Source Protection Zones in the Chalk (open version)

Environmental Change, Adaptation & Resilience Programme

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BRITISH GEOLOGICAL SURVEY

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Karst stream sink in Hertfordshire. Photo A. Farrant.

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Foreword

This report has been written for the Environment Agency as part of a NERC knowledge exchange fellowship on karst in the Chalk and Jurassic and Permian limestones held by Lou Maurice at the British Geological Survey. The knowledge exchange work carried out in the last few years has resulted in compilation of data and evidence for karst and rapid groundwater flow in the Chalk, which has also been highlighted by other recent research. The aim of this report is to consider the implications of the new evidence for karst in the Chalk for source protection, and to provide a basis for future discussions on this topic.

This report is based on a previous report (CR/21/054) which included sections reviewing specific SPZs at two groundwater abstractions. These sections contained confidential information and have been removed in this report which is otherwise identical.

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Contents

1 Introduction

The aim of this report is to provide some general observations on the problem of delineating Source Protection Zones (SPZs) in the Chalk aquifer with particular consideration of the karstic nature of the Chalk. The SPZ delineation methodology for England is outlined in Environment Agency (2019), and the Source Protection Zone definitions are provided in Appendix 1. The high vulnerability of karst aquifers and the challenges of SPZ delineation in karst are highlighted in Environment Agency (2019); which details a bespoke manual approach to SPZ delineation for karst sources. This has been applied to sources where karst is obvious; principally in the Carboniferous Limestone. However, karst has not generally been considered for the majority of Chalk SPZs, which are mostly based on standard porous medium groundwater modelling approaches. Understanding of karst in the Chalk is rapidly evolving and in recent years considerable evidence of karst and rapid groundwater flow has become apparent, and the aim of this report is to consider the implications of this for source protection.

2 Chalk karst

2.1 INTRODUCTION TO CHALK KARST IN ENGLAND

The Chalk is a karst aquifer in which fractures have been solutionally enlarged to form extensive networks of solutional conduits and fissures (Atkinson and Smith, 1974; Banks et al., 1995; MacDonald et al., 1998; Maurice et al., 2006; Maurice et al., 2021). These networks are formed by two main processes (Maurice et al., 2006; Farrant et al., 2021a). The first is through the development of karstic stream sink to spring networks. These are associated with stream sinks which develop most commonly where there is surface runoff on low permeability formations overlying the Chalk (principally the Palaeogene deposits), which sinks at or near the contact with the Chalk. There may also be karst systems feeding springs which were formed as stream sink-spring networks in the geological past, when the Palaeogene was more laterally extensive (Maurice et al., 2006). Stream sinks associated with this cover would have been eroded away as the Palaeogene was eroded, but the karst networks supplying the springs would still be present.

The second process of fissure and conduit formation is mixing dissolution. This process enables subsurface karstic dissolution in the absence of point recharge via stream sinks, through the mixing of two groundwaters with different saturation (Farrant et al., 2021a; and references therein). Mixing dissolution can occur at any depth in the aquifer, and in isolation from surface karst; and fissures and conduits formed by mixing dissolution are likely to be present throughout the Chalk aquifer (Farrant et al., 2021a).

Both types of karst dissolution are geologically controlled, and often focused on inception horizons (hardgrounds, marls, flints) which enable some solutional networks to extend over long distances, as indicated by the evidence from tracer testing in the Chalk (e.g. Atkinson and Smith, 1974; Banks et al., 1995; Maurice et al., 2006; Cook, 2010; Maurice et al., 2021; see Appendix 2). It is these karstic networks, which occur throughout the Chalk, that provide the high transmissivity of abstraction boreholes and the focused spring outlets.

