess during different groundwater level conditions. Delineated based on groundwater level contours from observation boreholes and additional control points. Based on work by Atkins, 2007. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

Complexities arise where the groundwater catchment area differs from the surface water catchment area. An example of this is the Bourne Gutter, a typically dry valley situated hydrologically in the Gade catchment to the east. Groundwater models (e.g. Atkins, 2007) indicate that the upper reaches of this valley (almost always dry) are in the Chess groundwater catchment. The Bourne Gutter occasionally flows following sustained periods of high rainfall, when groundwater levels are high, as a spring fed stream (Pierpoint, 2014). The source of this stream may help constrain the eastern groundwater catchment boundary of the River Chess.

Aquifer recharge, superficial hydrogeology and aquifer discharge

It is expected that recharge predominantly occurs in the upper catchment to the north-west of Chesham and to the north of the flowing parts of the Chess to the east of Chesham. Dry valleys that are free from Clay-with-Flint deposits may also form zones of localised recharge. Enhanced recharge may occur where the chalk is exposed at the edge of the Palaeogene sediments such as those of the Lambeth Group. As these deposits have low permeability, surface water runs off them and becomes concentrated at the edges resulting in an increased concentration of dissolution features in the Chalk (Allen et al., 1997; MacDonald et al., 1998). However, Lambeth Group deposits are largely absent from the catchment (Figure 4). Enhanced recharge may also occur where there are pre-existing dissolution pipes (>20 m deep), sinks, or high concentrations of fractures, whilst the highly variable depth to rockhead and therefore variable thickness of the Clay-with-Flints will probably also affect recharge. Given that surface karst features have not been mapped in the catchment, there remains significant uncertainty with respect to the recharge pathways and amounts through the Chalk.

Clay-with-Flints that cover much of the Chalk in the catchment away from the valleys are likely to play an important role in aquifer recharge, although there are uncertainties in the literature regarding how they affect the amount and spatial and temporal distribution of recharge to the underlying Chalk. The Clay-with-Flints lithology comprises clay (predominantly smectite), silts and sands of various proportions sometimes containing flints, pebbles and cobbles (Klinck et al., 1998). Clay fractions vary from 16-50%, with some deposits comprising a high proportion (up to 70%) of fine-medium sand whilst silt rather than sand comprises a significant component of the more clay-rich deposits (Klinck et al., 1998). Trial pit samples derived from the Chilterns reveal porosities of 0.3-0.5, and hydraulic conductivity values range from 4 x 10^{-5} to 4 x 10^{-9} depending on whether horizons are sandy or clay-rich. Experiments which estimated recharge through the Clay-with-Flints at Rothamsted in the Chilterns indicate that they are capable of transmitting all of the effective rainfall as recharge under certain conditions (Klinck et al., 1998). Therefore, surface runoff will likely occur following high intensity rainfall events in areas where the Clay-with-Flints have an infiltration capacity less than 4 x 10^{-7} m/s, but where they are most permeable, the infiltration capacity is unlikely to be exceeded and recharge to the Chalk will occur (Klinck et al., 1998). It is likely that sandy horizons and sand filled pipes create suitable pathways for drainage into the underlying chalk, whilst karst features infilled with Clay-with-Flints may result in enhanced recharge. Other preferential flow paths within the Clay-with-Flints may include animal burrows, decayed roots and shrink-swell fractures caused by repeated wetting and drying.

Valdes et al. (2014) studied such deposits in Northern France and found that the thickness of the Clay-with-Flints influenced recharge rates. Thicker Clay-with-Flints allowed temporary storage in perched groundwater enabling evapotranspiration, whilst thinner Clay-with-Flints resulted in more diffuse infiltration (Valdes et al., 2014). Valdes et al. (2014) found that recharge to the Chalk is more likely to be focused at sinkholes / karsts where Clay-with-Flints are thick. From geochemical analyses, Valdes et al. (2014) suggest that the Clay-with-Flints are permeable (heterogenous with preferential pathways) and therefore the chalk is unconfined even where these overlying superficial deposits are thick. The absence of surface streams or ponding on the Clay-with-Flints in the Chilterns further supports that these sediments are permeable. A report by Mott MacDonald (2018) similarly suggest that the Clay-with-Flints do not significantly impede recharge to the underlying Chalk and that there is no evidence from the field that they generate runoff.

The Quaternary Proto-Thames deposits including the Beaconsfield Gravels, Chorleywood Gravels and Gerrards Cross Gravels are of high to very high permeability and therefore will not impede recharge into the underlying Chalk. Although not documented in the Chess catchment, there are outcrops of Chalk in the nearby Mimms Valley exhibiting large vertical and horizontal sheet pipes in the Chalk extending to depths of >18 m (Kirkaldy, 1949). These solution features are infilled with river terrace deposit materials (Kirkaldy, 1949) and may act as conduits for rapid recharge. It is therefore possible that enhanced dissolution may occur where these deposits overly the Chalk. As the Proto-Thames sediments are only present around the south-eastern catchment margins they are unlikely to significantly influence the hydrogeological functioning of the Chess, but they are important in the wider River Colne catchment.

There is limited information on the hydrogeology of the head deposits or alluvium that cover parts of the Chess valley floor.

Groundwater recharge in the catchment predominantly occurs during the winter months when rainfall is slightly higher and evapotranspiration is significantly lower, leading to saturation of the soils, percolation and eventual recharge. The amount of recharge during the winter months (when recharge potential is at its greatest) determines the state of groundwater levels for the proceeding summer. A dry winter such as in 1975-1976 was a major factor which led to the lowest groundwater levels on record in summer/autumn 1976 (Mott MacDonald, 2018). More information on recharge values and the implications of recharge for flows in the River Chess are discussed in the hydrological characteristics section.

Groundwater discharge occurs in the valleys where it flows into the Chess, either directly, via natural springs or through artesian boreholes. Groundwater will also flow out of the lower Chess valley around Rickmansworth bypassing the streamflow gauge, whilst groundwater is likely to also flow out of the catchment either towards the lowermost Misbourne and Colne or possibly towards the Bulbourne. This is further discussed in the Chess catchment water balance section.

Groundwater levels and flow direction

Groundwater levels in the catchment range from 120-140 mAOD in the upper catchment down to 45-50 mAOD where the Chess joins the River Colne. The general groundwater flow direction is from the north-west to the south-east, approximately parallel to the dip of the Chalk, though groundwater may flow towards the Chess locally in the valley (Mott MacDonald, 2018). The unsaturated zone (UZ) thickness during average groundwater conditions maybe >60 m in parts of the upper Chess and groundwater levels may vary annually by 20-30 m. Groundwater levels typically peak in the late winter/spring and are lowest in later summer and early autumn. River levels follow a similar pattern.

In the valleys the UZ thickness is much less, and the groundwater level range is typically <10 m. Groundwater levels in the Chess valley are shallow, resulting in groundwater discharge into the Chess along much of the Chess (gaining), though in some sections groundwater levels remain below the riverbed resulting in losing reaches, mostly in the lower Chess. Mott MacDonald (2018) report a steepening of the groundwater gradient in the river valley through Chesham which is possibly related to the natural springs and artesian boreholes discharging into the valley. This steepening of the groundwater gradient could also be from infiltration into the sewerage network in Chesham (Marsili, 2024). Observation boreholes from around Chesham have been used to create groundwater level contours in 2018 (Figure 7) (Mott MacDonald, 2018).

As the course of the Chess has been highly modified, so many smaller channels and parts of the main channel maybe perched along the valley sides and consequently isolated from groundwater during periods of low water levels. Therefore, natural groundwater discharge to the Chess maybe somewhat limited to where the channel is situated in the base of the valley apart from where springs flow directly into the river (Mott MacDonald, 2018).

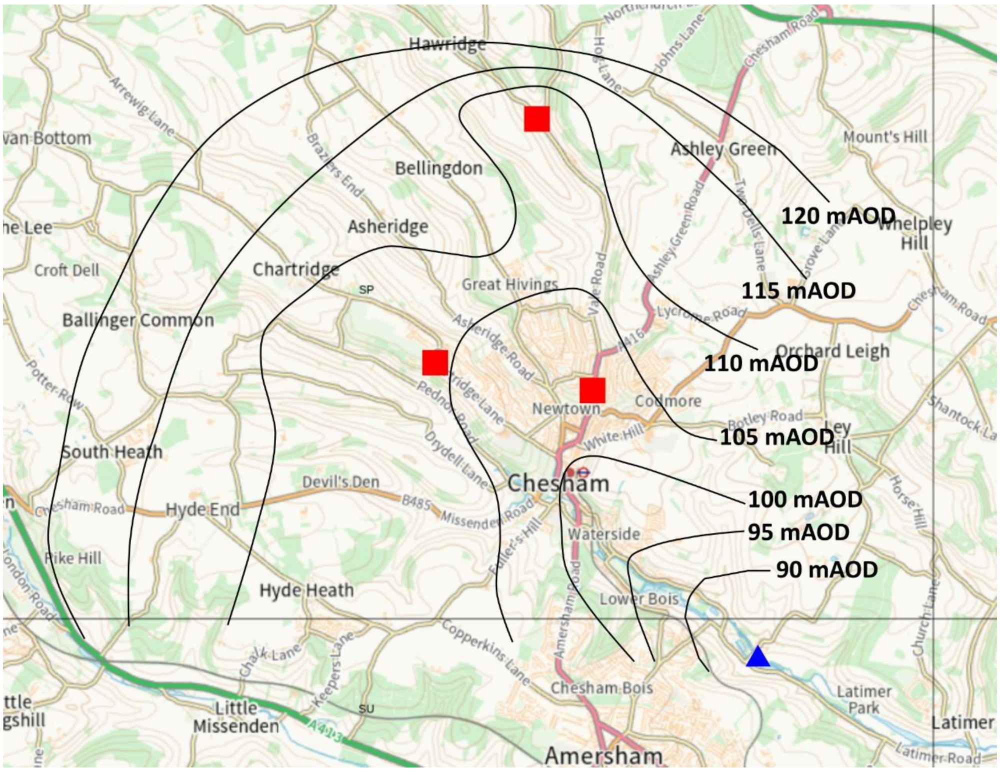

Figure 7: Groundwater level contours from observation boreholes in the upper Chess catchment in 2018. Red squares = approximate locations of abstractions at the time, blue triangle = STW discharge. Note that abstractions have since stopped at CHA and CHE PWS. Based on Mott MacDonald, 2018.

Groundwater flow from recharge areas to the Chess will be largely controlled by solution enhanced features and karst features within the Chalk. In the unsaturated zone, movement of groundwater is most likely to occur through solution enhanced faults and fractures, particularly conjugate fractures, though gradual movement of water though the matrix will also occur. Groundwater flow in the saturated zone is concentrated along bedding planes and joints, conjugate fractures, hardgrounds, marls seams and sheet flints.

