1MC05
Options for mitigation of the effects of piling on groundwater

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1 Scope

1.1.1 This technical note has been prepared to outline the options for mitigating the effects of piling at the Colne Valley viaduct on Affinity Water abstractions, including:

- identification of piling activities that could affect groundwater movement or quality (Section 4 of the report);
- aquifer characteristics, focussing on those of most relevance to the proposed construction and receptors (Section 5);
- potential effects of piling on Affinity Water abstractions (Section 6);
- identified risks (Section 7);
- options for mitigation of the effects and the proposed approach to managing mitigation (section 8); and
- conclusions (section 9).

1.1.2 The report builds on the findings of the hydrogeological risk assessment for the Colne Valley Viaduct and the two reports should be read in conjunction[1].

2 Client Objectives

2.1.1 The client objectives are to meet the requirements of the HS2 Technical Standards that support the Environmental Minimum Requirements.

2.1.2 An assurance is required that where the predicted effects of the Proposed Scheme on groundwater flows, levels and quality, have been assessed as significant adverse, a strategy to manage the risk will be agreed with the Environment Agency and Affinity Water. Potential significant adverse effects on groundwater, due to construction, (such as excavations to form cuttings or tunnels, including green tunnels), will be mitigated locally wherever reasonably practicable.

2.1.3 This report provides the strategy for managing risks to Affinity Water abstractions at the Colne Valley viaduct.

3 Technical Standards

3.1.1 The Technical Standard of most relevance to this hydrogeological assessment is:

[1] Align, 2019, Groundwater Assessment for Construction Tasks – Piling at the Colne Valley Viaduct, Document no.: 1MC05-ALJ-EV-NOT-CS01_CL01-100069

- Technical Standard – Groundwater Protection[2]

4 Proposed piling activities

4.1 Piling for temporary jetty construction

4.1.1 The temporary jetty will be constructed across the lakes in the Colne Valley to enable construction of the piles and pile caps for the viaduct piers. The design of the piling for the temporary jetty is under review and will not be finalised until after completion and interpretation of the additional ground investigation. However, it is likely to comprise steel tube piles that will be push driven through the superficial deposits and weathered chalk and into the top of the chalk rock (i.e. competent rock). The piles would remain in place following removal of the jetty as their removal could compromise ground conditions around the piles for the viaduct. The top of the driven piles would be cut off at lake bed level. In areas of ground in between the lakes a jetty would not be required and so piles would not be installed.

4.2 Piling for viaduct construction

4.2.1 The design of the piling for the viaduct is under review and will not be finalised until after completion and interpretation of the additional ground investigation and load pile tests. However, it is likely to comprise bored piles, with a diameter of between 1 and 2m (1.8m diameter is most likely diameter) to a depth in excess of 50m below ground level, but unlikely to be deeper than 80m. The piles would be cast *in situ*. Not all piles would necessarily be to the same depth nor of the same diameter.

4.2.2 The preliminary design requires piles to be drilled in groups of 4, 6 or 9 at each pier location, with the number of piles in each group being dependent upon the type of pier being constructed. The buttress piers which have a greater loading would require 9 piles, whilst the smaller piers that are closer together would only require four piles for each pier. In total, the preliminary design indicates that there would be 56 piers and two abutments (a north and a south abutment). For simplicity these are referred to as the 58 piers in this report, starting from pier 1 at the South Embankment to 58 at the North Embankment (Figure 1), with a total of just over 300 piles likely.

4.2.3 Both on land and over water the piles will require a casing to support the upper non-cohesive layers above the chalk. This will be large diameter steel casing, with material removed from within the casing to form the pile. The depth of the casing will be dependent upon ground conditions at each location. In the case of the piles constructed over water the casing will also prevent lake water from moving laterally into the pile hole during construction and placement of concrete.

[2] HS2, Technical Standard – Groundwater Protection, Document no:. HS2-HS2-EV-STD-000-000010

4.2.4 During boring of the pile hole beneath the base of the casing a drilling fluid will be required to support the chalk and ensure that the hole does not collapse. This fluid could be water, or it could be bentonite (as a 5% solution) or a polymer. The choice of drilling fluid will depend on the stability and quality of the ground and the outcome of pile load tests that will be completed at three locations along the length of the viaduct.

4.2.5 The procedure to be adopted for piling at each location will be as follows:

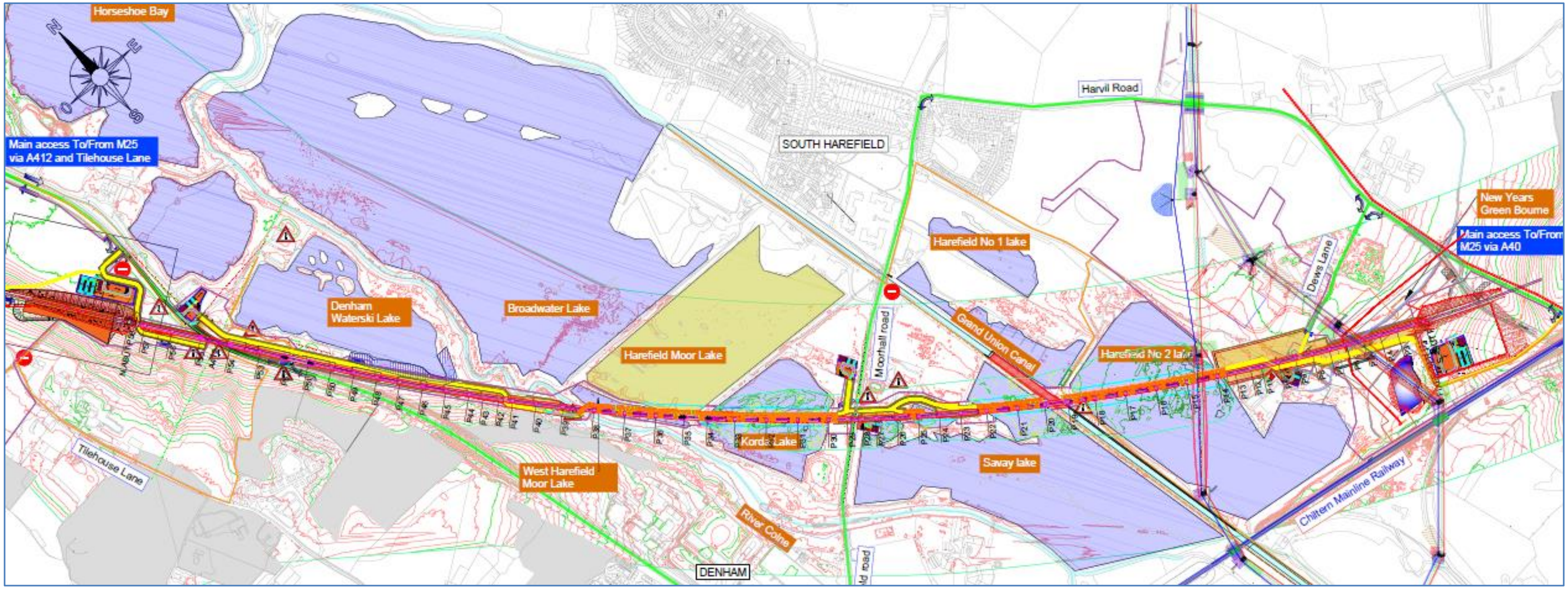
- Establish rig at pile position.
- On land, drill a small starter hole using auger to approximately 3m depth.
- Attach 1.8m casing to casing vibrator, confirm position and verticality and vibrate to depth to 'seal' into chalk horizon.
- Determine what support fluid (water, bentonite or polymer) is to be used based on arisings, regulatory authorisation and findings from the Load Test Piles and add support fluid to bore to balance the head as appropriate.
- Advance the bore to full depth using a combination of augers, drilling and core buckets. The majority of the bore would be open hole, with only the upper section cased.
- Once completion depth is reached commence cleaning of the base of the hole using a core bucket or auger to remove cuttings that have sunk to the base of the hole. If the support fluid is bentonite this will be exchanged for clean bentonite, if it is polymer then this would be cleaned or removed from the hole in preparation for concreting.
- Install reinforcement cage into the bored hole.
- Place concrete into the hole through full length tremmie pipe, removing support fluid from the casing as it rises. The support fluid would flow up the pile hole as concrete is poured in and would be collected at ground surface via an off-flow pipe that would discharge into a skip or tank. The support fluid would then be treated / disposed of appropriately. The area would be contained as necessary to prevent any loss of the support fluid to the environment. Any spills or losses would be dealt with in line with the Construction Code of Practice / Site Emergency Preparedness and Response Plan.
- Once the concrete has displaced all of the drilled fluid, the temporary casing would be removed (only for the land-based piles) using the piling rig with rotation as necessary to free the casing and the concrete would be topped up as necessary. As the removal is completed whilst the concrete is still wet it will flow under its own weight into any gaps left as the casing is removed. For the piles placed over water the steel casing would remain *in situ*.