Dissolutional conduit development is more limited in the Chalk than in classical karst aquifers. Some short caves (conduits large enough for humans to enter) are present, up to a few hundred metres in length (Lowe, 1992; Maurice et al., 2021; Reeve, 2021; Farrant et al., 2021a,b), but extensive cave development does not occur in the Chalk in England. The Chalk has much higher storage and much higher potential for attenuation than more classical karst aquifers, which provides it with a degree of protection. However, karst in the Chalk does still result in high vulnerability as there are rapid flowpaths (with flows of km/day over distances of many km), and there is potential for long distance contaminant transport in the saturated zone. Recent work suggests that rapid groundwater flow occurs throughout the Chalk (Foley and Worthington, 2021; Maurice et al., 2021). Groundwater velocities from 97 tracer test connections in the chalk demonstrate rapid groundwater flow (Maurice et al., 2021; Appendix 2). Whilst in the past karst in the Chalk was thought to be mainly associated with the Chalk-Palaeogene boundary, there is now considerable evidence for karst and rapid flow in areas more than 5 km from this boundary (Maurice et al., 2021; Appendix 3).

2.2 RISKS TO GROUNDWATER DUE TO KARST IN THE CHALK

The Chalk aquifer is especially vulnerable to pollution, because karstic networks of solutional fissures and conduits enable rapid groundwater flow. However, there is also high attenuation through dispersion and diffusion of pollutants into smaller voids, and high storage resulting in the retention of solute pollutants such as nitrate for many decades (Wang et al., 2012). Karst also affects water quality by enabling long distance transport of such pollutants, as observed in the case of the Hertfordshire Bromate plume (Cook et al., 2012, Maurice et al., 2021).

Karst processes in the Chalk result in risks from polluting activities carried out at the surface, and also from subsurface activities (e.g. borehole soakaways; oil and gas development beneath the Chalk; underground waste disposal); see Environment Agency (2018) for details of risks to groundwater.

Surface activities will only pose a substantial risk if there is a pathway from the surface to the saturated zone. Some of these can be fairly easily identified and include: karst stream sinks associated with Palaeogene or other cover; losing rivers on outcrop chalk; and karst dolines (although it is often hard to distinguish these from anthropogenic pits).

Vertical solution features with no surface expression can also provide a rapid flowpath for pollutants through the unsaturated zone. These features are known to exist as they can be observed in coastal outcrops extending vertically for up to 100 m (Farrant et al., 2021a,b; Maurice et al., 2021). Because these have no surface expression, if they have no direct water input it is not possible to identify their locations, other than in outcrops. Therefore, the Chalk aquifer is vulnerable to pollution from farmyard runoff, leaking sewers, septic tanks, or other point source pollutants, if they happen to be located on or near to these features. These types of solution features are also likely to be present where there are soakaways/drains/SUDs into the Chalk which have high infiltration rates. The threshold for “high” is uncertain but those of >1 l/s would require subsurface solutional networks to enable the rapid infiltration rate. We are uncertain about how frequently such rapidly infiltrating features occur, but current groundwater protection policies and permitting should ensure the quality of water in such discharges (Environment Agency (2018).

Subsurface activities could pose a risk wherever there are saturated zone solutional flowpaths. All high yielding abstractions are likely to be fed by saturated zone flowpaths that extend over long distances with travel times of 50 days or less. Given that the locations of these flowpaths are not known, there is a potential risk from subsurface activities from anywhere within the catchment if they happen to intersect the solutional networks. Saturated zone flowpaths can also extend beneath areas with low permeability cover, and hence are not in the surface catchment of the abstraction. These areas would fall within the protected cover designations outlined in Appendix 1.

3 SPZ delineation in Chalk

3.1 INTRODUCTION

SPZs in the Chalk in England have generally not been delineated using the manual karst method, and most of them have been delineated using standard groundwater modelling methods which usually do not take account of karst. This reflects a lack of data and knowledge of karst in the Chalk. However, recently, greater understanding of karst in the Chalk has developed. The BGS knowledge exchange work with universities, water companies and the Environment Agency has resulted in the compilation of much more evidence for karst and rapid groundwater flow in the Chalk, and an improved understanding of Chalk karst (Maurice et al., 2020; other knowledge exchange reports in progress, see reference list; Maurice et al., 2021). BGS investigations of karst at Chalk water supplies (see reference list) have also contributed new understanding of karst in the Chalk. Other peer reviewed papers have also advanced knowledge of chalk karst (e.g. Foley and Worthington, 2021).