Groundwater flow out of the Chess catchment to the neighbouring Misbourne and Colne catchments is likely to occur along the dip direction, especially in the lower reaches of the Chess, but also possibly eastwards along strike towards the Gade around Sarratt. Where the Chess flows over the lower Lewes Nodular Chalk Formation towards Rickmansworth, losses to groundwater may occur along the Chalk Rock resulting in groundwater flow out of the Chess catchment towards the Colne (Farrant, 2024).

Marls, flints and hardgrounds

Karst features in the Chalk can enable rapid groundwater flow (several kilometres per day in some cases), through complex conduit systems. Even where large visible karst features are not visible, rapid groundwater flow may still occur through networks of smaller conduits, fractures and other dissolution features (MacDonald et al., 1998). Rapid groundwater flow is likely to be focused along certain, well connected flow paths, with not all fractures or conduits supporting rapid flow. The occurrence of rapid groundwater flow is likely to be controlled by how saturated the features are; therefore, certain rapid flow paths may only become active when groundwater reaches certain levels (MacDonald et al., 2018). Evidence also suggests that such flow paths are often concentrated around the margins of overlying Palaeogene or superficial deposits where enhanced dissolution has occurred. No major karst features have been identified within the Chess catchment although a few surface depressions / dissolution pipes have been recorded around Chesham and Sarratt Bottom (Maurice et al., 2020).

Low permeability layers in the Chalk including laterally continuous marl bands and flint bands can result in vertical hydraulic discontinuity within the Chalk sequence (Karapanos et al., 2021). Marl bands are thin concentrations of terrigenous clay which are <0.2 m thick, but they can result in vertical hydraulic separation and resulting artesian wells where intercepted by boreholes (Karapanos et al., 2021). There are several marl seams in the New Pit Chalk Formation in the Chess catchment including the New Pit marls 1 & 2 and the Glynde Marl. Conjugate fractures also tend to dissipate along these marl seams (Farrant et al., 2023). These marl bands are therefore likely to act as a barrier to vertical flow, resulting in horizontal flow along them (directly above them). Preferential flow may occur above these bands where dissolution mixing of different waters has occurred and generated a higher frequency of dissolution conduits. Which marl is implicated will vary across the catchment. In the upper Chess it will be marls in the lower-mid New Pit Chalk Formation or even in the Holywell Nodular Chalk Formation. In the lower catchment it will be those in the upper New Pit Chalk Formation and the Lewes Nodular Chalk Formation. It is likely that many of the springs in the Chess valley are associated with marl bands.

Flint bands may also locally focus groundwater flow (Howden et al., 2004). The presence and location of these marls and flints in the Chess Valley may exert a strong influence on groundwater - surface water interactions and hydrology of the Chess (see Bailey, 2024).

Hardgrounds, formed from a hiatus in deposition, are also common throughout the Chalk sequences (Farrant et al., 2023). The Chalk Rock hardground situated in the lower Lewes Nodular Chalk Formation is a set of coalesced hardgrounds (Bromley & Gale, 1982). The Chalk Rock is brittle and is highly fractured compared to the surrounding chalk, increasing the likelihood of dissolution features (Farrant et al., 2023). Therefore, preferential groundwater flow through the Chalk Rock is likely (Figure 8). As the Chalk Rock is situated within the River Chess valley in the mid-Chess, it may be a focused source of groundwater discharge here (via springs), or a zone of groundwater recharge where the Chess intercepts it around Sarratt Bottom.

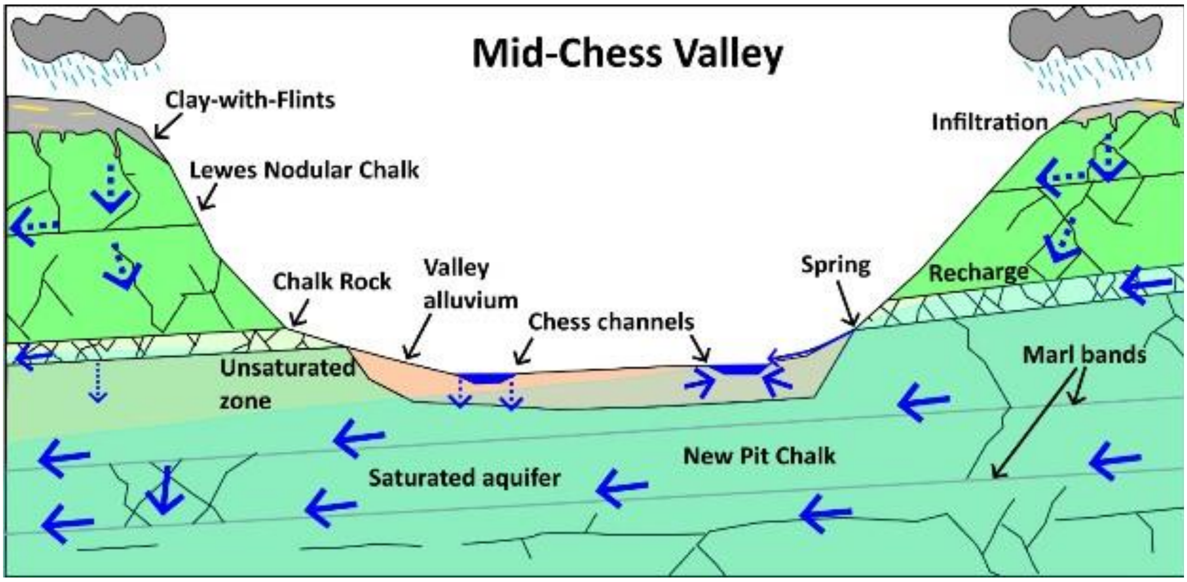

Figure 8: Schematic cross-section sketch of the mid-Chess valley (left = south, right = north) showing groundwater flow in the New Pit Chalk Formation and how marl bands and the Chalk Rock may influence flows.

Observation boreholes

There are a number of existing observation boreholes (OBH) which have been used to help understand groundwater levels, flow directions and responses to changing abstraction. Figure 9 shows the OBH used in the catchment for the AMP6 low flow investigations report (Mott MacDonald, 2018) with two additional boreholes identified. In 2018, groundwater levels were monitored at 20 sites by Affinity Water (Mott MacDonald, 2018).

There are many OBH located in and around Chesham both in the valleys and on the interfluves, but there are very few further downstream except for Mill Farm Barns and Amersham Road. AMR Road OBH lies outside of the catchment but maybe useful for understanding groundwater catchment boundary dynamics. There are no OBH in the far north-west of the catchment. There are also observation boreholes in the nearby catchments (e.g. Colne, Misbourne and Gade) which may be useful for determining the catchment boundary, particularly of the lower Chess. It is thought that most of these OBH are open at depth and therefore intercept multiple formations and layers through the Chalk.

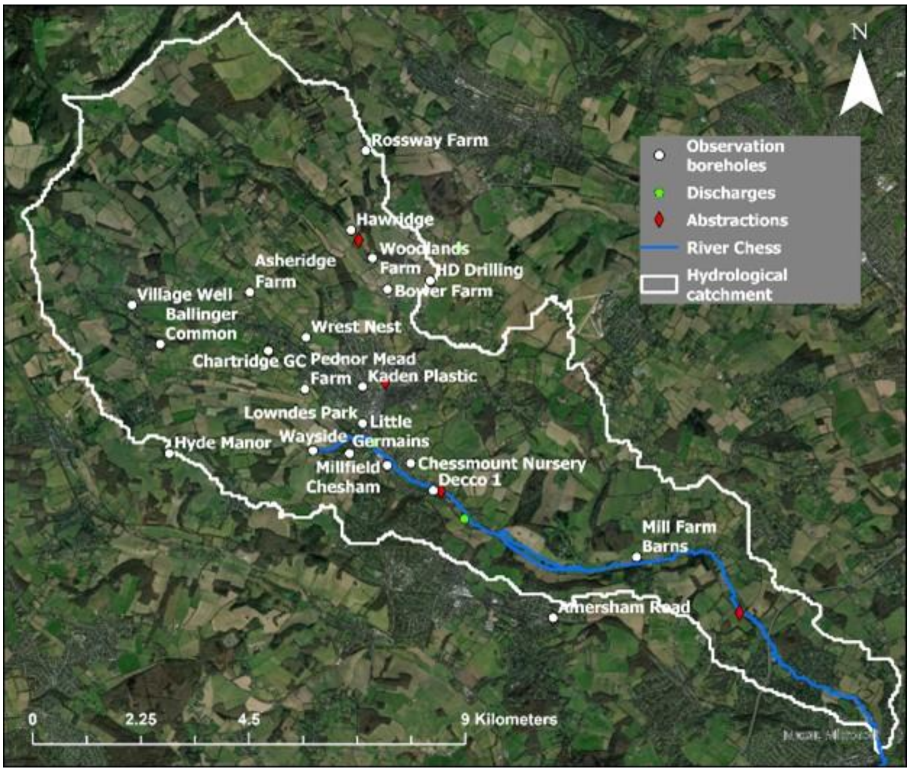

Figure 9: Locations of active and unused observation boreholes in the catchment. Approximate locations of abstractions in 2018 are marked. Chesham sewage treatment works are also shown as the discharge location. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

3. Hydrological characteristics of the Chess

3.1 Precipitation

The average annual rainfall is about 750 mm/a, varying only slightly across the catchment. Modelled averages from 1998-2020 indicate 700 mm/a in the lowermost catchment near Rickmansworth and ~800/a mm in the upper catchment in the north-west (Stantec, 2024). There are records for three rain gauges within or close to the Chess catchment, however, only Chenies TBR (Reference: 278744TP, NGR: TL 01686 00016) is in operation and has been since 1998. The other two located at HAW PS and CSTW have data from 1961-1980 and 1961-1990 respectively (Mott MacDonald, 2018). At Chenies, the mean annual rainfall (Oct-Sep) from 1998-2023 is about 730 mm whilst the highest annual rainfall was 1107.2 mm in 2000-2001 and the lowest recorded was in 459.6 mm in 2004-2005 (EA, 2024a). The highest daily rainfall (9am-9am) over the period was 66.6 mm on 15/09/2015.

3.2 Evapotranspiration and recharge

No evapotranspiration observations are available for the Chess catchment. However, evapotranspiration modelled from 1998-2020 indicate annual potential evapotranspiration (PET) of 620 mm/a in the lowermost catchment and 570-580 mm/a in the upper catchment in the north-west (Stantec, 2024). Atkins (2007) modelled PET for the South West Chilterns Conceptual Model. Using MOSES, PET was estimated at around 500 mm/yr (1961-1990) whilst MORECS PET estimations ranged from 655-720 mm/yr. From this, Atkins (2007) calculated annual average recharge for the Chess at 339.1mm/yr from 1970-2004 (Table 2). Recharge estimates show that maximum recharge typically occurs in December and January, whilst the lowest recharge occurs in July and August (Table 2). Atkins (2007) also modelled average annual recharge using MOSES for the Chess catchment from1994-2004 at 370 mm/yr. This was higher than the recharge calculated using CATCHMOD for the Chilterns East which was 301 mm/yr over the same period.