4.2.6 The above process is shown schematically for construction on lake and land in Appendix 1.

4.2.7 The type of equipment likely to be used could include the following:

- Bauer BG45 or similar piling rig.
- 160 tonne handling crane.
- 50 tonne handling crane.
- 1.8m diameter temporary casing approx. 12m long (land).
- 1.8m diameter permanent casing approx. 16m long (water), 12mm wall thickness.
- PTC 50 Casing Vibrator

Figure 1 Pier location and numbering

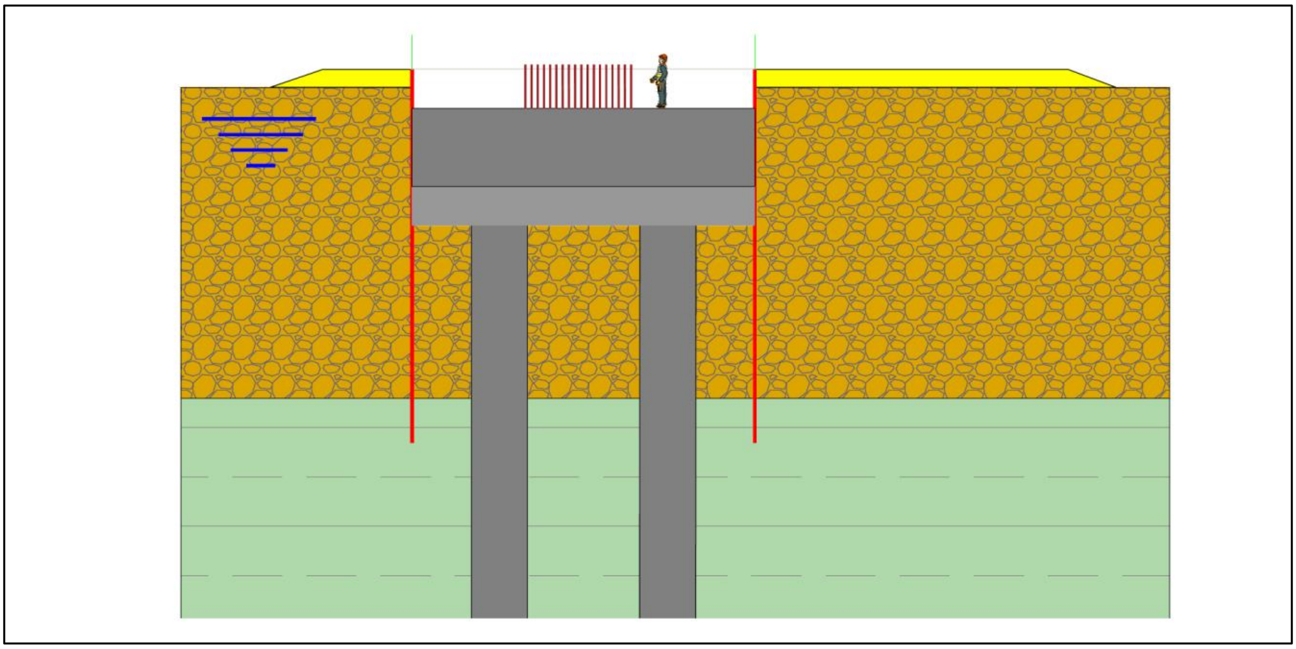


4.3 Piling for pile cap construction

4.3.1 The weight of the viaduct will be transferred to the piles by means of a pile cap which is a large concrete slab constructed across all of the piles in each pile group. The construction method for the pile caps will differ between the lake and land. Those on land will be constructed *in situ* and will require soil to be excavated to allow the top of the pile cap to be located at, or just below, ground level. Where water levels are high (anticipated for the majority of the viaduct route) this will require construction of a coffer dam using sheet piles.

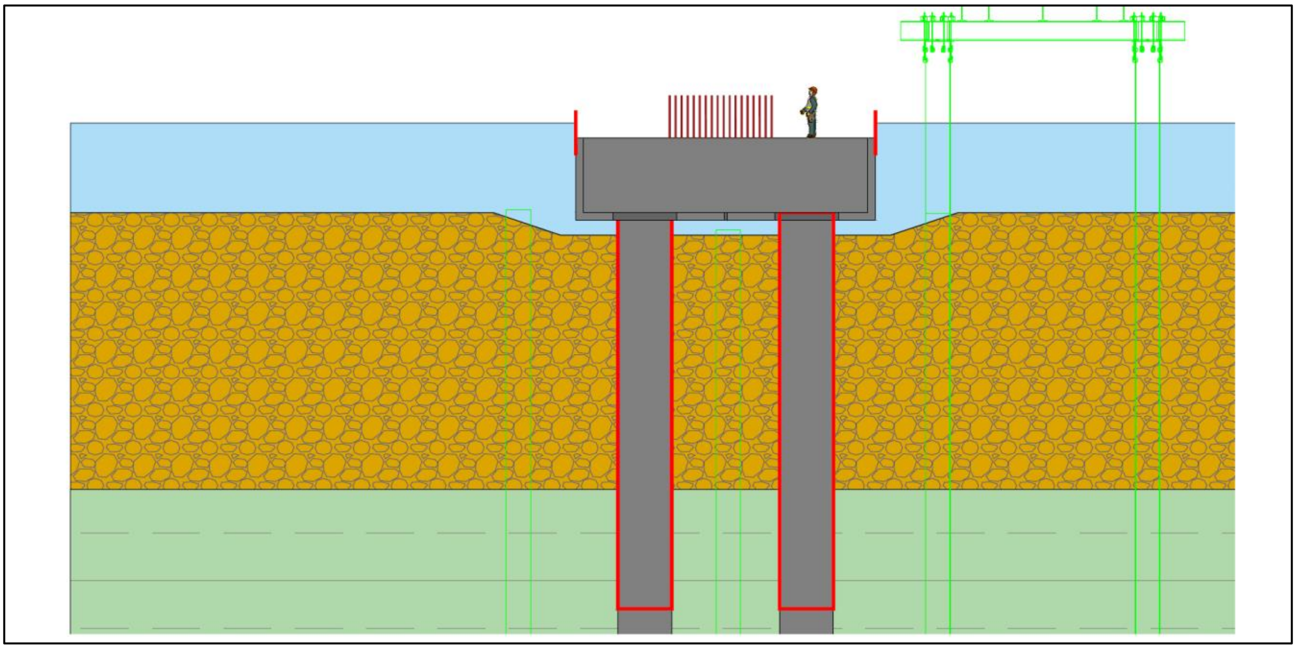
4.3.2 The sheet piles will be driven or vibrated through the superficial deposits and into the top of the chalk to form the coffer dam and the pile caps will be constructed within the enclosed area. In the first instance a basal concrete plug will be installed and allowed to cure. This will prevent groundwater upflow and will allow the area inside the cofferdam dewatered. This will be the relatively small volume of water contained within the coffer dam. The water will be discharged to lake if it is clean, if not it will be tankered off site for treatment, or treated on site, or discharged to sewer. Following construction of the pile cap the sheet piles will remain in place. This is shown in Figure 2 with the full procedure shown schematically in Appendix 1.

Figure 2 Completed piles and pile cap (sheet piles shown as vertical red lines) on land



4.3.3 The pile caps for the piles installed over water will be constructed within a shell that will be placed over the piles, sealed and then dewatered. There will therefore not be any requirement for sheet piling, although the tubular steel piles from the temporary jetty will remain in place. This is shown in Figure 3. with the full procedure shown schematically in Appendix 1.

Figure 3 Completed piles and pile cap (piles for jetty shown in green, pile casing in red) on water



4.4 Piling at the South Embankment

4.4.1 The South Embankment is a 16m wide (at the top), 225m long, 10m (maximum) high embankment with 1 in 2.5 side slopes that forms the northern approach to the Colne Valley viaduct. Ground improvement at the embankment will include the installation of 935 displacement piles that are 400mm square. Of these, 553 are 8m long, 36 are 6m long and the remaining 346 are between 1 and 4m long. The piles would be placed at a range of spacings from 2x2m to 2.5x5m, with 278 into the Reading Formation and the remainder into structureless chalk. The piles would be placed between chainage 25,774 and 26,025.