The evidence for karstic dissolution and rapid groundwater flow in the Chalk is now extensive (Maurice et al., 2021; Foley and Worthington, 2021; see Appendices 2 and 3). If we consider the definition of SPZ1 - the area in which groundwater travels through the saturated zone to the source in 50 days or less, then all large Chalk abstractions, e.g. public water supplies, are likely to require a large SPZ1, because to support this level of abstraction (yield) there is likely to be karst/rapid flow.

3.2 APPROACHES TO SPZ DELINEATION IN THE CHALK

In this section some general principles that could be applied to source protection in the Chalk are outlined.

The current approach to SPZ delineation in England is to apply the karst specific zoning methodology for sources where karstification is known or expected. Therefore the first part of this section provides an overview of factors indicating karst and rapid groundwater flow at Chalk abstractions.

The first stage in source protection zone delineation is determining the contributing catchment area (also known as the hydraulic capture zone) of the abstraction. In the second part of this section we provide some general principles of catchment delineation specific to the Chalk drawing on principles outlined in Environment Agency (2019), Gunn (2009) and conceptual understanding of karst in the Chalk.

Finally, in the last part of this section, we provide some principles for manual delineation of SPZ1 based on where groundwater is likely to reach the abstraction in 50 days or less.

3.2.1 Evidence for karst at abstractions

There are a number of factors that provide evidence that a Chalk abstraction is likely to be affected by karst and rapid groundwater flow, and where any of these occur, the role of karst should be considered in source protection, and a manual method of SPZ delineation is likely to be appropriate:

1) Surface karst within the catchment:
   caves, stream sinks, losing rivers, springs, winterbourne behaviour, or dolines.
2) Rapid infiltration soakaways/drains within the catchment.
3) Tracer tests indicating rapid flow to the abstraction.
4) Water quality Indicators of rapid groundwater flow at the abstraction. These include:
   - Substances which are rapidly degraded in the subsurface and would not be present in longer residence time groundwater. For example coliforms which have a short half-life in groundwater; and some rapidly degrading pesticides (e.g. Metaldehyde).
   - Turbidity caused by transport of sediment in karstic voids. Turbidity occurs due to karst processes where there is rapid transport of sediment from surface karst features to the groundwater outlet, or where flow is rapid enough to re-suspend sediment within the aquifer which was previously deposited in karstic conduits (Massei et al., 2003). Turbidity can also occur due to non-karst processes, such as where very fine chalk particulate matter causes turbidity. Identifying turbidity due to karst could be done by analysis of the particles producing the turbidity. Specific Electrical conductance (SEC) measurements could also be used to identify sediment transported from the surface where there is a decrease in SEC during the turbidity event, as this decrease in SEC indicates transport of fresher surface water (Fournier et al., 2007).
   - Salinity occurring within a short time of road salt applications.
5) Water quality indicators of extensive connected networks of solutional conduits and fissures over long distances. This could include salinity indicating saline intrusion some distance inland, or water quality indicating connectivity with a surface river over long distances.

6) CCTV images indicating conduit development at the abstraction, with flow logging or dilution testing to confirm that they are flowing.

3.2.2 Delineating the catchment

Catchment delineation in karst is challenging due to the uncertainties regarding the locations of the conduit and fissure networks supplying the spring or borehole, and because catchment areas are often different under different hydrological conditions. Principles of identifying hydraulic capture zones and catchment delineation in karst are detailed in Environment Agency (2019), and a good approach to contributory area delineation in karst is outlined by Gunn (2009) involving hydrogeological mapping; hydrological, hydrogeological and hydrochemical observations; and tracer testing.