Table 2: Modelled monthly recharge values for the Chess catchment from 1970-2004 (Atkins, 2007).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
64.3	40.5	35.2	24	12.8	10	8.1	9.6	13.4	28.3	41.2	52	339.1

The Colne CAMS resource assessment calculated effective rainfall (precipitation - actual evaporation) as 211 mm/a (unknown time period) (Kidney, 2006), whilst Stantec (2024) calculated effective rainfall for the Chess at Rickmansworth to be 83.1 Ml/d (approx.265 mm/yr) from a 4R model (1998-2017).

3.3 Hydrological functioning of the catchment

The Chalk aquifer underlying the Chess catchment is recharged via rainfall falling on the Chiltern Hills and percolating through the Clay-with-Flints into the Chalk. The River Chess is predominantly groundwater fed through a series of springs around Chesham. Therefore, the Chess has a very high baseflow index (BFI) of 0.95 (UKCEH, 2024), 0.79 (Stantec, 2024), 0.87-0.94 (Atkins, 2007). The Stantec (2024) value of 0.79 is not directly comparable to the UKCEH BFI as the UKCEH BFI is purely based on hydrograph curve shape analysis, whilst the Stantec (2024) water balance BFI considers the net groundwater - surface water interaction across the whole catchment using model assumptions (calculated net baseflow / total flow). River levels typically peak in the springtime around February-May, whilst lowest levels are typically in late summer and Autumn between August-November (UKCEH, 2024). Data indicates a two-month lag between increased rainfall and a positive response in groundwater levels (Kidney, 2006). Because of the high BFI and limited runoff, large rainfall events typically only have a small influence on flow increases in the Chess.

3.4 Sources and springs

The Chess typically originates from three known sources; Bury Brook, Missenden Road and Vale Road (Figure 10) and is approximately 18 km in length. However, the source and therefore length of the Chess can vary by 2-3 km depending on antecedent conditions (Figure 10) (Stantec, 2024; Kidney, 2006). The upper reaches of the Chess are classified as intermittent, with sections becoming dry following periods of low groundwater levels. The upper catchment upstream of Chesham consists of dry valleys which only exhibit ephemeral flows during wet periods when groundwater levels are at their highest. The location of the source of Chalk rivers such as the Chess tend to show seasonal variability, with the source being located further upstream during the late winter and spring when groundwater levels are at their highest, compared to late summer and early autumn when the source is further downstream (Sefton et al., 2017).

There are many other springs within the Chess catchment in addition to the three main source springs. Mott MacDonald (2018) report various springs and artesian boreholes (which are described later) adding to flows, particularly around Millfields and Chesham Moor. Bailey (2024) states that there are a 'typical' number of springs in the Chess valley (for a Chalk catchment). A combination of historic and modern maps, information and local knowledge has identified approximately 85 springs and 15 artesian wells in and around the River Chess catchment. Approximately 40 springs have been identified on the scarp slope beyond the north-west of the catchment around Princes Risborough, Wendover and Tring. Over 20 springs have been identified around Chesham, along with most of the artesian wells. A cluster of springs are present around Latimer in the mid-Chess, and there are also several in the lower catchment opposite the Royal Masonic School for Girls. Bailey (2024) logged 11 springs between Latimer and Scotsbridge Mill and three more likely springs at spring fed ponds. At least eight springs have been identified near Rickmansworth High Street, presumably from groundwater flowing southwards in the lower Chess catchment, with many more springs likely in this area. Although there is limited information for most of these springs, some like the Chess source springs and Wendover springs have significant discharge, whilst others are very small or temporary.

Springs occur close to the Lewes Nodular Chalk Formation – New Pit Chalk Formation boundary, particularly in and around Chesham. It is likely that marl seams within the upper parts of the New Pit Chalk intercept the surface around Chesham resulting in groundwater outflow. Farrant et al. (2016) notes that the Chesham artesian springs occur where the base of the New Pit Chalk starts to dip > 20m below the valley floor.

In the Lower Chess, springs mostly occur within the Lewes Nodular Chalk Formation below the slope breaks created by the underlying Chalk Rock unit and where groundwater flows along marl bands such as the Caburn and Southerham Marl Beds close to the boundary with the New Pit Chalk Formation (Bailey, 2024).

Springs on the scarp slope such as those at Wendover appear to occur from the Zig Zag Chalk Formation or the West Melbury Marly Chalk Formation.

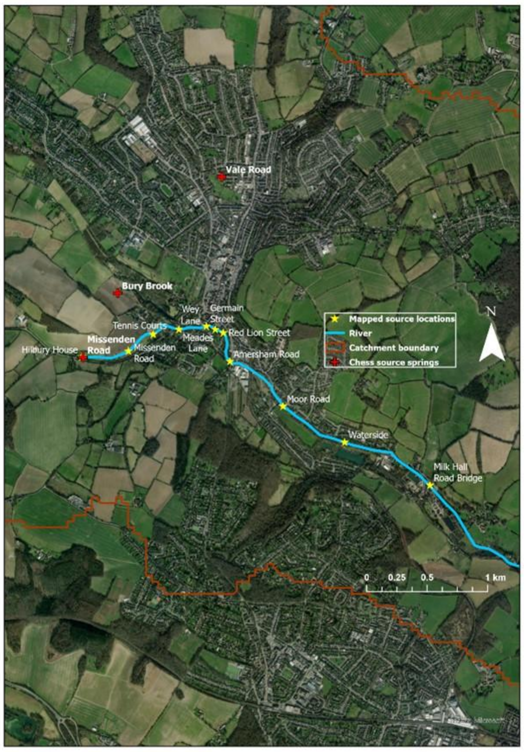

Figure 10: Three main source springs of the Chess in and around Chesham. Varying starting points of the Chess from 1997-2018 mapped by the EA are also shown. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

3.5 Gauging the Chess

Discharge on the River Chess is gauged at Rickmansworth (NRFA 39088) (NGR TQ0657394809) and has a mean flow of 0.542 m^3/s or 46.74 Ml/d (1974-2023). The Q95 is 0.18 m^3/s and the Q5 is 1.08 m^3/s. There is also a river level gauge in Chesham (station reference: 2852TH) (NGR SP9857301341) which has been in operation since 2006 (EA, 2024a).

The EA, Affinity Water and volunteers have spot gauged the Chess at over 20 locations at a variety of frequencies (Figure 11), but often at fortnightly-monthly intervals. Data has been collected sporadically at some locations since the 1950s, but intensive spot gauging has taken place since December 2015. Although such data cannot give an accurate temporal overview of flows in the Chess, it provides valuable information on where flow accretion occurs and of losing reaches. Flow accretion/losses are discussed below.

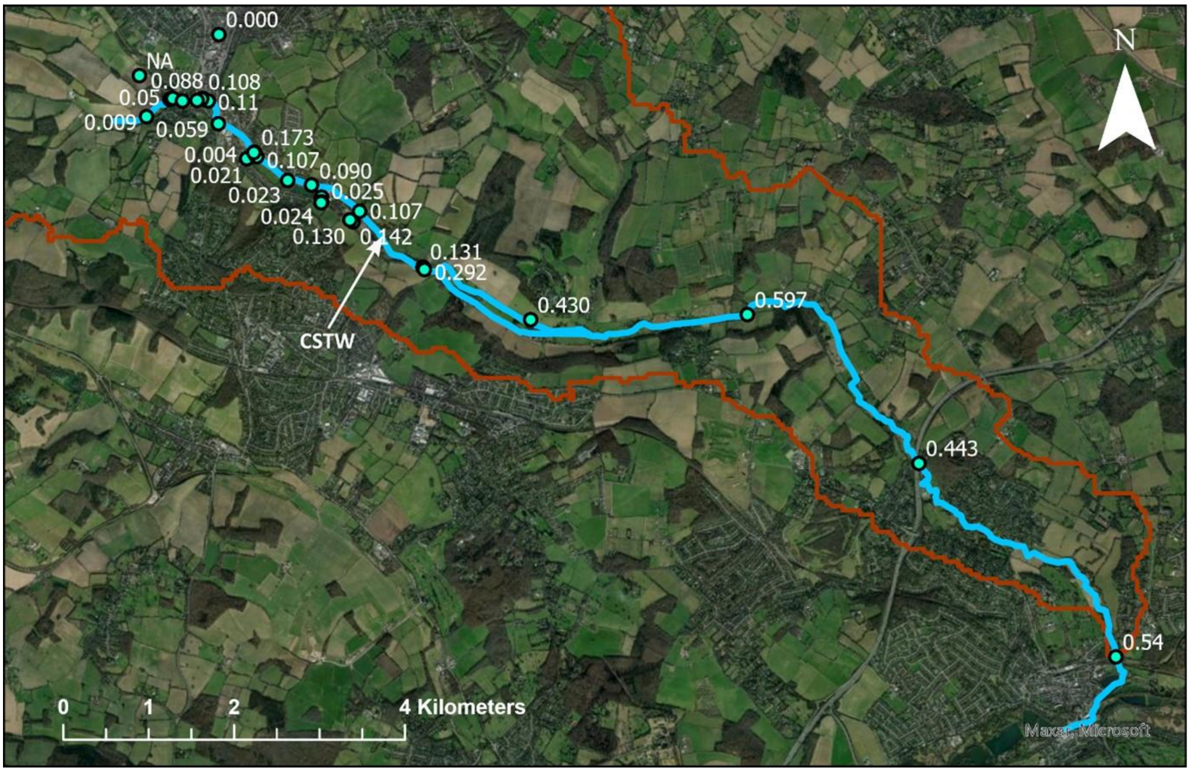

Figure 11: Spot gauging locations with mean discharge values (m3/s). Values collated from numerous sources collected over different time periods at different frequencies. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

3.6 Historic channel modifications

The Chess has undergone a number of changes over the centuries. Parts of the upper Chess are confined to culverts, particularly the Vale Road tributary which runs past the Chesham abstraction before being culverted under Chesham High Street. Many mills were constructed on the Chess since the 17th century (Mott MacDonald, 2018). At Lords Mill (Figure 14, near site 3), the natural channel has been diverted and split into two or more channels. Some diverted channels run in an elevated position above the valley floor (e.g. Weir House Mill and Cannons Mill Weir) (Figure 12). Downstream of the CSTW, the River Chess is split into two parallel channels which, the main River Chess and the Little Chess within to which the treated waste is discharged. These two channels are present along much of the mid-Chess. Parts of the Chess channel have also been widened for watercress beds. There are also small waterfalls and associated dammed and ponded sections such as at Latimer.