4.4.2 The piles would not penetrate the chalk rock, i.e. they will not go deeper than weathered chalk / chalk soil. The final technique(s) and number of piles to be installed will be selected following completion of the additional ground investigation. As all piles will be terminated in the chalk soil (putty chalk) the potential for a significant effect on the aquifer or sensitive groundwater receptors is very low and is therefore not considered further in this report. More detail regarding the hydrogeology at the embankment is provided in the groundwater assessment report for the North and South Embankments.

4.5 Piling at the North Embankment

4.5.1 The North Embankment is an 18m wide (at the top), 315m long, 12m (maximum) high embankment with 1 in 2.5 side slopes that forms the northern approach to the Colne Valley viaduct. Ground improvement is required at the North Embankment and this would likely include soil excavation and replacement, piling and installation of a very small number of vibro concrete columns (VCC).

4.5.2 The majority of the ground improvement would be by use of driven displacement piles with a square section of 400mm x 400mm. These would be placed between chainage 29,399 and 29,673 at a spacing of 2x2m. There would be 208 piles of 10m length and 112 piles of 6m and 112 piles of 6m. Due to the shallow depth proposed for these the potential for a significant effect on the aquifer or sensitive groundwater receptors is very low and is therefore not considered further in this report. More detail regarding the hydrogeology at the embankment is provided in the groundwater assessment report for the North and South Embankments.

5 Aquifer characteristics and data limitations

5.1 Available information

5.1.1 A detailed assessment of the hydrogeology along the alignment of the Colne Valley Viaduct is provided in the groundwater assessment report for piling at the Colne Valley Viaduct. Information from this report is summarised below.

5.1.2 The sand and gravel present in the Colne Valley in the vicinity of the viaduct has been removed by mineral extraction to a significant degree, although the depth of removal, and the thickness of material remaining, is very variable, partly being dependent upon the amount of silt in the deposits. Mineral extraction generally ceased when the sand and gravel became very silty. The sand and gravel is classified as a Secondary A aquifer. It is underlain by the Chalk which is classified as a Principal aquifer and which is used extensively for water supply, with Affinity Water taking some [redacted] (average, peak can exceed this) from this region under a group licence. There are only limited options if an abstraction borehole has to be shut down, and if more than one borehole is shut down this could have a significant effect on water supplies. The aquifers also provide baseflow to rivers, including the River Misbourne, a sensitive chalk stream.

5.1.3 The Chalk aquifer is a dual permeability aquifer which is characterised by very low flow rates through the rock matrix and much higher rates of flow through fissures. In some areas these fissures are enlarged by solutional weathering which can result in extremely fast flow rates. Typically, permeability is highest in the valleys and lowest in the interfluve areas.

5.1.4 All of the large groundwater abstractions have groundwater source protection zones (SPZ) defined for them. These comprise three zones:

- Inner zone (zone 1) - defined as the 50 day travel time from any point below the water table to the source.
- Outer zone - defined by a 400 day travel time from a point below the water table.
- Total catchment area - defined as the area around a source within which all groundwater recharge is presumed to be discharged at the source.

5.1.5 The SPZs are defined by modelling and are based on best available data at the time of modelling, and licensed (rather than actual) abstraction rates. These zones are best estimates and in heterogenous aquifers such as the Chalk should be taken as indicative rather than definitive. The inner and outer zones could be greater in extent and may be a slightly different shape where there are preferential flow zones. All modelling is dependent upon the data available at the time and where this is limited there can be significant interpolation. SPZs should therefore be used with a degree of caution. The SPZs will also change as abstraction rates change, and in the case of those in the area of the viaduct, are considerably different as the [redacted] although it is still licensed.

5.1.6 The whole area around and to the north of the viaduct route is designated as SPZs (Figure 4). The viaduct is largely within SPZ1 for the [redacted] and [redacted] abstractions and even taking modelling errors into account, part of the viaduct would always be within the SPZ1 for one or other of the abstractions. A small part (about 500m) of the eastern end of the viaduct is in SPZ2. It is possible that the very eastern end of the viaduct is just inside [redacted] SPZ1, although as [redacted].

Figure 4 Source Protection Zones in the vicinity of the viaduct

[redacted]

Notes: Red – SPZ1, Light Brown – SPZ2, Green – SPZ3, No colour – outside SPZ

5.1.7 The current groundwater models are regional models and could be updated to provide a model that is more specific to the Colne Valley, drawing on the additional ground investigation boreholes that have been drilled since the model was prepared and on additional monitoring data. However, as the key risks to the Affinity Water abstractions are related to the potential for encountering solutionally enlarged voids, which cannot be predicted by the model, there would be limited benefit in such modelling.

5.1.8 The period of most concern to Affinity Water is the peak demand period between May and September (inclusive) as this is when demand is highest and the resilience in the supply system is lowest. Timing is therefore important in planning the construction works and with regard to the most appropriate mitigation.

5.1.9 Information provided by Affinity Water indicates that the [redacted] and [redacted] abstraction boreholes have had collapses in their lower sections in the past. In addition, the [redacted] borehole has historically had problems with high turbidity. This also suggests that the Chalk in the Colne Valley is well fractured and highly permeable, something that is not unusual in valley locations.

5.2 National Environment Programme (NEP)

5.2.1 Assessment has been completed by Mott MacDonald[3] for Affinity Water as part of the NEP (now know as Water Industry National Environment Programme) studies to try to identify effects on sensitive hydrological and ecological receptors in the Colne Valley. The assessment included extensive hydrogeological investigations that are of relevance to the assessment of potential effects on the [redacted] PWS. Of particular interest are the signal tests that were used to try to identify the extent of the effects of pumping.

5.2.2 Some of the findings of the assessment are as follows:

- Groundwater movement is to the south east but locally flow is from the west and the east. The flow directions do not change significantly with the seasons.
- Historical groundwater levels indicate a hydraulic connection between the Chalk and superficial deposits, but a layer of putty chalk restricts the interaction between the two aquifers to a degree.
- Groundwater abstraction from the Chalk, by reducing Chalk groundwater levels, increases the amount of leakage from the superficial deposits and the lakes. This is of concern to Affinity Water as if construction reduces flow in the Chalk and abstraction continues at the current rate this would result in increases in manganese concentrations at [redacted] PWS.
- Signal tests at [redacted] PWS indicate that there is a connection between the PWS that was tested and the [redacted] gravels monitoring borehole (126m from the [redacted] PWS), the observation boreholes at Delux Studios (715m to the north west), Long Pond Deep (900m to the north west), Broadwater West Deep (1336m to the north west) and in Korda, Harefield and Savay lakes.
- Analysis of the [redacted] signal tests indicate transmissivities in the Colne valley in the range 3,000 to 18,000 m^2/d.
- Analysis of lake drawdown data suggests that over a 44 day test some 31% of the water abstracted from [redacted] was derived from the lake, although it is suggested that this percentage would reduce with time. The volume of water abstracted from [redacted] that was derived from the gravels was estimated to be 5%.
- Analysis of the [redacted] PWS signal test suggested that the boreholes are connected to Allen lake, and to a lesser degree Broadwater. An effect was seen in the following boreholes: Delux Studios (1km to the south), Long Pond Deep (800m to the south south

[3] Mott MacDonald, February 2014, Mid Colne and Lakes AMP5 National Environment Programme (for Affinity Water)

east), Broadwater West Deep (300m to the south south east), Broadwater East (750m to the east), Denham Park Farm (1.4km to the west) and Tilehouse Lane (1.2km to the north north west).

- Analysis of the [redacted] signal tests indicate transmissivities in the Colne valley typically in the range 1,000 to 9,000 m2/d, albeit with extreme values outside of this range.

5.2.3 The majority of the observation boreholes are in the Colne Valley and so measuring a response to changes in abstraction rates in the PWS is not surprising. However, a response was also observed in Denham Park Farm on the interfluve between the Colne and the Misbourne valleys. This confirms the importance of the east and west flow component to the large PWS, in addition to the predominant north west to south east flow.

5.3 HS2 Ground Investigation

5.3.1 HS2 has completed a ground investigation across the Colne Valley. Preliminary assessment of the data has been completed and a series of draft geological sections along the line of the viaduct have been prepared (see Appendices in the hydrogeological risk assessment for the Colne Valley Viaduct). The geological long sections show the thickness of: (i) superficial deposits, (ii) strucureless chalk, (iii) weathered chalk and (iv) unweathered chalk (competent chalk). Along the majority of the route there is at least 3m thickness of structureless chalk soils which can be clay like in consistency. However, in one small section between piers 32 and 33 the chalk soil thins to around 1m thick, and in addition the superficial deposits are relatively thin in that area, which is also beneath a lake.