Here, some principles that could assist with delineating catchments in the Chalk are outlined, to compliment the principles outlined in Environment Agency (2019) and Gunn (2009):

1) Development of a good conceptual model of where the catchment area is likely to be based on a combination of geological, hydrogeological and karst data and understanding.
2) Where available, tracer test data can be used.
3) Perennial and ephemeral spring locations and geological data can be used to identify inception horizons and inform the conceptual model of where flowpaths feeding the abstraction are likely to be. If data are available, fissures/conduits and their inception horizons can be identified from borehole imaging and flow logging at the abstraction. These could be used to asses where saturated zone flowpaths (and hence the catchment) are likely to extend based on the dip and strike of bedrock.
4) Geological information and surface karst data can be used to assist with identifying surface areas which are likely to have connectivity with the saturated zone. This could be areas where direct infiltration is observed (e.g. stream sinks and rapid infiltration drains/soakaways) or where geological strata are known to have vertical solution fissures (e.g. Seaford Chalk). Areas where there is unlikely to be connectivity with the surface (e.g. with impermeable cover), can also be identified.
5) Groundwater contours, and water balance can be used to contribute to the understanding of the likely size and location of the catchment.
6) If they are consistent with the karst conceptual model, groundwater models can assist with determining the location of the catchment. The effective porosity value used in groundwater models needs to be considered. A value of 0.01 is currently used in Chalk groundwater models, and this is likely to be too high based on recent research. Effective porosities in karst aquifers have been shown to range from ~ 0.00001 to 0.001 (based on tracer tests in the Chalk and other karst aquifers, Foley (personal communication, 2020), Appendix 4. A recent paper highlights the low effective porosity in karst aquifers with limited cave development (Medici and West, 2021). Medici et al. (2019) suggest an effective porosity of 2.8×10^{-4} for the Permian Limestone in England, which has limited cave development. Recent studies also report very low effective porosities for the Chalk in England. For example, Agbotui et al. (2020) report effective porosities of 0.004 to 0.0003 for the Chalk. Worthington et al. (2019) report effective porosities of ~ 0.0001 to 0.001 for the rapid flowing part of the Chalk aquifer (based on pumping tests, flowmeters, injected tracers, electrical conductivity and turbidity, and nitrate) and 0.381 to 0.388 for the slow moving groundwater in the Chalk matrix (based on environmental tracers and matrix porosity). Foley and Worthington (2021) also highlight and discuss the low effective porosity of the fissure component of the Chalk. Given that abstractions are supplied by the solutional fissure/conduit networks, lower values of effective porosity are likely to be needed to represent the distance from which the groundwater within fissures and conduits supplying the abstraction has travelled.

3.2.3 Delineation of SPZ1 at Chalk sources

In this section, some general principles that could be applied to manual delineation of SPZ1 are outlined, based on where it is likely that groundwater will travel through the saturated zone in less than 50 days as indicated by studies of tracer tests and karst in the Chalk:

1) Surface karst stream sinks and their topographic catchments should be in SPZ1 if they are in the total catchment of the abstraction. This is because they are likely to feed into caves/conduits/very well developed fissure systems which enable rapid bypass recharge to solutional networks in the saturated zone.
2) Dolines in the total catchment area should also be in SPZ1 as they are indicative of rapid flowpaths in the subsurface.
3) Sections of chalk rivers within the catchment with big or point losses into the Chalk aquifer (and their catchment areas) should be in SPZ1 because they are likely to be feeding into well developed conduit/fissure systems which enable rapid bypass recharge to the saturated zone.
4) Areas where Soakaways/SUDs/Drains have high infiltration rates should be in SPZ 1 if they are within the total catchment of the abstraction. This is because they are likely to be feeding into well developed fissure systems which enable rapid bypass recharge to the saturated zone.
5) Areas which have been proven by artificial or natural tracers to be connected to the abstraction within 50 days should be in SPZ1, together with the area between them and the abstraction. The actual location of the flowpath(s) is not known and therefore a pragmatic approach is to assume the solutional network takes a broadly direct route between the input point and the abstraction, in the absence of other evidence.
6) Areas within the total catchment which are along, and with a buffer either side of, the Chalk-Palaeogene margin should be in SPZ1 because it is likely that there will be focused recharge to the Chalk all along this boundary.