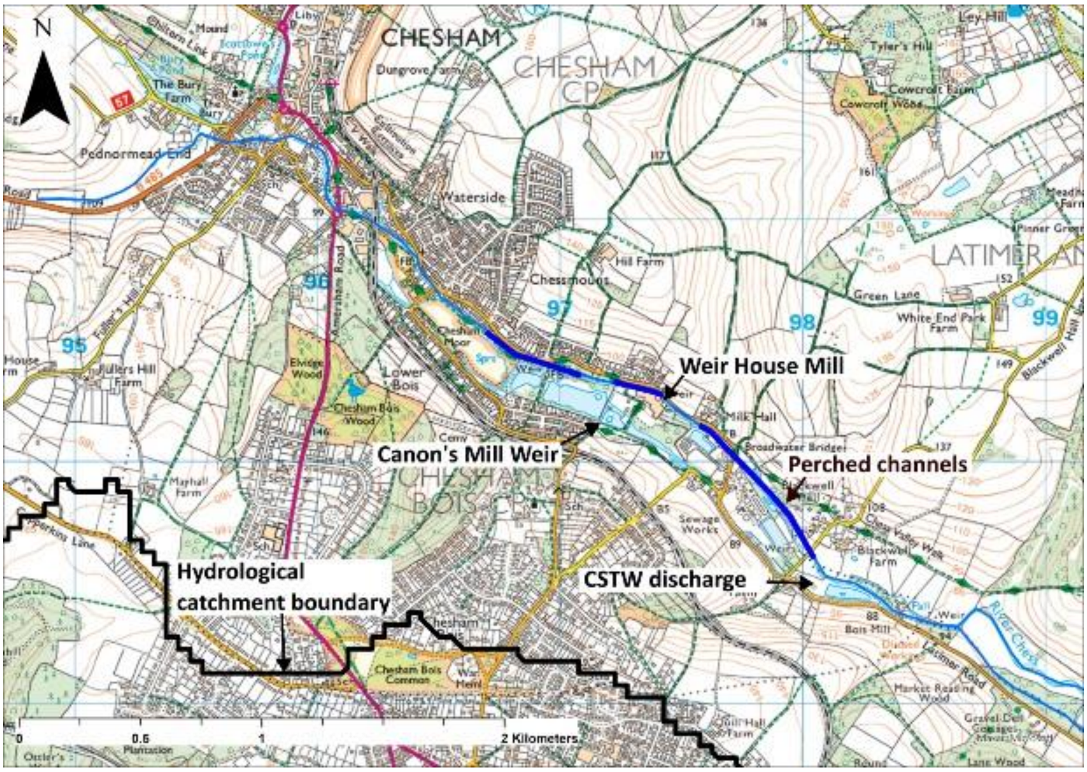

Figure 12: Perched channels near Chesham. Contains Ordnance Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290.

3.7 Historic artesian wells

Artesian wells constructed between 1850-1950 for water cress farms have resulted in artificial springs which discharge into the Chess resulting in artificially derived baseflow. Up to 30 artesian boreholes are present in the area between Millfields and the Decco site, some of which still flow (Stantec, 2024). This artificial baseflow has not been properly quantified but it was documented that three artesian boreholes maintained the lake at the Nestle POWWOW site (Decco) (Ewan, 2007), and Jacobs (2008) stated that these boreholes increase flows in the Little Chess by 20%. At the time, the bottling plant had a licence to abstract 0.18 Ml/d from flowing artesian boreholes (Mott MacDonald, 2018). These artesian boreholes discharge into the Little Chess first, before flowing into the Chess. During the 2018 drought these artesian flows were the main source of water for uppermost reaches of the Chess. The artesian wells around the Decco site coincide with the base of the New Pit Chalk Formation or top of the Hollywell Nodular Chalk Formation and are believed to be caused by marl layers at the base of the New Pit chalk Formation (Mott MacDonald, 2018). There are other artesian wells situated in Chesham and downstream between Latimer and Sarratt Bottom but there is little information on the total contribution of artesian flows to the Chess.

3.8 Abstractions

Major current and historical abstractions are listed in Table 3 and shown in Figure 13. CHE PWS (stopped 2020) was possibly going to resume abstractions from June 2024 - April 2029 at a daily rate of 2 Ml/d with the potential to increase to 7 Ml/d during high groundwater levels. This resumption was to be undertaken as a precaution to mitigate potential flood risk whilst a fluvial/flood risk model is being undertaken (EA, 2024b), however, it no longer appears to be happening. The Weir House Mill private, non-consumptive abstraction is situated just downstream of Chesham (Figure 13). There are no known water imports into the catchment from surrounding areas.

Table 3: Summary of abstractions in the catchment using data from multiple sources including Affinity Water (2024), Stantec (2024) and Mott MacDonald (2018).

Site	Public/ private	Groundwater/ surface water	Current/historic abstractions	Abstraction period	Current abstraction rate (actual Ml/d)	Abstraction licence (max permissible Ml/d)	Historic abstraction rates (Ml/d)/times
CWD	Public	Groundwater	Current	1987-2024	8.7	9	
HAW	Public	Groundwater	Current	Pre-1970	6	9.12	3.7 (2005) 6.5 (until Jan 2021)
CHE	Public	Groundwater	Historic	1971-2020	NA		3.11 - 3.2 Ceased Aug 2020
CHA	Public	Groundwater	Historic	1971 to Jan 2018	NA		1.8 (2005) 1.2 more recently
WDN	Public	Groundwater	Historic	Ceased Jan 2018	NA		
Weir House Mill	Private	SW	Current	?	1.16	18.6 (throughflow)	
POWWOW (Holywell spring)	Private	Groundwater	Historic	<2006?	NA	0.42	0.1-0.34 (2005)

1

Total abstraction in the upper Chess catchment has reduced significantly in recent years from 16.4 Ml/d in the early 2000s when there were five licensed abstractions (three public supply) (Kidney, 2006). Since then, total abstraction in the upper Chess has decreased to around 10 Ml/d in 2015-2017 and then to around 5.5 Ml/d as of November 2022 (Affinity, 2023). This decrease is largely due to stopping abstractions at CHA and most recently CHE.

Abstraction at CWD in the lower catchment has remained stable at around 8.7-9 Ml/d. Therefore, total abstraction in the Chess have decreased from around 25.5 Ml/d in 2004 to ~14.5 Ml/d by 2022. Over 50% of the abstraction in the catchment is non-consumptive, which may need to be considered in the water budgets. Some non-consumptive water maybe returned to the Colne, rather than the Chess which could result in water balance errors. Any future abstractions from CHE PWS would be returned into the catchment, as were abstractions from CHA PWS when this was used to supply Chesham. Abstractions from HAW (6 Ml/d) are exported out of the catchment and are not returned. Most of the abstractions from CWD are used to supply water to Chesham (Marsili, 2024). Once used, it is treated at the CSTW and returned to the Chess (EA, 2024c). A minor proportion of water from CWD is exported outside the Chess catchment and is not returned to the Chess (Marsili, 2024).

There is also a large abstraction (10-50 Ml/d) just to the east of the lower Chess between Rickmansworth and Watford. It may be possible that this abstraction draws down groundwater levels in the area, perhaps reducing river flows or altering groundwater flow directions (Atkins, 2010).

The HGCM model (Mott MacDonald, 2019) was used to consider the impacts of cross-catchment impacts from abstraction. It predicted that the low flows in the perennial Chess would be increased slightly (higher discharge) following groundwater abstraction reductions within the intermittent Misbourne catchment (Stantec, 2024).

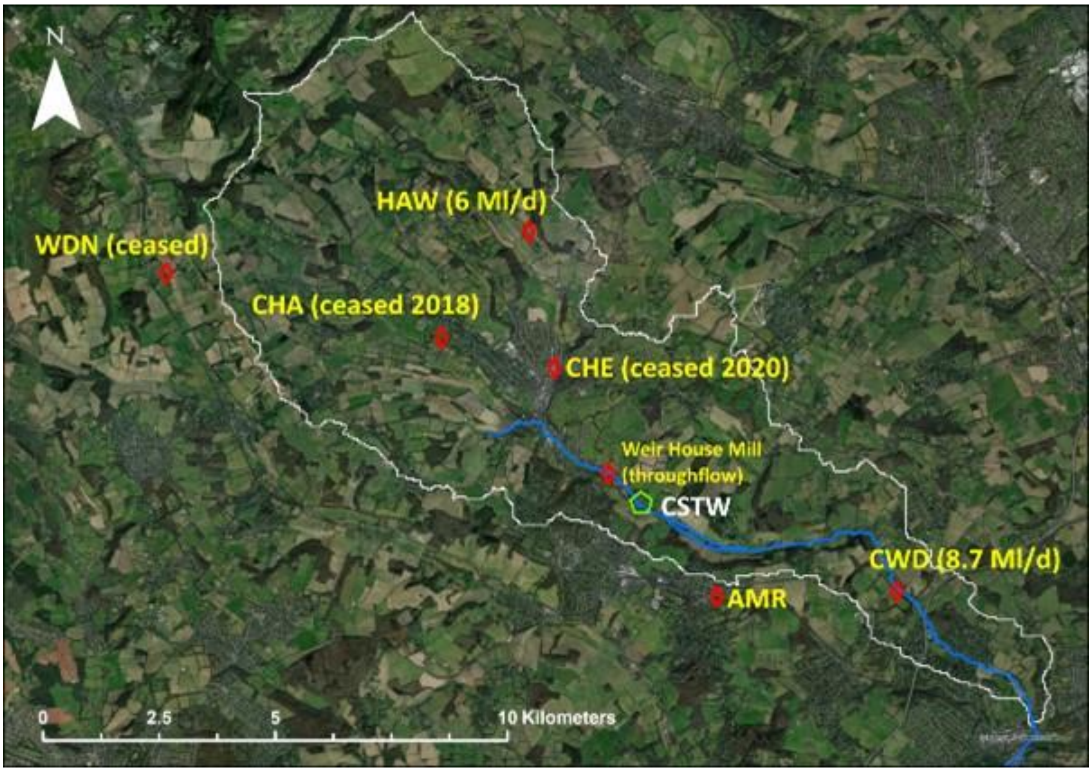

Figure 13: Main operating and recently ceased public water supply abstractions showing mean abstraction rates. Borehole locations approximated. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

Abstraction signal tests

Investigations into the impact of abstractions and recovery from stopping/ceasing abstractions at two public water supply abstractions (CHA and CHE) were undertaken in the catchment in 2016 and 2017 (Mott MacDonald, 2018). Both shutdowns occurred during dry periods.

CHA abstraction was 1.2 Ml/d before the shutdown which lasted for 15 days (4th-20th Oct 2016). CHA recovery test findings observed changes in groundwater levels in shallow and deeper observation wells. These changes indicated that the impacts of abstraction from producing horizons at CHA are readily transmitted through the Chalk to the aquifer intercepted at a shallow depth at Wrest Nest, situated 830 m to the west. Therefore, abstraction might have an impact on groundwater flow in any Chalk fissures at shallow depths which support flows in the Chess just upstream of Chesham. However, the test showed no indication of an increase in river flow at three sites from the shutdown at CHA (Mott MacDonald, 2018). Given the vertical hydraulic discontinuity observed in the Chalk due to the marl bands, abstractions from a particular horizon may not affect flows in the nearby river which maybe fed by another flow path at a different depth. However, abstractions may affect a river in another location if it is fed by groundwater from the flow paths tapped by abstraction (Karapanos et al., 2021).