5.4 Additional Further work

5.4.1 Align is currently undertaking a ground investigation that includes drilling a number of boreholes, some of which will be installed with well screen for long term monitoring. These boreholes are likely to be largely complete by the end of 2019, although investigation could continue into 2020. Borehole drilling in the vicinity of the viaduct will include rotary coring to 70m depth. Geophysical testing will be completed on selected holes. Water level data loggers will be installed in some holes to try to identify any signal from variations in Affinity Water abstractions. This additional information will all help to further refine this report.

6 Potential effects on Affinity Water groundwater abstractions

6.1 Potential effects

6.1.1 Each of the potential effects on Affinity water abstractions is considered below with a risk assessment included in section 7 in order to determine which represent the highest potential risk and require mitigation.

6.2 Chalk and sediment turbidity

6.2.1 Chalk generally comprises coccoliths, foraminifera and other shell debris, cemented together to lesser or greater degrees. The coccoliths are particularly small, being several μm across. Any construction work can result in disintegration of the chalk mass into these fine particles which, when the work is below or close to the water table, has the potential to induce chalk turbidity in groundwater. Due to their small size these particles do not settle quickly and can rapidly migrate through fissures in the aquifer, especially under pumping conditions within the cone of depression of the abstraction boreholes. The Affinity Water abstractions have very low limits on turbidity as it can limit the effectiveness of UV water treatment. If the limits are exceeded the abstracted water cannot be used for supply.

6.2.2 There is little information on the migration of chalk turbidity through chalk aquifers to abstraction boreholes during construction activities. However, it is an issue that is known to Affinity Water (who have some data on this) and there have been instances during HS2 ground investigations when turbidity has increased at an abstraction borehole due to below water table construction work[4]. Research has been completed on the migration of natural turbidity through karstic systems, including the effects of this on potable water supplies, but these turbidity events are due to movement of turbid water into natural sinkholes rather than from below ground construction activity[5][6].

6.2.3 The potential effects of an increase in chalk turbidity were recognised during the EIA and so HS2 and Affinity Water agreed some broad mitigation solutions. These included cessation of abstraction from the [redacted] abstraction boreholes during construction of the viaduct for a period of 2 years commencing October 2019. The loss of water into supply from the shutdown of the [redacted] abstraction is likely to be made good by increasing abstraction rates at other Affinity Water abstractions and importing water from Thames Water Utilities. Furthermore, additional water treatment facilities would be installed at the [redacted] and [redacted] abstractions to treat chalk turbidity up to 144 NTU[7]. The latter is being designed with a view to installation around October 2019.

6.2.4 In addition to chalk turbidity, there are other sources of natural turbidity such as from sediment that could be washed into fissures from surface water runoff. This sediment can be washed through the groundwater system to Affinity Water abstractions, natural discharge points, or it can become deposited in fissures in the chalk and remobilised at a later date, particularly if there are changes to groundwater the rate and direction of groundwater movement.

[4] MWH, 2017, [redacted]r
[5] Hobbs, S.L., 1988, Recharge, Flow and Storage in the Saturated Zone of the Mendip Limestone Aquifer, UnPub PhD Thesis, Univ. Bristol
[6] Rico G., P.Juignet and R.Meyer, 1993, Water turbditiy in chalk aquifers in Normandy: a genuine tracer
[7] NTU – nephelometric turbidity units, a standardised unit for measuring turbidity

6.3 Bentonite turbidity

6.3.1 Bentonite includes a number of naturally occurring clays with sodium bentonite and calcium bentonite being most widely used in industry. As clays, they have very fine particle sizes and so may not settle quickly and could migrate through fissures in the aquifer, depending upon flow rates and flow type. For the piling, bentonite is mixed with water to form a 5% (or thereabouts) solution which is used to stabilise the piled hole prior to installation of the reinforcing cage and concrete. The bentonite has thixotropic properties such that it gels when left undisturbed but flows when it is agitated. Bentonite slurry can penetrate the wall of the bore and then gels to form a skin on the walls of the pile hole and can restrict water movement into or out of the hole, provided the hydrostatic pressures are balanced. It is also possible that the bentonite (depending on its characteristics, including viscosity) could limit migration of chalk turbidity by a combination of binding to chalk particles and forming a skin on the walls of the bored piling hole.

6.3.2 Where the pile hole encounters a void the bentonite can move out of the hole and if the void is well connected to the aquifer could result in migration. However, as noted above, when the bentonite is not agitated it will form a gel which will limit the potential for migration. What is not known is what flow velocity is required for bentonite to migrate, nor how quickly it would settle out in the aquifer, nor whether changes in pumping rates could re-instigate migration in the future.

6.4 Use of polymers

6.4.1 The use of or polymers, rather than bentonite as a support fluid / formation stabiliser is being considered by Align as there are a number of potential benefits associated with their mixing, storage, use and disposal. Polymers would act in a similar way to bentonite, supporting the walls of the bored hole and limiting the potential for collapse. Affinity Water has expressed concerns regarding the toxicity of polymers and the potential for them to cause turbidity.

6.4.2 With regard to the toxicity of polymers, Align has obtained details of their chemistry from suppliers and in particular, information regarding their use, any approvals gained from regulators and toxicity information. If polymers are selected, only those that can be demonstrated to be appropriate, to the satisfaction of Affinity Water and the Environment Agency would be used.

6.4.3 With regard to turbidity, polymers would have a similar effect on the groundwater to bentonite, although this could vary depending upon the actual polymer selected and the below ground conditions encountered. The effectiveness of the turbidity treatment system proposed at the Affinity Water boreholes in treating polymer turbidity is not known at this stage.

6.5 Use of cement / concrete

6.5.1 Cement / concrete tends to be highly alkaline and can pollute water supplies if it gets into them, with pH of 10 to 12 not being uncommon. The upper pH limit for drinking water is 9.5. There is a risk that migration of cement or concrete could impact water quality, although the potential for this can be restricted by careful use and by using quick setting materials and where necessary thickening the cement to reduce its potential to flow. For these there is limited potential for migration if the raw materials are appropriately managed and those pumped underground are quick setting. For the piles concrete with a typical cure time of around 6 hours is used. Further assessment of the risks from cement or concrete, or mitigation is therefore not required.

6.5.2 In addition to quality effects there is the potential for the below ground use of cement or concrete to block fissure systems in the immediate vicinity of the piles which could result in a localised change in the rate and direction of groundwater movement. This would be a particular issue in hard limestones where development of single isolated conduits can occur. However, in strata such as chalk development of isolated conduits is far less common, and instead, fracture and fissure systems tend to develop, often along preferential routes, such as in valleys. The potential for complete blockage of a fissure is therefore relatively low. In addition, any localised blockage would lead to a head build up behind the blockage such that water would be forced around the blockage. Furthermore, as the flow to an abstraction borehole comes from 360°, the blockage in one small segment of this, at distance from the borehole, is extremely unlikely to have a significant effect. Any effects are therefore likely to be small scale and localised and do not require mitigation.

6.5.3 Th exception to the above is the piling that will take place close to the [redacted] boreholes. As the boreholes are extremely close to the viaduct route, it is possible that important fissure systems could be blocked resulting in changes in groundwater movement. The potential for this will not be known until the piling holes are drilled. In the event of a significant blockage at this location mitigation could be required.

6.6 Creation of preferential pathways

6.6.1 Affinity Water has indicated that the water pumped from the [redacted] and [redacted] abstraction boreholes has elevated concentrations of manganese. Like pH, there are limits to the concentration of manganese in water that can be used for public water supply (50µgMn/l). The manganese is thought to come from the lake water / sands and gravels that overlie the Chalk aquifer. Although the sands and gravels may naturally be in hydraulic continuity with the Chalk, the degree of water movement may be limited by the presence of silts in the lower layers of the sand and gravels in addition to the presence of putty chalk at the top of the weathered chalk horizon (see Appendices in hydrogeological risk assessment for the Colne Valley Viaduct). The connectivity between the lake water and groundwater was estimated to be 31% by Mott MacDonald (2014), although it does vary with pumping duration and it varies across the Colne Valley.

6.6.2 Any construction activity that could result in a preferential pathway between the lake water / sand and gravel and the Chalk aquifer, particularly where the latter is well fissured, could result in greater water movement than is currently the case. This in turn could increase manganese concentrations at the abstraction boreholes. There is also a risk that other substances in the lake water could get into the Chalk aquifer and then the abstracted water.

6.6.3 As well as the immediate risks of causing a preferential pathway by pile construction there are concerns that the steel casing for the viaduct piles, steel tubes for the temporary jetty, and the sheet piles for the coffer dams, could rust in the long term and result in the creation of a preferential pathway as they degrade. This is assessed in detail in Section 7.2 of this report.