3.3 CONCLUDING REMARKS

In this section, some principles to assist with SPZ delineation in Chalk have been outlined, and many of these could be fairly easily applied using the current approach to SPZ delineation in karst.

A difficulty remains, however. There is now extensive evidence that karst and rapid groundwater flow occurs throughout the Chalk, and that Chalk abstractions are fed by connected networks of solutional fissures and conduits that extend over long distances (Section 4). At all high yielding abstractions there is likely to be some flow within 50 days from several km away from the abstraction. There will also be parts of the aquifer in which groundwater flow is slower. If we want to be certain that all saturated zone flowpaths with a travel time of </= 50 days are in SPZ1, we would need to put the entire catchment in SPZ1 because it will not be possible to know where all the flowpaths are, and they could be anywhere in the catchment. If the whole catchment is not in SPZ1, it is important to recognise that there will be some flowpaths in SPZ2/3 that enable groundwater to reach the abstraction with travel times </= 50 days.

Putting entire catchments in SPZ1 should not necessarily be the approach adopted, and providing the highest level of groundwater and source protection to such large areas would present challenges. However, the new evidence shows that rapid groundwater flow and extensive saturated zone networks of solutional conduits and fissures are ubiquitous in the Chalk (Foley and Worthington, 2021; Maurice et al., 2021), and it is important to consider how this new understanding can be incorporated into source protection.

One option might be to adopt the manual method of SPZ delineation outlined in Environment Agency (2019) and use factors that are indicative of karst and rapid groundwater flow (e.g. stream sinks, dolines, rapid infiltration soakaways and SUDs, Chalk-Palaeogene margin, tracer tests to the abstraction; other areas indicated by conceptual model) and put those areas in SPZ1, and accept that there will be some groundwater flow with travel times </= 50 days from other areas in SPZ2/SPZ3.

Some principles could be used to take a pragmatic approach to groundwater protection where there are large areas in which groundwater could reach the abstraction in less than 50 days – for example the risks from surface activities are much less where there is a thick impermeable cover, or where there is a thick unsaturated zone (Environment Agency (2019). A vulnerability type approach to groundwater protection such as those widely used in Europe (Doerfliger et al., 1999; Pochon et al., 2008) could be considered, if it was adapted for the Chalk.

4 Conclusions

This report has provided a short overview of the development of karst in the Chalk aquifer, which occurs both as the result of stream sink to spring karstic flowpaths, and mixing dissolution. These processes make it possible for the development of solutional fissure and conduit networks throughout the Chalk, and new evidence from recent studies suggests that karst and rapid groundwater flow is much more common in the Chalk in England than previously thought. The new evidence for the role of karst in the Chalk suggests that adopting the karst specific Environment Agency (2019) approach to Source Protection Zone delineation is likely to be appropriate at many Chalk abstractions.

This report provides some suggestions on the types of evidence that could be used to assess whether abstractions are impacted by karst and rapid groundwater flow, some comments on the delineation of catchment areas, and suggestions to assist with identification of areas from which flow is likely to reach abstractions in less than 50 days. Further work is recommended to consider the best approach to SPZ delineation in the Chalk in light of the recent studies identifying the karstic characteristics of the aquifer.