CHE abstraction was at 3.11 Ml/d before a 13-day shutdown (2nd-15th May 2017). Following the shutdown, recovery test findings saw small recoveries in groundwater levels observed in shallow and deeper observation wells. For instance, a borehole about 500 m away saw a recovery of <0.3 m or about 6% of the total seasonal fluctuation (Marsili, 2024). Similar impacts were observed when CHE PWS abstraction ceased in 2020, with measured recoveries in boreholes around Chesham, including a 0.04 m recovery at Millfields, approximately 1.8 km downstream (Affinity Water, 2023). These shutdowns indicate that abstraction impacts from producing horizons around Chesham are rapidly transmitted through the Chalk aquifer.

Analyses of flow monitoring data from Mott MacDonald (2018) following the shutdown of CHE PWS in 2017 suggests that river flows in the Chess between Meades Water Gardens and the Decco site recovered by 0.8-1.8 Ml/d (including some rainfall effects). This recovery was equivalent to 26-58% of the average daily abstraction occurring at CHE PWS prior to the test (Mott MacDonald, 2018). As these reaches are known to be heavily influenced by artesian flow, it is likely that at least some of the flow recovery is associated with increases from the artesian wells around the Decco site given the abstraction borehole intercepts similar horizons. Abstractions at CHE might also impact groundwater flow in any Chalk fissures which support springs or seepages feeding the Chess upstream of Lords Mill, where marl layers are believed to crop out (Mott MacDonald, 2018).

HAW abstraction was 6 Ml/d prior to a 12-hour outage in August 2016. During this outage, a groundwater level response was observed in a deep borehole and also potentially in a shallow borehole down-gradient of the source. The response in the shallower borehole could indicate that the effects of a short-term change in abstraction at the HAW source may be transmitted to the Chalk above the casing depth of the HAW boreholes.

3.9 Sewage treatment works discharge and mains leakage

Chesham has a population of over 20,000 and is the largest urban area in the catchment. Much of the water abstracted from the Chalk is used by the population of Chesham and is then returned to the catchment via the Chesham sewage treatment works located next to the Chess just downstream of Chesham (no major import or export). The works are situated in the valley relatively close to the perennial head of the Chess. CSTW plays a significant role in flows on the Chess, with flow accretion profiles (Figure 14) showing a large increase in flow downstream of the works.

Atkins (2007) reported that sewage treatment works discharges and leakage combined were slightly higher than abstractions. Recent modelling of CSTW discharge to the river is estimated at 6.3 Ml/d (Stantec, 2024), though it was as high as 14.5 Ml/d in 2005. Peaks in sewage discharge normally occur one-two months after groundwater levels peak at Ashley Green STW OBH. Treated sewerage discharge based on the population of Chesham and water per capita is around 6.3 Ml/d during dry weather conditions. However, CSTW regularly treats much higher volumes, sometimes exceeding 28 Ml/d during periods with high groundwater levels due to groundwater ingress into the sewerage system (Thames Water, 2015). This indicates that groundwater ingress into the sewerage system can exceed 22 Ml/d. Discharge of treated flows during periods of high groundwater levels can therefore significantly contribute to baseflow in the Chess (with a mean flow of 46.7 Ml/d at Rickmansworth).

There have been incidences where the sewage treatment works have not been able to cope with all incoming flows, triggering spills to the storm tanks in periods of dry weather (storm tanks are meant only for high volumes associated with wet weather). Consequently, spills have occurred to the river on both dry and wet days (Thames Water, 2021). Overspills during drier weather occur as groundwater ingresses into the sewers at various points in the Chess valley, especially in Chesham and near to the sewage treatments works. This is because here groundwater levels are shallow (especially late winter and spring) and often enter the sewerage system. Approximately 16.3 km of sewer length is estimated to be vulnerable to groundwater ingress (med-high risk), whilst a survey in 2019/20 revealed 30 groundwater infiltration locations in the sewers, of which six were significantly flowing (Thames Water, 2021). Spills were massively reduced by 2022 following works and upgrades to the sewage network.

Atkins (2007) also report a minor additional STW discharge into the river at Latimer (0.1 Ml/d in 2005), at Chenies (0.02 Ml/d in 2005) and a small unquantified discharge to ground at Snowhill Cottages on an interfluve.

Stantec (2024) estimate an additional 1-2.5 Ml/d of water enters the Chess at Chesham through mains leakages. They estimate that the overall mains leakage contribution to the Chess at Rickmansworth is 3.1-3.2 Ml/d, but can vary between 2.5-5 Ml/d.

3.10 Flow accretion and groundwater – surface water interactions

As mentioned, the length of the flowing Chess varies depending on seasonal variation on groundwater levels. During a survey from March 2004 – March 2019, the proportion of the Chess flowing was 0.83, whilst the proportion of the ponded Chess was only 0.01. During this study, the lower ~13 km of the Chess was always flowing (Sefton et al., 2019). The Chess is also characterised by continuous flow along much of its length with little fragmentation. It is also characterised by a lack of high flows along its length, due to the predominance of groundwater baseflow (Sefton et al., 2017).

Spot gauging at >20 sites along the Chess by the EA, water companies and volunteers indicate that the River Chess flow accretion (discharge increases) occurs downstream from the sources near Chesham. The graph in Figure 14 shows flow accretion at various locations from upstream (left) to downstream (right) at different dates. Monitoring of flow accretion in the upper Chess around Chesham highlights that near continuous flow accretion occurs in the upper reaches. Gauging has revealed that significant flow accretion occurs further upstream of the CSTW, between Lords Mill and the Decco site (sites 6b-7 & 8) which is 3-15 times greater than modelled flows). This is probably because of the groundwater discharging from artesian boreholes and entering the Chess along this reach. There is sometimes a loss of water between Chesham Weir and CSTW due to the diversion in flow between two channels (Mott MacDonald, 2018). The CSTW is situated between sites 9 & 10 and 11 & 12. Here, a significant increase in flow is always observed due to the sewage discharge into the Chess (Mott MacDonald, 2024).

Flows in the middle reaches of the Chess from Bois Mill (sites 11 & 12) to Valley Ford show more complicated flow accretion patterns (Figure 15). A small increase in flow is sometimes observed between Bois Mill (Figure 15 lower right) and Latimer, probably in large due to two more artesian boreholes at Bois Mill. However, other data show a slight decrease in discharge between Bois Mill and Latimer, indicating losses to groundwater. The Chess splits into the main Chess and Little Chess channels along much of this reach but it is unclear whether the EA measurements at Latimer incorporate both channels. River discharge sometimes peaks at Latimer where the Chess has started to dog-leg, or more typically at Valley Ford Farm near the corner of the dog-leg (Mott MacDonald, 2018; Atkins, 2007). EA data suggest that there are sometimes losses and sometimes gains between Latimer and Valley Farm Ford (Figure 15). Recent satellite imagery (08/05/2024) following the wet winter and spring of 2023/2024 shows two visible springs entering the River Chess immediately downstream of Latimer Bridge, with one of these originating from the large dry valley to the north of Latimer (Figure 16). As well as springs in this area there maybe a palaeochannel of the Chess which is faintly visible, running parallel to the north of the existing river channel (Figure 16). The springs here would explain the gains often observed between Latimer Bridge and Valley Ford Farm. Unlike most of the Chess which flows approximately parallel to dip (south / south-east), this section of the Chess flows east / north-east, closer to strike. It is possible that losses occur along this section when groundwater levels are low as groundwater is believed to flow beneath the river to the south / south-east; whilst during high groundwater levels, flow accretion occurs as the groundwater flowing from the north / north-west intersects the river, flowing out at springs. These springs occur toward the top of the New Pit

Formation. There is also a watercress farm with an artesian borehole near Valley Ford Farm which may increase flows here (Mott MacDonald, 2018).

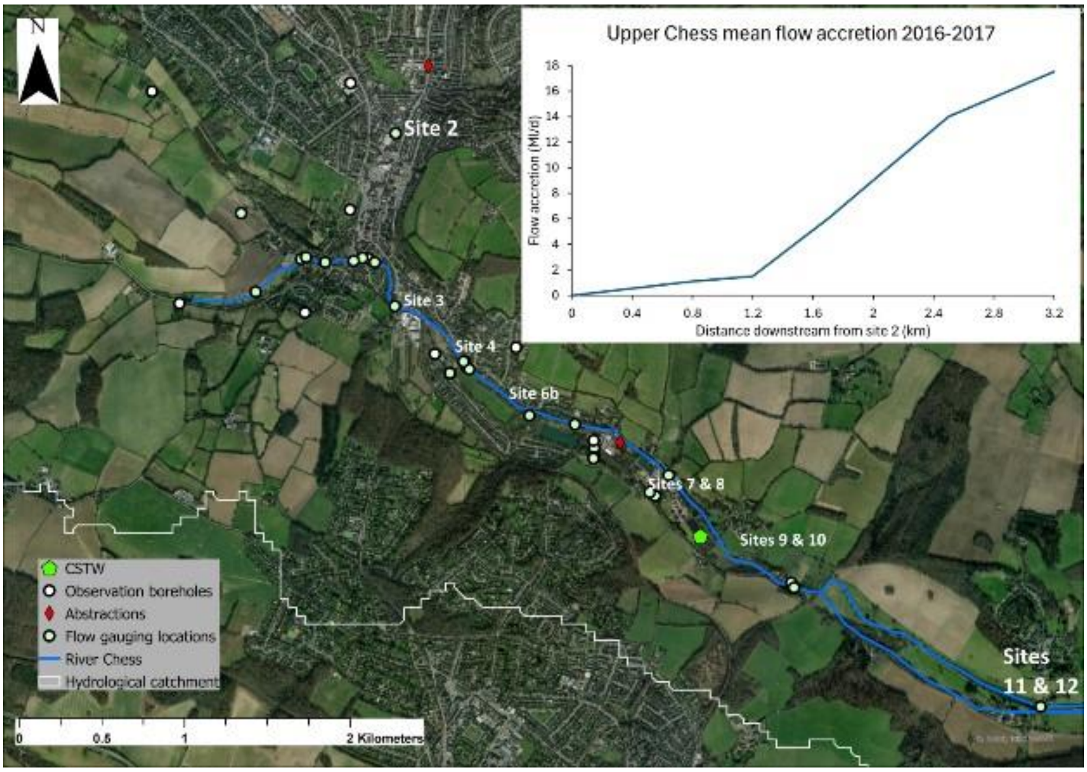

Figure 14: Flow accretion in the upper Chess during 2016-2017 from 10 rounds of approximately monthly spot gauging. Graph based on Mott MacDonald, 2018. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