6.7 Aquifer destabilisation

6.7.1 As noted above, records held by Affinity Water indicate that the [redacted] and [redacted] abstraction boreholes are unstable and have suffered several collapses in the past. There is therefore concern that piling activities close to the abstractions, even if they do not include hammer action/vibration, could result in further collapse at one or both of these abstraction sites. The potential for this at the [redacted] abstraction is extremely limited due to its distance from the viaduct, but there is a small risk to the [redacted] source.

6.7.2 The shallow strata at the abstraction boreholes are cased and there are three boreholes at [redacted] and any collapse that does occur is unlikely to significantly affect the volume of water supply, and so the risks are not deemed significant. This is not assessed further and no additional mitigation is required. However, Affinity Water is concerned that any collapse in the boreholes could affect water quality by affecting flow paths. Their primary concern is that any collapse in the lower sections of the borehole could reduce inflow from the Chalk at depth with the result that more water is drawn downward from the lakes due to an increased downward vertical gradient. Options for mitigation of this are considered further below.

6.8 Changes to flowpaths

6.8.1 There is the potential for the installation of the piles for the viaduct to change flow characteristics and potentially to reduce yield at public water supplies in the vicinity of the viaduct. The changes could take the form of localised changes to flow routes due to blocking of preferential flowpaths by piling/ground improvement operations, and/or a reduction in flow through the aquifer due to a reduction in the cross sectional area of the aquifer through which groundwater can move. This applies primarily to the piles for the viaduct piers due to the number of these across the full width of the Colne Valley, their size and spacing and their depth. However, any effect could be exacerbated by the smaller and shallower piles for the temporary jetty which would remain in place, although this only applies at the locations over water.

7 Risks

7.1 Environmental Statement

7.1.1 The Environmental Statement does not specify the use of a particular piling technique for construction of the viaduct and so the risk assessment in the Environmental Statement is generic rather than specific. However, the document does state that "The method of piling will be selected to avoid creating hydraulic pathways, such as cracks and cavities between the construction and the natural rock and will be selected to avoid creating pathways between the aquifer and shallower surface water and groundwater". The risk from piling is therefore recognised along with the requirement for mitigation.

7.2 Risk assessment

Turbidity

7.2.1 Given the nature and extent of construction activities and their proximity to the [redacted] and more particularly [redacted] abstractions, the creation of chalk turbidity is inevitable, although neither the concentration nor duration of turbidity likely at the abstraction boreholes is known. Due to the high risk and high uncertainty mitigation will therefore be required to manage the potential effect of chalk turbidity on public water supplies.

7.2.2 The potential for creation of bentonite turbidity is also high, although the potential rate and extent of migration of bentonite through the aquifer is not known. Mitigation will therefore be required to reduce the potential effect, although the exact nature of the effect will depend upon the location of each pile group in relation to the abstractions. In order to identify the piling locations that represent the greatest risk to Affinity Water supplies, and to determine the level of risk posed, a turbidity assessment matrix has been prepared. This matrix uses a number of broad parameters such as topography, known solution features and proximity to source protection zones (taking into account the connections identified by the signal tests reported by Mott MacDonald, 2014) and ascribes a score to each. The higher the score, the greater the risk to an abstraction borehole from any particular pile group.

7.2.3 The risk assessment has been completed for the piles at the two embankments and for each pile group associated with a viaduct pier and those groups which represent a similar risk to the abstractions have been assessed together. This is purely a guide to the locations that are the greatest risk and is a comparative rather than definitive tool. The matrix is included in Appendix 2 whilst the risk for the viaduct pile groups at each pier is summarised in Table 1. The numbering of each pier is shown in Figure 1.

7.2.4 The assessment has been completed for the [redacted] abstraction and assumes that [redacted] is shut down and [redacted]. This will affect the currently mapped SPZs (shown in Figure 4) and for the purposes of the assessment it is assumed that the SPZs for [redacted] and [redacted] change such that SPZ1 becomes SPZ2 and SPZ2 becomes SPZ3.

The assessment also assumes that all piling is undertaken during the peak demand period as this provides the most conservative scenario. Those pile groups classified as very high risk are of most concern regarding the requirement for mitigation during construction.

Table 1 Risk summary for embankments and pile groups at each pier location

Viaduct Piers	Risk rating	Comments
1-19	Moderate	Shown as in SPZ2, but [redacted] and when [redacted]s shut down, they may be in SPZ3, or most likely not within the SPZ for [redacted]
20-36	High	Shown as in SPZ1 for [redacted] [when [redacted] is shut down, the cone of depression may change such that the piers may no longer be within the area of 50 day travel time to [redacted] All piers are greater than 1km down gradient of [redacted] and so the actual risk is likely to be lower than estimated using the spreadsheet tool.
37-46	Very high(2)	In SPZ1 for [redacted] and all less than 1km from supply.
47-58	Very high(1)	In SPZ1 for [redacted] and all less than 0.5km from supply borehole.
South Embankment	Low	Distant and down gradient from [redacted] and only risk is chalk turbidity from driven piles.
North Embankment	High	Close to [redacted] and in SPZ1. Risk is from chalk turbidity, although this is limited by shallow depth of piles / VCCs.

Note: (1), (2) although piers 37 to 58 all fall within the same risk rating group, the risk is highest at piers 47-58 such that different mitigation may be appropriate for each group.

7.2.5 The assessment indicates that piers 37 to 58 have a very high risk to the [redacted] abstraction indicating that mitigation is required to reduce the risk of an outage at [redacted] during construction.

Aquifer destabilisation

7.2.6 The risk of further collapse at [redacted] and the effect of this on manganese concentrations in the abstraction water, particularly in the long term is not known. Further collapse could happen naturally and manganese could also increase with or without collapse. Due to this uncertainty it is necessary to consider monitoring and mitigation options.

Creation of preferential pathways (vertical)

Steel casing used for upper section of viaduct piles, steel sheet piles for coffer dam and tubular steel piles for the temporary jetty

7.2.7 As detailed in Section 4.3, the sheet piles for the coffer dams for pile cap construction will only be installed to relatively shallow depths in the chalk and the piles will remain in place following construction of the pile caps. As the geology will be silty sand and gravel over putty chalk, and the piles will not be driven into chalk rock, vertical flowpaths are not likely to be created. In addition, the coffer dams will only be required for the piers located on land and so the effects are likely to be very limited and will not require mitigation. They are therefore not considered further. This notwithstanding, the assessment below regarding the degradation of the tube piles for the temporary jetty also applies to the sheet piles.

7.2.8 The primary concern regarding the use of steel piles is those for the temporary jetty which would be constructed across the lake areas on steel tubes. In addition, the casing installed to stabilise (and keep lake water out) the shallow strata where the viaduct piles will be drilled (see Figure 3) would pose a similar risk. The tubes and casing both have the potential to result in the creation of preferential vertical pathways between the lake water / groundwater in the sand and gravel, and that in chalk rock. The risks are two-fold: (i) upon insertion; and (ii) associated with long term decay.

7.2.9 The piles selected for the temporary jetty and the casing are all driven tubes. The casing and piles will laterally displace the material that they pass through, thereby causing a local reduction in volume, increase in density and a decrease in vertical permeability. However, this is only the case where the material they pass through is cohesive rather than granular or blocky. If the superficial deposits are particularly silty and/or the weathered chalk a putty chalk (i.e. clay like), then a seal is likely to form and additional mitigation will not be necessary, provided that these types of deposits are at least 2m thick. Based on ground investigation completed to date there is significant variability in the putty chalk thickness and lithology and so there may be limited instances where a good seal is not achieved (this can only be determined from ground investigation data). However, based on the geological sections (see Appendices in hydrogeological risk assessment for the Colne Valley Viaduct), along the majority of the viaduct route the chalk soil (putty chalk) is likely to be over 5m thick, the exception being Piers 32 to 34.

7.2.10 The steel piles that will be driven into the Chalk will remain in place after the jetty has been removed and Affinity Water has expressed concerns that the piles would degrade and collapse in the long term (i.e. tens to hundreds of years) resulting in the creation of a preferential vertical pathway between the lake / sand and gravel water and the underlying chalk. In order to assess the likelihood of this a brief literature review has been completed to determine what information is available regarding decay rates for steel piles installed in natural soil and below the water table. The majority of documents identified are concerned with two aspects: (i) the structural integrity of the piles in terms of their load bearing characteristics, particularly over the design life of the structures; and (ii) the use of supplemental protection to prevent or limit corrosion. However, some of the documents include relevant information regarding rates of degradation in various environments and so provide some data to assess the implications of long term pile decay on the creation of preferential vertical pathways.