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Karst Knowledge exchange reports (in progress)

C1) Karst in the Chalk of the Yorkshire Wolds
C2) Karst in the Chalk of Lincolnshire
C3) Karst in the Chalk of East Anglia
C5) Karst in the Chalk of the Wessex basin
C6) Karst in the Chalk of the North Downs
C7) Karst in the Chalk of the South Downs
C8) Karst in the Chalk of Dorset
C9) Karst in the Chalk of the Isle of Wight

Glossary

Karst: Term applied to rocks which are soluble and in which rapid groundwater flow occurs over long distances. The development of subsurface solutional voids creates characteristic features including caves, dolines, dry valleys, stream sinks, and springs.

Conduit: A subsurface solutional void which is often circular or cylindrical in cross section.

Cave: A subsurface solutional conduit large enough for humans to enter (usually > ~ 0.5 m wide).

Fissure: An enlarged fracture with aperture of ~ 0.5 to ~15 cm, and a planar cross-sectional shape, that largely retains the geometry of the original fracture. Those developed on bedding partings may extend laterally both along strike and down dip.

Inception horizon: Lithological horizon which favours dissolution and the development of fissures, conduits and caves.

Appendix 1 Definition of SPZs (from Environment Agency, 2019)

The Source Protection Zones as outlined in Environment Agency (2019) are defined as:

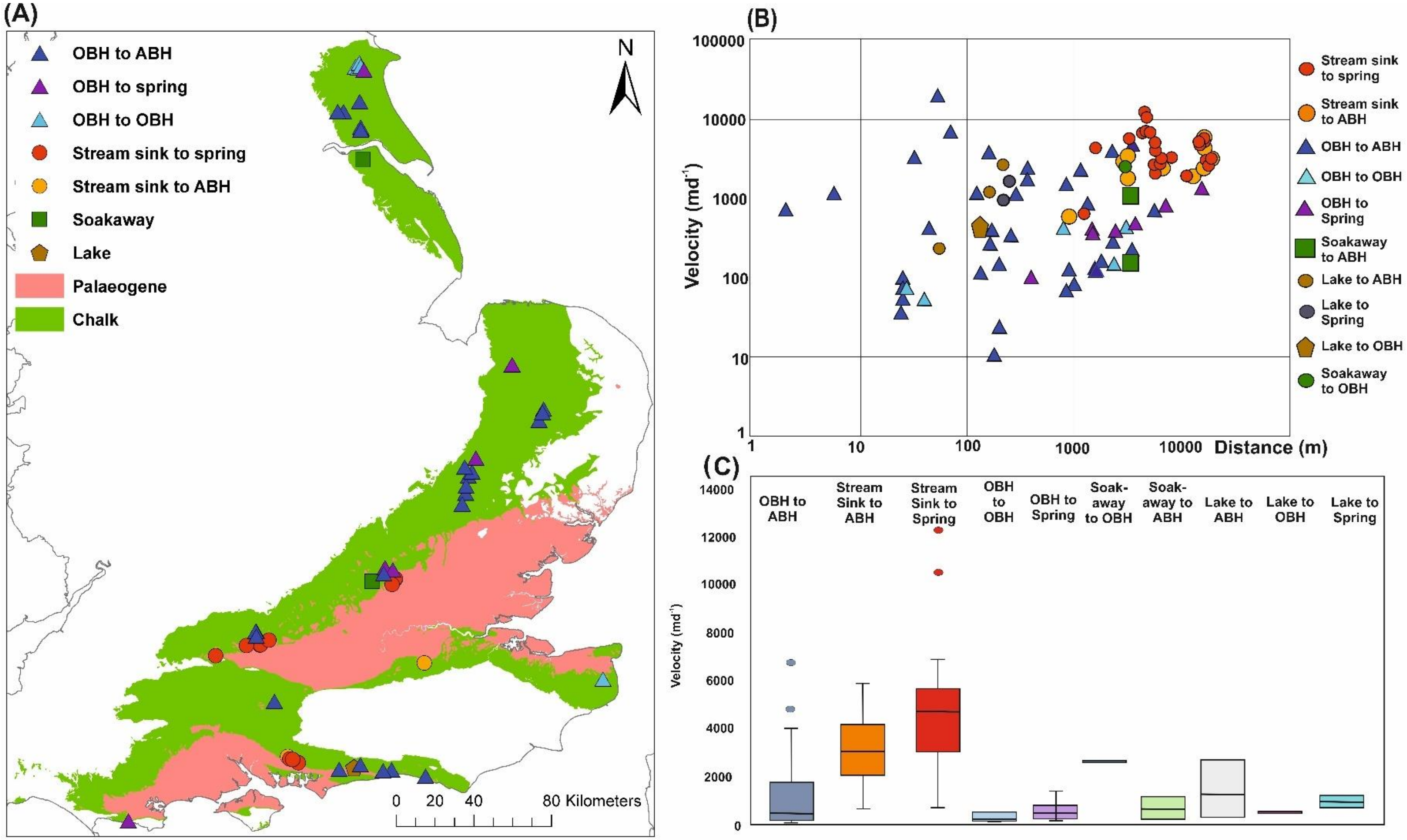
SPZ1: Inner Protection Zone defined by the 50-day travel time from any point below the water table to the source, with a minimum radius of 50 metres.