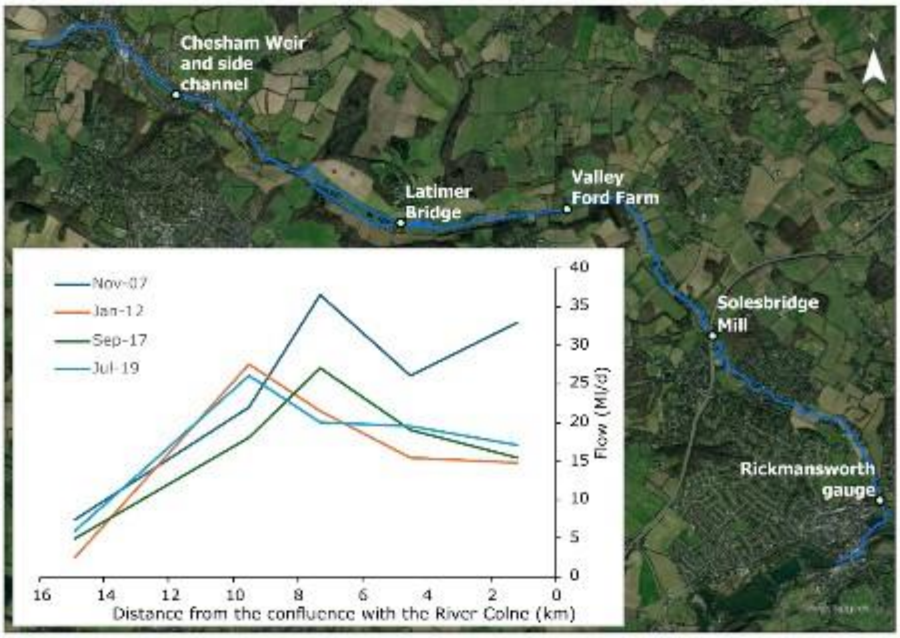

Figure 15: Flow accretion in the mid-lower Chess. Data collected by the EA, graph based on Marsili, 2024. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

Figure 16: Some of the springs at Latimer. Modified from Google Earth (Airbus), 2024.

Downstream of Valley Farm Ford to Solesbridge Mill in the Lower Chess a general decrease in flow is observed (Figure 15). Decreases along this section occur independent of the season/ preceding groundwater level conditions (Kidney, 2006; Atkins, 2007). Note that the CWD abstraction borehole is situated between these two sites. However, studies have shown that CWD PWS abstraction cannot be wholly responsible for losses in the lower Chess which averaged 19.3 Ml/d (ranging from 10-26 Ml/d) in 2023, as CWD PWS never exceeds 9 Ml/d (Bailey, 2024). Table 4 shows losses in the River Chess from Valley Farm Ford to Rickmansworth in Ml/d over six months in 2023. Chess flow accretion profiles from Jun-Nov 2023 show a major decrease (sometimes 30-40%) in flow between Latimer-Valley Ford and the gauging station at Rickmansworth (Figure 18) (Affinity, 2023). This approximates to where the Chess flows over the uppermost New Pit Formation and lowermost Lewes Nodular Chalk Formation (Bailey, 2024).

Table 4: Flow losses along the lower reaches of the Chess in 2023. Data from Affinity, 2023.

Month	Total estimated daily losses (Ml/d) between Valley Farm Ford and Rickmansworth
Text	Text
June 2023	10.4
July 2023	18.2
August 2023	25.8
September 2023	22.7
October 2023	15.5
November 2023	24
Average	19.3

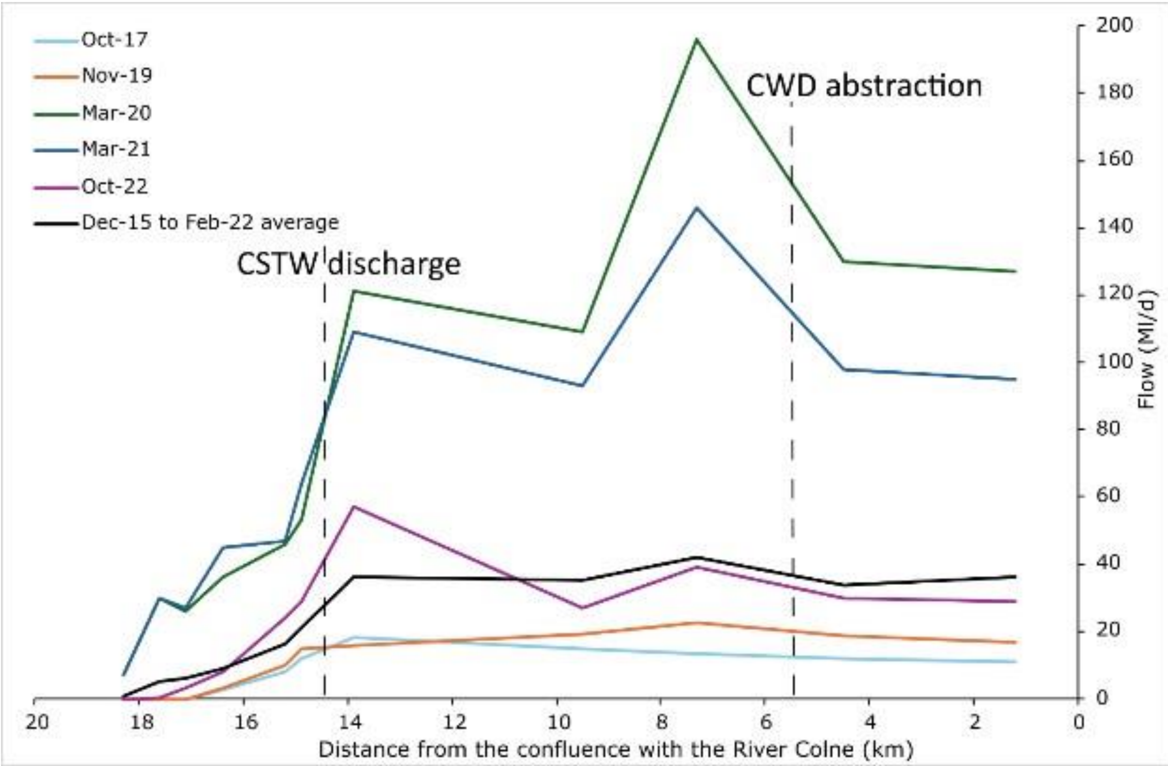

Figure 17: Flow accretion along the entire River Chess profile at various times between 2017-2022 during different hydrological conditions. Graph based on Affinity Water, 2023.

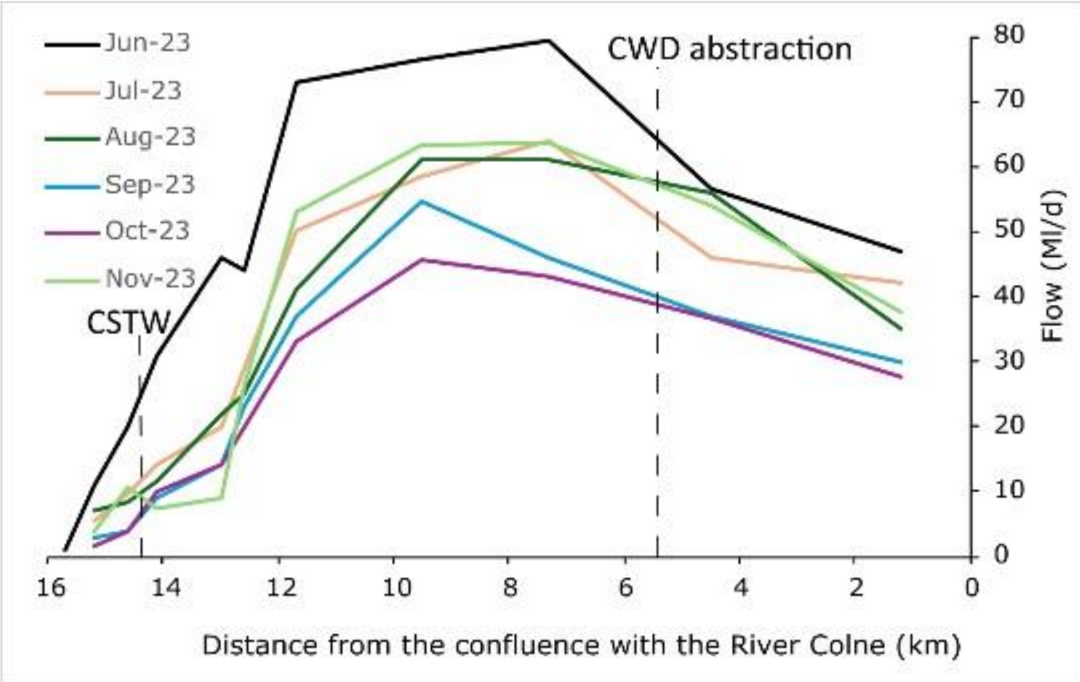

Figure 18: Discharge (Ml/d) along the Chess in 2023. Graph based on Affinity Water, 2023.

Karapanos & Marsili (2024) suggest that groundwater in the lower Chess may flow eastwards along/sub-parallel to strike towards the Gade rather than southwards towards Chorleywood, thus explaining the losing reach. The other possibility is that groundwater continues to flow along dip to the south-east towards the Colne and lower Misbourne. Historic maps support this hypothesis of south-eastward flow, as they show numerous springs in the Colne Valley between Rickmansworth to Maple Cross (Farrant, 2024). Given the surface water and groundwater catchment areas along this reach are very narrow there would naturally be less flow accretion. It could be that groundwater in the lower reaches is flowing more southwards towards Chorleywood and ultimately to the Colne which flows southwards. If groundwater levels are below the riverbed along this section (i.e. groundwater gradient exceeds river valley gradient), there will gravity drainage losses to groundwater independent of groundwater - surface water flow direction. However, the presence of flowing artesian boreholes around Sarratt indicates overpressure of groundwater with heads above the riverbed elevation. The depth and therefore geological horizons that these artesian boreholes intersect is unknown. The main River Chess channel between Valley Ford Farm and Solesbridge Mill sometimes diverges into two channels along the valley floor, therefore the artificial channel (possibly the main channel) maybe perched above the valley base which could increase infiltration losses along the reach. There may also be solution enhanced features beneath the riverbed in places which could also affect flow accretion depending on whether such features in the Chalk are saturated or not. Observations along the equivalent reaches of the neighbouring River Misbourne similarly show discharge losses, indicating that geological controls may be affecting surface flows.

3.11 Overland flow

Although a groundwater dominated catchment, a combination of high intensity rainfall events occurring on relatively steep valley slopes make the catchment valleys somewhat vulnerable to flash flooding. Urban run-off may also contribute, though to what extent is unclear. Evidence suggests that runoff only forms a small component of flow in the Chess, however, during extreme rainfall events there may be a significant runoff component, as indicated in some of the historic flood events reported below. It is likely that a number of factors are required for significant surface runoff to occur. For instance, a combination of extreme rainfall falling on either saturated ground or very dry, hard ground would increase runoff rates. Runoff rates would be further exacerbated in areas of compacted soils through agricultural practices and possibly on arable land where ploughing has taken place. Although the Clay-with-Flints have a degree of permeability, runoff processes may occur if rainfall intensity exceeds the infiltration threshold (refer to section 2.5.3).