7.2.11 The documents reviewed generally state that steel piles installed in naturally occurring soils are not subject to significant corrosion within the design life of the piles. A review carried out in the US by Schwerdtfeger and Romanoff[8] stated that "in general, steel pilings are not significantly affected by corrosion in undisturbed natural soils, regardless of the soil types and soil properties." Work by the North American Steel Sheet Piling Association (NASSPA)[9] indicates that clean fresh water has low corrosion potential and corrosion protection for piles is not warranted. However, the NASSPA document does suggest that corrosion could increase at the water surface in cases where there is very limited water movement (e.g. canal banks). This is also reflected by other documents including Corus[10] which indicates that unless the soil or water has a pH less than 4 steel pile corrosion in natural soils / freshwater is negligible.

7.2.12 With regard to the rate of corrosion, various estimates are included in the literature, with Oshsaki[11] indicating a rate of steel loss of about 0.01 mm/year over a 10 year period based on direct assessment of about 130 steel piles of 15m length driven into natural soil deposits at ten locations in Japan. Based on extrapolation of existing data, NASSPA [6] suggest a loss of steel thickness of 1.2 mm over a 100 year period in soil (with or without the pile being in groundwater). However, the NASSPA also suggest that with time the rate of steel corrosion decreases due to the formation of rust, which if not removed will form a protective coating on piles thereby limiting further corrosion (although it should be noted that this layer does not protect the underlying metal in the same way as surface oxidation of aluminium or copper). In addition, the NASSPA indicate that "Pitting corrosion is more common than uniform loss on steel pilings" suggesting that where corrosion does occur it could be in patches. BS 8002[12] indicates a maximum corrosion rate in natural soils of 0.015mm/year.

7.2.13 The above assessment suggests that corrosion rates for the steel piles below the water table will be very low, with somewhere of the order of 1 mm thickness being lost from both the inside and outside of the steel tubes over a 100 year period, and a reduction in the rate of loss beyond that as the rust forms a protective layer. With a steel pile wall thickness of 10 to 15mm, at this rate decay of the piling tube would take well over 500 years. Taking into account the reduction in decay rate caused by the presence of the rust layer, complete tube decay may take 1000 years or more.

7.2.14 During the rusting process, the steel would react with oxygen (in the water) and the water to form iron oxide(s). On production the oxides expand (see Kim et al[13] for example) and this

[8] Schwerdtfeger, W. J. and M. Romanoff, 1972, NBS Papers on Underground Corrosion of Steel piling, 1962-197
[9] North American Steel Sheet Piling Association (NSSPA), 2008, Guidance on Corrosion, Steel Sheet Piling Technology Paper T.02.
[10] Corus Construction and Industrial, 2005, A corrosion protection guide for steel bearing piles in temperate climates
[11] Oshsaki, Y, 1982, Corrosion of steel piles driven in soil deposits, Soils and Foundations, Volume: 22, Issue Number: 3, Japanese Geotechnical Society.
[12] BS 8002, 1994, Code of practice for earth retaining structures (withdrawn and not yet replaced, although BS EN 1997-1:2004+A1:2013 Eurocode 7. Geotechnical design provides some information, but does not provide detail of corrosion rates).
[13] B. H. Oh & K.H. Kim, B. S. Jang, J. S. Kim and S. Y. Jang, undated, Realistic model for corrosion-induced cracking in reinforced concrete structures, Dept. of Civil Engineering, Seoul National University, Seoul, Korea.

would serve to reduce rather than increase the space available to form a preferential pathway. In addition, as ferric oxides tend to have a relatively low solubility, they would not be removed in any great volume by water in the aquifer moving past the piles and so there would not be a reduction in material. In addition, the rust would be expanding into soil that had already been compressed by the insertion of the piles so reducing the likelihood of a preferential flowpath. This assessment therefore suggests that the potential for the piles to form vertical preferential pathways is very low.

7.2.15 The current design for the temporary jetty is for the insertion of some 300 steel tube piles, each with a diameter likely to be of the order of 900 mm. In the unlikely event that these do increase leakage from the lakes to groundwater, an assessment has been made in Table 2 of the potential long term effect on the [redacted] abstraction, which is the closest to the viaduct. The assessment has been completed on the worst case assuming that the whole cross sectional area of the pile leaks, not just that associated with the circumference of the pile tube.

7.2.16 Assuming that the SPZ1 for [redacted] is about 500 m in radius and the whole of this area is fed by lake water, this indicates that the piles would represent 0.02% of the total SPZ1 / lake area (Table 2). This is a very small percentage and suggests that a significant increase in vertical permeability would be needed to have a significant effect on lake water influx to the [redacted] abstraction.

7.2.17 It has been estimated by Affinity Water that some 30% of the water abstracted from the [redacted] boreholes is derived from surface water. The average demand capability at the [redacted] source is around 16 Ml/d, which assuming a 30% influx from surface water suggests approximately 4.8 Ml/d is derived from surface water. The 16 Ml/d is derived from the total catchment, whilst the surface water influx will largely be from the SPZ1 area where the lakes are located. It is therefore likely that some 4.8 Ml/d is derived from an area of about 785,500m^2 (i.e. 500m radius). If it is assumed that the vertical hydraulic gradient is 1, then based on Darcys Law, the effective vertical permeability (k_v) would be about 0.006 m/d. This is an order of magnitude estimate, but based on typical values for clayey strata is not unreasonable.

Table 2 Estimate of the effect of an increase in leakage caused by piling

Aspect	Size	Basis
No. of piles	300	Preliminary design (could change)
Pile radius	0.45 m	Preliminary design (could change)
Pile cross-sectional area	0.64 m^2	Assumes all of pile leaks, not just at the pile circumference
Total area for all piles	191 m^2	

Aspect	Size	Basis
Approx. radius of [redacted] SPZ1	500m	Estimated from EA SPZ map (mostly lakes)
Approx. area of [redacted] SPZ1	785,500 m^2	
Percentage of SPZ1 occupied by piles	0.02 %	
Current estimate of surface water contribution to [redacted]	30% (4.8Ml/d at average)	Affinity Water
Estimated effective current vertical permeability (k_v)	0.006 m/d	Assumes 4.8 Ml/d from 785,500m^2 with a vertical hydraulic gradient of 1
Proportion of surface water to [redacted] assuming a ten-fold increase in k_v	30% (0.01Ml/d increase)	Assume k_v=0.06 m/d, no change in total volume abstracted
Proportion of surface water to [redacted] assuming a hundred-fold increase in k_v	31% (0.1Ml/d increase)	Assume k_v=0.6 m/d, no change in total volume abstracted
Proportion of surface water to [redacted] assuming a one-thousand-fold increase in k_v	37% (1.1Ml/d increase)	Assume k_v=0.8 m/d, no change in total volume abstracted

7.2.18 In order to estimate the effect of increased permeability caused by piling various increases in the vertical permeability (k_v) have been made in Table 2 for all 300 piles. The additional downward flux of surface water has then been added to the existing downward flux to determine if it is significant in terms of the [redacted] abstraction. The calculations indicate that a ten-fold increase in vertical permeability at every pile would only increase the proportion of surface water abstracted at [redacted] by about 0.01Ml/d, whilst a one hundred-fold increase in k_v would result in 0.1Ml/d more water (equivalent to 31% of the total abstraction being from surface water), and a thousand-fold increase would result in 1.1 Ml/d more water (equivalent to 37%).

7.2.19 Although there are a lot of assumptions in the above calculations, they do suggest that for the proportion of surface water to increase significantly the vertical permeability at all of the piles, across the whole cross sectional area of each pile would need to increase by several hundred-fold across the full width of the pile.

7.2.20 In addition to the direct effect of an increase in vertical permeability, Affinity Water has concerns that changes in flow paths, caused by localised blocking of fractures and fissures could result in [redacted] abstracting more lake water to compensate for the reduction in chalk water caused by the blockage (Affinity Water has not indicated that this is a concern at [redacted] but if it were then the same assessment would apply). The potential for this is unknown at this stage. However, the likelihood of a significant effect is not high as the majority of inflow to [redacted] is derived from up gradient of the viaduct. This notwithstanding, there is some risk and so monitoring will be required to determine if this becomes significant in the long term. Mitigation in the event of this being identified is considered in Section 8.

7.2.21 In summary, the above assessment suggests that the vertical steel tubes will not form a preferential pathway, either when installed (due to displacement causing a reduction in soil permeability) or due to long term decay. If the piling did cause an increase in permeability, it would need to be several hundred-fold and at all 300 piles across their full area to have a noticeable effect at [redacted] abstraction borehole. However, this is dependent upon the superficial deposits being silty and/or the weathered chalk being a putty chalk at the majority of the piled locations. Figure 5 indicates that this is likely to be the case, with the exception of a small area between piers 32 and 34 which are in Korda Lake.