SPZ2: Outer Protection Zone defined by the 400-day travel time from any point below the water table to the source, with a minimum radius of 250m or 500m dependent on abstraction size.

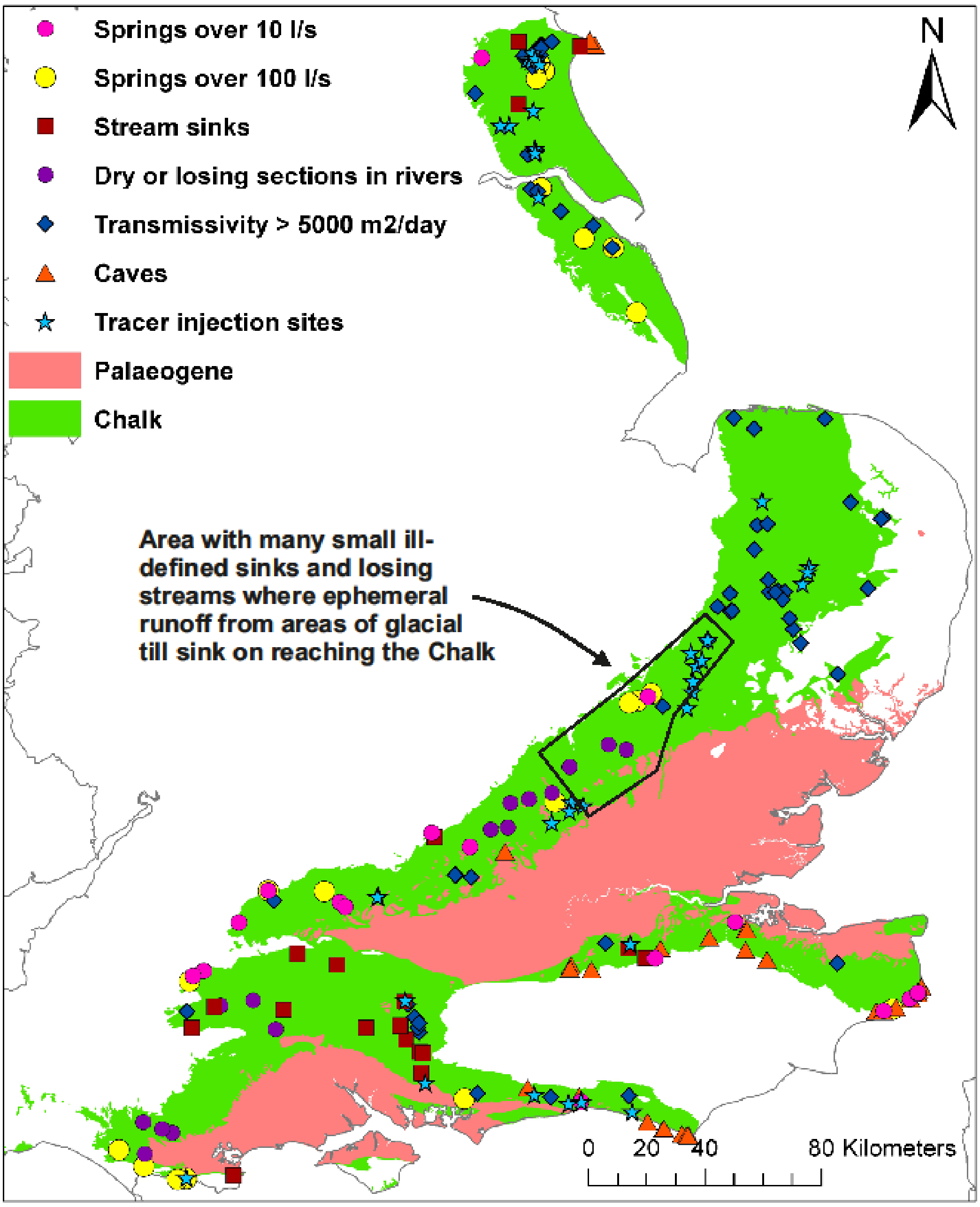
SPZ3: Source Catchment Protection Zone defined as the area around a source within which all groundwater recharge is estimated to discharge at the source. In confined aquifers, the source catchment may be displaced some distance from the source.