3.12 Flooding

The worst historic flash flood occurred in May 1918. It was generated following an intense cloud burst upstream of Chesham around Pednor, Ballinger and Chartridge. Runoff flowed down the valley resulting in lower parts of Chesham being flooded up to 1.2 metres deep with significant damage to buildings, roads and pavements (Graves, 2024). Other similar but smaller magnitude events have also been reported. A combination of high groundwater levels (which typically peak in April-May) with intense rainfall has the potential to cause similar events in the future. Future high intensity rainfall events predicted as a result of climate change could occur more frequently and be further exacerbated by the increase in impermeable surfaces through urbanisation. Historical accounts show that several streets in Chesham are vulnerable to flooding.

A major flood occurred in spring 2001 following the wet 2000-2001 winter. During this event the Chess started almost 1 km upstream of the Bury Brook spring (Kidney, 2006) and the river reached its highest recorded discharge of 2.48 m^3/s at Rickmansworth (UKCEH, 2024). This flood was predominantly driven by extremely high groundwater levels across the Chalk. One of the reasons why this flood was so extreme is that it occurred following a wet spring in 2000 which resulted in above-average groundwater levels over the summer period despite near-average rainfall over the summer (Finch et al., 2004). October 2000 to April 2001 saw the highest 7-month rainfall total since 1885, resulting in exceptional groundwater levels by spring 2001 and extensive flooding (Hughes et al., 2011; Morris et al., 2007). The groundwater catchment memory (whereby current groundwater levels have an influence on groundwater levels in the future) of the Chess is estimated at 21 months (Jackson et al., 2024). Therefore, the effects of long-term above average rainfall are retained in the Chalk, thus compounding the impacts of shorter-term (e.g. monthly) exceptional rainfall totals.

During extremely wet periods, the Chess source can also be found upstream of Hilbury House. Groundwater emergence in and around Chesham is thought to have contributed to more recent flood events in the Chess catchment in Feb-Mar 2014.
Reducing/stopping abstraction in catchments like the Chess may increase baseflows under certain conditions, particularly during high flows when catchment connectivity and river length is greater. This could exacerbate flood risk, most likely in areas where post-abstraction urbanisation has occurred in valleys (Taylor et al., 2023). However, as groundwater recharge is the dominant process controlling flows in the Chess, the effects of stopping/reducing abstractions may have little overall impact on flooding.

3.13 Droughts

There are many references to droughts dating back to the 19th century, frequently referring to the Chess 'going dry this year'. A drought in 1893 seemed particularly severe (Graves, 2024). More recent notable droughts occurred in 1976-1977, 1997-1998, 2006-early 2007 and summer 2018. The lowest recorded discharge at Rickmansworth was 0.053 m^3/s (4.58 Ml/d) in August 1976. During droughts the source of the Chess can be as far downstream as Moor Road, possibly even Waterside (Kidney, 2006). In 2006 during very dry conditions the source of the Chess was even further downstream at Mill Hall Road Bridge (Figure 12) (Mott MacDonald, 2018).

During some droughts such as the one in the summer of 2018, artesian discharge from uncapped boreholes penetrating confined parts of the chalk may be the only source of water for parts of the river (Karapanos & Marsili, 2024). Drought resilience is mostly controlled by recharge (~90%) as the cessation of some abstractions appears to have made little difference to river flows (Karapanos & Marsili, 2024). Data from Mott MacDonald (2024) showing flows on the Chess during dry conditions before, during and after nearby signal tests (temporarily stopping abstractions) show no increases in flows from CHA PWS shutdown, rather a slight decrease in surface flows. A small increase in flows was observed in the Upper Chess following the shutdown of CHE PWS. During these signal tests in low flow conditions, CSTW discharge trends appear to have the greatest influence on river flows.

Mott MacDonald (2019) found that cross-catchment impacts may occur as a result of changes to abstractions. For instance, a reduction in abstractions on the intermittent reach of the Misbourne catchment may increase flows in the perennial Chess (HGCM model (Mott MacDonald, 2019). Impulse Response Function models used to simulate baseflow in the Chess predict that drought severity due to climate change in the Chess will likely increase and that the length of the Chess could decrease by 190 m during droughts by 2050s as a result of more extreme groundwater droughts. Model outputs showed that mean baseflows (from 12 ensembles) in the Chess (Q95-Q5) could also decrease in the future (Jackson et al., 2024). As for floods, the long-term catchment memory has a strong influence on droughts. As recharge is normally low during the summer months, the onset of droughts in Chalk catchments such as the Chess are more strongly affected by below-average winter rainfall and subsequent lack of winter recharge. If low winter rainfall is followed by a dry summer, a drought is likely to occur. However, the long-term catchment memory means that if the following winter is also drier than average, a groundwater drought is likely to persist into the next year with greater severity. As the baseflow of the Chess comprises mostly of groundwater, there is a direct relationship between groundwater droughts and river levels.

3.14 Water quality

Groundwater levels are very shallow in Chesham, therefore groundwater ingress into the sewerage system occurs frequently following prolonged wet conditions (Thames Water, 2021). Storm tanks sometimes become overloaded by incoming flows during both wet and dry periods, sometimes resulting in spills into the river (Thames Water, 2021). As well as more recent water quality concerns in the Chess surrounding Chesham STW, there are numerous historic reports and accounts concerning poor water quality in the river, dating back to the 19th century; mostly concentrated around sewage and paper mills with particular concerns during hot and dry conditions.

Household and industrial wastewater, road runoff and groundwater ingress mostly from in and around Chesham all contribute to the wastewater signature, typically increasing electrical conductivity of river water downstream of discharge sites. The highest electrical conductivity (EC) values of 600-900 uS cm are typically recorded immediately downstream of the CSTW (ChessWatch, 2024). EC typically peaks when river levels are at their lowest and the contribution of effluent to baseflow is highest. There are marked seasonal patterns and also daily-sub daily patterns associated with times of peak STW discharge into the river. Elevated EC values are detectable up to 5 km downstream and can be used to estimate water travel times (Schäfer et al., 2022). Schäfer et al. (2022) also found that the STW increased river water temperature by 1°C, 2 km downstream from the STW outlet during the lowest flow conditions.

Recorded phosphate levels in the Chess are high, and as of 2022, the Chess was rated poor for phosphate. It has a moderate ecological status (EA, 2024d).

4. Chess catchment water balance

Into the catchment

- Precipitation (rainfall): Hertfordshire chalk conceptual 4R rainfall model estimates 700-850 mm annually across the catchment, mostly 750-800 mm (1998-2020 average). More on high ground, less in south-east.
- Groundwater flow into the catchment: Possible groundwater flow into the Chess catchment from the Bulborne/Gade surface water catchments in the north-east (Atkins, 2007).

Into the River

- Springs: There are many springs in the Chess valley, mostly occurring where groundwater flows along marl bands in the chalk, and through the Chalk Rock in the mid-Chess (Figure 8). Many springs occur below the slope breaks created by the underlying Chalk Rock Unit within the Lewes Nodular Chalk Formation. Some exist close to the Lewes Nodular Chalk - New Pit Chalk Formation boundary.
- There are also numerous artesian wells throughout the Chess valley, generated by pressure head exiting the New Pit Chalk Formation as the boreholes do not appear to be deep enough to reach the Holywell Nodular Chalk Formation.
- Runoff and direct rainfall.
- CSTW discharges a minimum of 6.3 Ml/d into the Chess (excluding significant groundwater infiltration into the sewer network). During wet periods values may exceed 28 Ml/d. STW discharges in the Chess are moderately significant at>10% of average gauged flow (Stantec, 2024).
- CSTW contributions of flow to the immediate downstream river reaches from CSTW fluctuate from 40-70% depending on groundwater levels and recent rainfall (Schäfer et al., 2022), therefore the STW plays a very important role in maintaining baseflows here.

Into the Aquifer

- Recharge via infiltration through the Chalk, Clay-with-Flints (and other superficial deposits) or from surface water bodies including the Chess, smaller streams and ponds.

- Recharge model developed by Atkins (2007) estimates recharge at 339.1 mm/yr using MOSES whereas a previous model using MORECS PE had a recharge value of 370 mm/yr. Stantec (2024) calculated recharge at Rickmansworth at 265 mm/yr.
- Mains leakage: Outputs from the Chess at Rickmansworth modelled 3.1 Ml/d and were estimated at 3.2 Ml/d by water companies (Stantec, 2024). Mains leakage in Chesham is estimated at around 12-14% of water supplied (Marsili, 2024).

Out of the catchment (though some abstracted water is returned to the Chess)

- Evapotranspiration: Hertfordshire Chalk report 4R model estimates 570-620 mm/year PET (1998-2020 average) (Stantec, 2024).
- Groundwater abstractions: Currently two PWS abstractions: CWD (lower Chess 8.7 Ml/d), HAW (upper catchment 6 Ml/d). Current total = approx. 14.7 Ml/d. Total 17.9 Ml/d over the period 1998-2017 (Stantec, 2024) or 16.1Ml/d (Atkins, 2007). Note that the largest private abstraction licence in the catchment (18.6 Ml/d) is a through flow licence (non-consumptive) resulting in minimal loss of water from the river.
- HAW PWS abstraction is not returned to the Chess catchment. CHE PWS abstractions were returned to the Chess. Since CHA abstraction stopped in 2018 and CHE abstractions stopped in 2020, CWD PWS abstraction is partly used to supply the Chesham area. This proportion is returned to the Chess.
- There are three other private SW abstractions; volumes are unknown but likely to be very small (Mott MacDonald, 2018).
- Estimated groundwater outflow across catchments for the Chess is 38 Ml/d, of which 8 Ml/d was modelled at the bottom of the catchment across an 800 m wide area (Atkins, 2007).

4.1 Water balance summary

STW and mains leakage returns approximately balance abstraction in the catchment (abstractions have reduced significantly since peaking in 2000-2015). Table 5 below compares water balance summaries from two different models. Many models (both conceptual water balance and numerical) had imbalances with higher inputs than outputs, perhaps from underestimating groundwater outflows, especially when cross-catchment. Groundwater outflows and/or groundwater catchment area values are adjusted to help resolve water balance discrepancies. These water balances are for long-term average conditions, not for extremes which is something the FDRI monitoring needs to address.

Table 5: Modelled water balance summaries for the Chess catchment.