7.2.22 Although the above calculations indicate that there will not be a significant effect on preferential flow paths from the lakes and gravels to the chalk, Affinity Water has concerns that even small changes in the influx of lake or gravel water to the abstraction borehole could have significant effects on water quality, particularly the manganese concentrations. The effect of an increase in leakage rates from the lakes and gravels on manganese concentrations at [redacted] (as an indicator of water quality changes) is considered in Table 3. The calculations assume that the current background manganese concentration in the chalk is low (10 µg/l) and that in the gravels it is high (130 µg/l), which combine to give a concentration at [redacted] that is just below the drinking water standard (50 µg/l). The measured concentration at [redacted] is less than this, but the calculations serve to indicate the type of increase in vertical permeability that would be required to drink potable water standards. Although other combinations are possible (lower chalk concentration and higher gravel concentration), the current assumptions serve to illustrate the effect of increasing leakage at piles on manganese concentrations and the increase in influx of lake or gravel water necessary to result in an exceedance of the drinking water standard at the abstraction borehole.

Table 3 Effect of changes in leakage rates on manganese concentrations in [redacted] abstraction

Aspect	Conc (µg/l)	Comment
Assumed Mn concentration at [redacted]	46	Drinking water standard = 50 µg/l, so current abstraction would be less than this value
Chalk groundwater conc of Mn	10	assumption of low concentration in groundwater
Concentration of Mn in gravel or lake water	130	assumes 30% of abstraction is lake or gravel water
Mn concentration with 10x increase in vertical permeability at all 300 piers	46.1	
Mn concentration with 100x increase in vertical permeability at all 300 piers	46.9	
Mn concentration with 400x increase in vertical permeability at all 300 piers	49.8	

7.2.23 The calculations indicate that a 400 fold increase in vertical permeability across the full width of all 300 piles would be required to result in an increase in manganese concentrations at the [redacted] abstraction borehole from being currently below drinking water standard, to that which could exceed the standard. The likelihood of this occurring is, as noted above, extremely low so the potential for the piling for the temporary jetty to have a significant effect on manganese concentrations at [redacted] is also extremely low.

7.2.24 Affinity Water's main concern regarding an increase in manganese is the effect on its infrastructure as manganese can precipitate out of solution and coat the inside of pumps and pipes reducing their effectiveness and increasing maintenance costs. The calculations summarised in Tables 2 and 3 indicate that the potential for a significant change in downward flux of water and a significant increase in manganese concentrations is low. In all likelihood any increase would be in the range of 0.1 to 1 µg/l, assuming a maximum increase in vertical permeability of 100 fold at the location of all 300 piles. This is not considered significant and mitigation is not required. However, monitoring will be implemented to check this and in the unlikely event of manganese increasing in concentration at [redacted] (or any other Affinity Water abstraction) due to HS2 piling activities, then additional mitigation may be required. Any such additional treatment could also be classed as a deterioration of the Water Framework Directive (WFD) status of the water body.

Viaduct Piles

7.2.25 The below ground permanent works will include installation of the main piles for construction of the viaduct piers. As these will be cast *in situ* they will not result in the creation of a preferential vertical pathway. Cement poured into the bore will fill fractures and any void space associated with the bore and will therefore not create a preferential vertical pathway.

Changes to flowpaths (horizontal)

7.2.26 As indicated in Section 6.7 there is the potential for the piles to cause a reduction in yield at public water supplies in the vicinity of the viaduct by reducing the available aquifer cross sectional area for water movement, or by blocking individual pathways. This has been assessed and is not considered to be significant at [redacted] nor [redacted] for the following reasons, although it is acknowledged that the level of certainty regarding potential effects at [redacted] is much lower than at [redacted]

- [redacted] and [redacted] abstractions are up hydraulic gradient of the viaduct and the vast majority of their catchment areas are up hydraulic gradient. Although there will be some water derived from down and across gradient (cross gradient connections were identified by the signal tests (see Mott MacDonald, 2014)), the majority will be from up hydraulic gradient.

- At its closest [redacted] is some 300m from the viaduct and so localised effects are not likely to reach the abstraction borehole. [redacted] is much closer, being within 100m of the viaduct and so there is a much higher risk of an effect.

- Although the aquifer is heterogeneous, it is not characterised by a small number of large isolated conduits. There are preferential flow paths associated with fractures, fissures and solutionally enlarged voids, but in chalk these tend to form interconnected networks rather than isolated conduits. The potential for a significant effect at [redacted] is therefore low. However, as noted in Section 6 of this report, at [redacted] there is a much greater risk of fracture blockage due to the proximity of the abstraction boreholes to the viaduct, and mitigation may be required. The need for this may become apparent during the piling works, but it will not become completely clear until [redacted] is brought back into supply after the piling works are complete. It will then be possible to establish if any reduction in borehole performance has occurred.

- The piles will reduce the cross sectional area of the aquifer across the valley, and so will act as a partial barrier reducing flow rates through the ground. The effect of this reduction in cross sectional area on groundwater flow through the aquifer will depend on whether the piles goes through highly fractured or unfractured sections of chalk. Critically, it will be whether the piles in one pile group act independently of each other (i.e. allow water to pass between them) or act as a single block not allowing any water movement between them. These two represent the extreme cases and in reality, there will likely be a mixture of both effects. Where there is backing up of water around piles this could result in an increase in water level on the upgradient side of the pile which in turn would increase flow rates, although this would not be sufficient to compensate for the reduction in cross sectional area. However, as the highest permeability tends to be in the zone of groundwater fluctuation, an increase in water level could result in water movement through higher permeability rock which would reduce the effect on the abstraction rate from [redacted] In addition to the potential to reduce abstraction rates, there is also the potential to increase abstraction rates if water that would otherwise flow southwards beneath the Colne Valley is prevented from doing so and backs up on the northern side of the piles allowing more water to be abstracted. As noted above there is a high degree of uncertainty regarding the actual effect which will not become apparent until the piling is complete and the [redacted] supply is switched back on. Monitoring before and after the commencement of work is therefore critical to understanding the impacts and the requirements for mitigation.

7.2.27 An estimate of the potential reduction in groundwater flow towards [redacted] has been made by assessing the likely reduction in aquifer cross sectional area and the contributing flow to the abstraction from the south western (down hydraulic gradient) side of the viaduct. This assessment suggests a reduction in flow of less than 0.4% (Table 4) assuming a homogenous flow system. Although the flow is heterogeneous, in highly fractured aquifers, at the scale of the valley, it could approach an approximation of heterogeneity, assuming that there is no single conduit which dominates flow in the valley. This reduction in flow is not significant, particularly given the likely pump / well losses associated with the abstraction, and with the collapses that the boreholes have suffered in the past. Clearly if there were a very small number of conduits feeding [redacted] then this situation would be different).

Table 4 Estimate of possible reduction in yield from [redacted] abstraction

Best case - full flow between all piles	**Value**	**Unit**	**Comments**
Total cross sectional area of piles	11790	m^2	based on preliminary design
Colne Valley width at viaduct	3376	m	full width of viaduct from P1 to P58
Active saturated thickness	50	m	best estimate
cross sectional area	168799	m^2	
% of cross sectional area occupied by piles	7%		
[redacted] abstraction rate	16	Ml/d	AW information
SPZ1 radius	500	m	best estimate
SPZ1 area	785500	m^2	
SPZ1 south west of viaduct	392750	m^2	assume half from SW of viaduct (conservative)
Total catchment of [redacted]	11000000	m^2	Estimated (conservative value), based on erain (350mm) and support to abstraction from lake water (30%)
Area of SPZ1 SW of viaduct as % of total	3.6%		
Inflow from SW of viaduct	0.57	Ml/d	
Reduction in flow from SW (assuming homogeneous)	0.04	Ml/d	
Abstraction rate post viaduct construction	16.0	Ml/d	
Reduction in abstraction rate post construction	0.2%		
Worst case - no flow between piles			
Worst case - no flow between piles	**Value**	**Unit**	**Comments**
Total cross sectional area of piles	18360	m^2	based on preliminary design
Colne Valley width at viaduct	3376	m	full width of viaduct from P1 to P58
Active saturated thickness	50	m	best estimate
cross sectional area	168799	m^2	
% of cross sectional area occupied by piles	11%		
[redacted] abstraction rate	16	Ml/d	AW information
SPZ1 radius	500	m	best estimate
SPZ1 area	785500	m^2	
SPZ1 south west of viaduct	392750	m^2	assume half from SW of viaduct (conservative)
Total catchment of [redacted]	11000000	m^2	Estimated (conservative value), based on erain (350mm) and support to abstraction from lake water (30%)
Area of SPZ1 SW of viaduct as % of total	3.6%		
Inflow from SW of viaduct	0.57	Ml/d	
Reduction in flow from SW (assuming homogeneous)	0.06	Ml/d	
Abstraction rate post viaduct construction	15.9	Ml/d	
Reduction in abstraction rate post construction	0.4%		

7.3 Summary of potential effects that require mitigation

7.3.1 Of the effects outlined above, the potential for chalk turbidity is of greatest concern as it is known to occur and all of the construction activities below the water table have the potential to cause it. This is closely followed by bentonite contamination, most likely causing turbidity, but also potentially in high concentrations in the water. These will therefore both require mitigation. Cement is unlikely to be an issue due to setting times and potential to use thicker mixes to reduce migration. The potential to create preferential vertical pathways is also limited and does not require mitigation. The potential for aquifer destabilisation and the potential for piles to change flowpaths through the aquifer are unlikely to be significant, but there is a much greater uncertainty at [redacted] than at [redacted] regarding the potential effects. These effects could be on water volume and quality and so monitoring is required to check these effects, particularly when [redacted] is re-started after the agreed outage during piling works.