There is also an SPZ4 or "Zone of Special Interest" which is primarily for surface water catchments which drain into the aquifer feeding the groundwater supply via stream sinks (Environment Agency, 2019). Additionally, there is a modification for areas where there is at least 10 m of protective cover resulting in little or no risk from surface activities but where subsurface activities pose a greater risk (Environment Agency, 2019). In these areas the designations are Zone 1 – Inner Protection Zone (Protective Cover), Zone 2 - Outer Protection Zone (Protective Cover) and Zone 3 - Total Catchment (Protective Cover).

Appendix 2 Groundwater velocities from tracer tests in England (from Maurice et al., 2021, Fig. 4).



Appendix 3 Evidence for karst in the Chalk in areas > 5 km from the Palaeogene boundary (from Maurice et al., 2021, Fig. 5)



Appendix 4 Effective porosities in karst aquifers compiled by Foley (personal communication, 2021)

Source	Lithology	Value
Atkinson (1977)	Carboniferous limestone	0.0003
Price (1987)	Chalk	0.001
Sims (1987)	Chalk	0.000038
Kachi (1987)	Chalk	0.000115
Kachi (1987)	Chalk	0.001
Kachi (1987)	Chalk	0.0012
Bradbury & Muldoon (1994)	Dolomite	0.002 – 0.003
Muldoon & Bradbury (1998)	Dolomite	0.0003
Barker *et al* (2000)	Chalk	0.005
Atkinson *et al* (2000)	Chalk	0.005
Rayne *et al* (2001)	Dolomite	0.0005
Maloszewski *et al* (2002)	Triassic limestone	0.0001
Sauter (2003)	Jurassic limestone	0.00025
Watson (2004)	Chalk	0.001
Worthington et al (2005)	Cenozoic limestone	0.005
Foley (2006)	Corallian oolite	0.000147
Worthington (2009)	Mississippian limestone	0.0006
Worthington & Ford (2009)	Silurian dolostone	0.0003
Cook *et al* (2012)	Chalk	0.00014 – 0.00046
Gunn & Bottrell (2013)	Carboniferous limestone	0.00048
Worthington *et al* (2012)	Palaeozoic limestone / dolostone	0.0004 0.0017 0.0006