Water balance parameters (Ml/d)	Stantec, 2024 Model period (1998-2017)	Atkins, 2007 Model period (1994-2004)
Effective rainfall	83.1	79
Mains leakage	3.1	Included in recharge
Surface water discharges	6.4	?
Discharges to groundwater	0	?
Storage change		1
TOTAL IN	92.6	80
Runoff	-9.4	?
Baseflow	-35.5	-44
Surface water abstractions	0	0
Groundwater abstractions	-17.9	-15
Cross catchment groundwater outflow	-29.8	-21
TOTAL OUT	-92.6	-80
Groundwater balance		
Recharge (inc. mains leakage)	83.2	79
Discharges to groundwater	0	1
Baseflow	-35.5	-44
Groundwater abstractions	-17.9	-15
Cross catchment groundwater outflow	-29.8	-21

Water balance parameters (Ml/d)	Stantec, 2024 Model period (1998-2017)	Atkins, 2007 Model period (1994-2004)
Calculated net baseflow / total flow	0.79	0.78
BFI (UKCEH website)	0.95	0.95
Groundwater balance components as a % of recharge		
Baseflow	43%	55%
Groundwater net abstraction	21%	19%
Cross catchment groundwater outflow	36%	26%

Other water balance considerations include cross-catchment exchanges. There is possible groundwater flow to the Chess catchment from the Bulborne/Gade surface water catchments to the north-east (Atkins, 2007). Meanwhile, groundwater losses from the Chess catchment to the Misbourne occur, especially in the SW during wet periods (Stantec, 2024). Groundwater which would typically flow south-eastwards during low-normal groundwater conditions may also flow northwards out of the catchment down the scarp slope during wet periods. The groundwater catchment memory is an important factor to consider when understanding the water balance. The River Chess catchment groundwater memory is estimated at 21 months (Jackson et el., 2024), highlighting significant long-term groundwater storage and subsequent impacts on baseflows. The main elements of the catchment water balance and key uncertainties in the Chess catchment are shown in Figure 19.

- Distributed groundwater models (e.g. Stantec, 2024; Atkins, 2007) show significant uncertainty when closing the water balance (more in than out), but both inputs and outputs can change significantly depending on preceding catchment conditions and the area of the groundwater catchment.
- Relatively little is known about the influence of superficial deposits including valley alluvium, head deposits and interfluve Clay-with-Flints, on groundwater recharge, storage and river baseflow.
- Locations of groundwater catchment boundaries and how these vary during droughts and floods need to be better constrained, particularly in the north and far west of the catchment, and to a lesser extent along the eastern boundary.

- Groundwater outflows bypassing the Rickmansworth gauge in the lower Chess, and also flows to other catchments such as to the Misbourne, and to the Colne.
- A complication of flow gauging the Chess is that the channel has been divided into multiple channels along many sections (Chess and Little Chess). It has also been dammed in places forming ponds/lakes which will temporarily store water, slightly delaying hydrograph peaks.
- Although not yet identified, there are likely to be karstic features in the catchment as observed across much of the Chilterns. Large dissolution pipes may also exist but they would be infilled with Palaeogene deposits. Geophysical investigations using ERT, EM and possibly gravity meters should be able to identify these features if present.
- Cross-catchment impacts: A Hertfordshire Groundwater Model Numerical Report Model (Mott MacDonald, 2019) predicted that low flows in the Chess would increase following groundwater abstraction reductions in the Misbourne catchment (Stantec, 2024).
- Abstraction changes using the Hertfordshire Chalk Model (Stantec, 2024) predicted small reductions in flows in the lower Chess when abstractions were reduced by 15.11 Ml/d in the Ver and Gade and increased by 15.11 Ml/d downstream in the Gade and Colne.
- There is a large groundwater abstraction site (10-50 Ml/d) just to the east of the lower Chess between Rickmansworth and Watford (Vale of St Albans Conceptual Model). Could this affect groundwater levels and surface flows in the lowermost Chess?
- Abstraction rates in the catchment are frequently changing but are generally decreasing. Therefore, care is needed when making decisions based upon information and evidence from past reports. The most up to date sources of information (abstraction, STW discharge etc.) are also required to close the water balance.

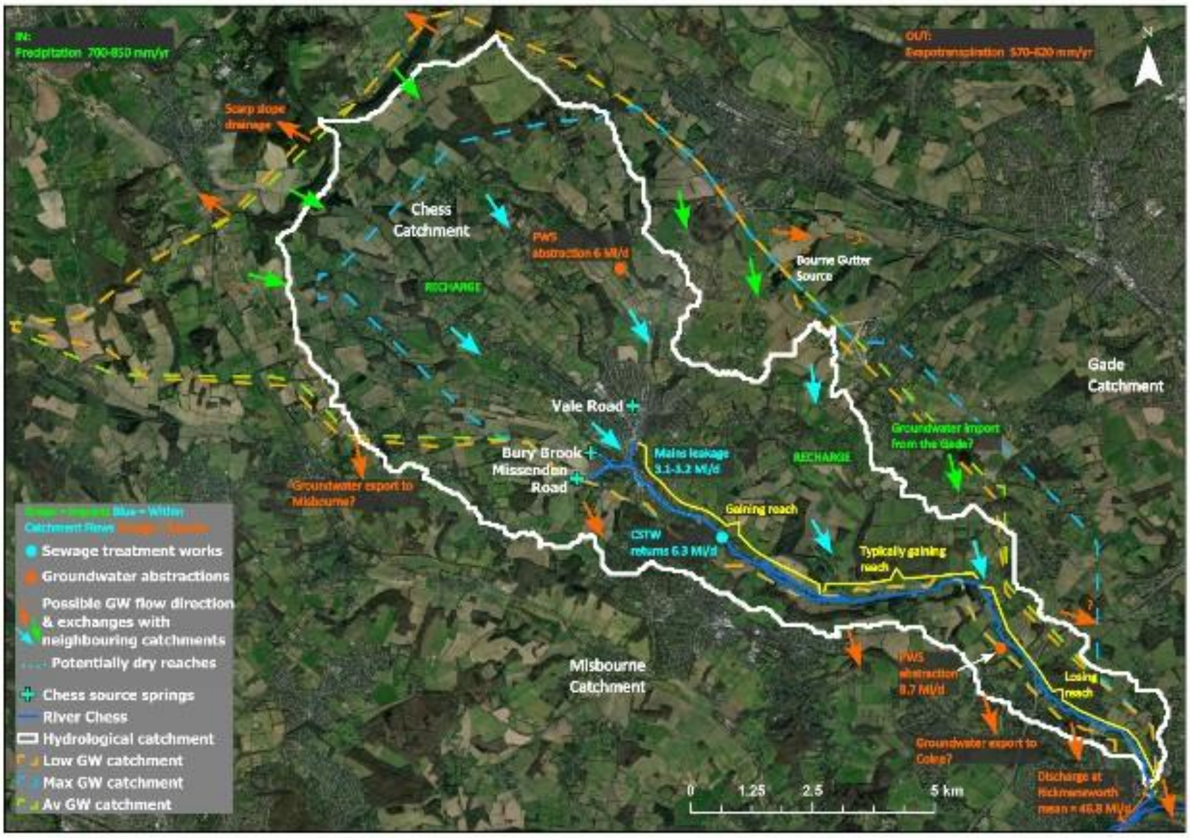

Figure 19: Water balance summary of the River Chess catchment. All quantitative information is as up to date as possible, and the balance does not show historic data. The map also shows possible groundwater flow directions and exchanges between catchments. Basemap source: ESRI, Maxar, Earthstar Geographics, and the GIS User Community, 2024.

4.2 Pre-monitoring characterisation options

1. Detailed spot flow gauging of losing/gaining reaches of the Chess under low and high flows to identify any discrete areas of changes in river flow. Flow gauging of the Colne in proximity to the Chess confluence to understand whether there are significant gains due to groundwater, which may be coming from the Chess catchment.
2. Water features survey to identify springs/artesian wells and understand their significance for river flow and groundwater flow.
3. River geomorphology survey to understand the channel network and its modifications over time.

4. Electromagnetic (EM) and electrical resistivity tomography (ERT) to map structure of river valley superficial deposits (alluvium). Potentially ground-truthed by shallow drilling. These deposits may exert some control on groundwater-surface water connectivity.
5. As (4) but for Clay-with-flints. This would be concentrated on the interfluves and could include passive seismics, if a larger area is needed to be characterised, to understand variability in the Clay-with-flints composition.
6. Sample the CWD public water source, and other relevant borehole(s), to understand if river water is being drawn into the abstraction and is a cause of the key losing section of the Chess.
7. Produce piezometric map the Chess and neighbouring catchments to better define the catchment boundaries, ideally under high and low groundwater level conditions.
8. Produce geological model of the Chess, including marl horizons that are strong controls on vertical groundwater movement. May require geophysical logging of available boreholes if there are few geophysical logs available.
9. LIDAR survey of the river channel to produce detailed topographic maps and understand energy potential across the multiple channels by mapping the water surface.

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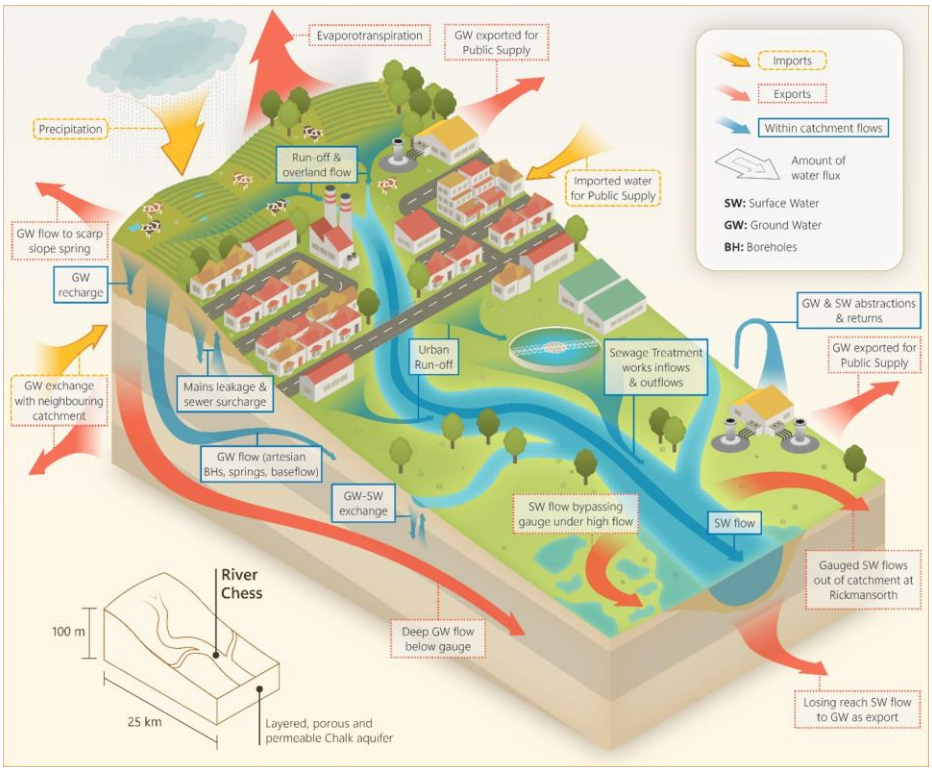
Appendix

The initial perceptual model summarising hydrological and hydrogeological processes, imports to and exports from the catchment.



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Partners

Funder:

- UKRI-NERC (£38 million)

Lead partner:

- UK Centre for Ecology & Hydrology

Other partners:

- British Geological Survey
- Imperial College
- University of Bristol

Natural Environment Research Council

UK Centre for Ecology & Hydrology

British Geological Survey

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