8 Mitigation

8.1 Options for mitigation of chalk turbidity

8.1.1 Mitigation of chalk turbidity will take the form of treatment at the public supply abstractions and the cessation of pumping from [redacted] abstraction. This mitigation has been commenced and Affinity Water is having an appropriate treatment solution designed and installed. No further specific mitigation for this is proposed, although it is recognised that some mitigation for bentonite turbidity may also limit chalk turbidity.

8.2 Options for mitigation of bentonite or polymer turbidity

8.2.1 There are possible effects on water quality during piling for the viaduct due to the use of bentonite or polymer for formation support. In order to mitigate this a range of potential options have been considered which are outlined in Table 5 along with the advantages and disadvantages of each. Some of those that are considered viable options require further work as outlined in Table 5. In the case of bentonite turbidity the water treatment plants being constructed to mitigate the effects of chalk turbidity will also mitigate bentonite.

8.3 Options for mitigation of changes in flow paths changing water quality

8.3.1 In the event that flow paths are changed and result in an increase in lake or gravel water such that the concentrations of water quality parameters (especially manganese) increase significantly there may be a requirement for treatment at the abstraction boreholes. This requirement would be determined by long term monitoring in the groundwater and at Affinity Water abstractions, to identify any significant changes caused by the construction of HS2. The likelihood of a significant long term effect has been assessed in the WFD Compliance

Assessment[14] as low, albeit with a degree of uncertainty that would require checking by long term monitoring.

8.3.2 Options have not been evaluated, but there are a number of well proven techniques on the market, including oxidation followed by filtration of precipitates. At this stage the potential need for this mitigation is considered to be low, but due to the high level of uncertainty, it cannot be excluded. Clearly a review of long term records and changes during and after the construction programme would need to be evaluated to assess possible causes. Careful monitoring during the recommissioning of the [redacted] supply would be an essential part of this.

8.4 Options for mitigation of collapse at [redacted]

8.4.1 At this stage the potential for this event to occur is considered to be low, but due to the high level of uncertainty, it cannot be unequivocally excluded and three possible options for mitigating the long term effects on water quality at [redacted] due to borehole collapse have been considered below.

8.4.2 The first option is to install slotted steel well screen, with large openings, into the lower open hole section of the three boreholes. This would mean that any collapse would just fall against the screen and would not block the lower part of the abstraction borehole. This would mean that flow paths in the borehole would remain unchanged and provided that the well screen has a large enough open area it would not change wells losses or borehole yield. This option would need to be undertaken before construction begins on piles within 200m of the boreholes.

8.4.3 The second option is to make no changes during construction and to monitor [redacted] to see if there are any changes in borehole depth due to collapse and if any changes then result in changes to water quality. If such changes are identified then rectification could include cleaning out the collapse and installing well screen, along with well development and commissioning.

8.4.4 In the event that well cleaning is not possible, or is unsuccessful, then drilling a replacement abstraction borehole at the site (or another more appropriate site) to the original depth of any collapsed borehole may be the only effective mitigation.

[14] Align, 2019, Section C1 - Updated Water Framework Directive Compliance Assessment, Document no: 1MC05-ALJ-EV-REP-CS01_CL01-100082

Table 5 Mitigation options for the use of bentonite or polymer during viaduct piling

Technique	Advantages	Disadvantages	Consider further ?	Further work required
Do not use any additive for piling and rely on water inflow to provide stability	Low initial cost, effect on abstractions limited to chalk turbidity.	May not be able to complete piled hole resulting in need to backfill and re-drill, increased cost and programme. Re-drill could cause greater turbidity. May still need to use bentonite at some locations and these are likely to be the highest risk locations (i.e. where voids are present and migration is likely).	Yes	Estimate allowance for failed no. of holes and develop approach for backfill and re-drill.
Use bentonite but gain understanding of groundwater migration to manage risk	Bentonite use is well proven and common, equipment available.	Transport characteristics of bentonite in the aquifer not known, not effective in large solutional voids.	Yes	Undertake trial to ascertain extent and rate of bentonite migration.
Use polymer instead of bentonite	Although opaque, less likely to result in turbidity as high as that resulting from bentonite (uncertainty with this).	Unknown toxicity and transport characteristics, will not be effective where large solutional voids are encountered, treatment ability unknown.	Yes	Contact supplier for toxicity information and EA approval details. Assess migration potential. Undertake trial to ascertain extent and

Technique	Advantages	Disadvantages	Consider further ?	Further work required
				rate of polymer migration
Minimise the duration of works, particularly at the highest risk locations	Potential for loss of bentonite or polymer is reduced.	Highest risk locations are likely to be those with solutionally enlarged voids which are likely to be the most complicated and will take longer to construct. Technique will only reduce, not eliminate the problem. May not be options to reduce duration of works (i.e. programme will be optimised).	Yes	Contractor to assess methods to speed up piling (e.g. equipment selection, pile diameter, pile depth, esp at highest risk locations). Ensure partially completed holes are not left.
Limit all piling to periods outside of peak demand	If an effect occurs there is more resilience in the system to cope with an outage and demand is lower.	Would have substantial effects on programme and costs would markedly increase due to remobilisation costs.	No	
Limit piling at very high risk areas to periods outside of peak demand	If an effect occurs there is more resilience in the system to cope with an outage and demand is lower.	Could affect programme and result in inefficiencies in piling due to sub-optimal rig movements. May not identify high risk areas until ground investigation is complete.	Yes	Align to consider programming once ground investigation is complete and results available.

Technique	Advantages	Disadvantages	Consider further ?	Further work required
Recover bentonite or polymer using scavenger pumps	Recover lost bentonite / polymer before migration to an abstraction borehole so that there is no effect on water supply.	Need abstraction borehole downgradient of pile hole, need to hit same zone of migration as in pile hole, may not be possible to drill scavenger hole from temporary jetty so jack up rig would need to be mobilised (if practicable), need storage, treatment and / or discharge point for water abstracted from the scavenger well.	Yes	Assess borehole and pump requirements and treatment methods. Discuss licensing requirements with the EA.
Use [redacted] as a single large scavenger well	Borehole and infrastructure already present and borehole will not be used for abstraction during construction. Large volume of water could be pumped creating a large capture zone.	Could induce bentonite or polymer migration that would otherwise not happen. Would need to pump large volume of water to waste for the duration of construction. Volume of turbid water requiring treatment would be significantly greater than would be the case if bespoke scavenger wells were used at locations of concern. Would not be targeted at areas of particular concern but would rely on capturing water from a significant area. Would not be suitable for piles	No	Discussions with Affinity Water indicate resistance to this as it could result in more widespread movement of particles than would otherwise be the case and this could result in localised blockage of the aquifer.

Technique	Advantages	Disadvantages	Consider further ?	Further work required
		constructed along the northern half of the viaduct that are closer to [redacted] Would constrain any Affinity Water maintenance work on the boreholes.		
Local ground improvement at individual piles	Only targeted at locations identified by ground investigation as having significant solutional development, use of rapid setting grout would prevent grout migration.	Can only be completed after ground investigation, or after piling has commenced (hole stability issue when just using water).	Yes	Review ground investigation to identify locations where ground improvement may be appropriate.
Use casing when installing piles	Casing holds pile open hole negating the need for bentonite or polymer and provides a greater degree of certainty that hole will remain open through poor ground conditions.	Very high cost. Could create preferential pathway down outside of casing depending upon geology, depth and installation method (drilling and installation rather than displacement would mean no localised reduction in ground density), removal of casing requires specialist (heavy) equipment, may require more robust jetty to carry heavier plant, if casing remains in hole re-design required due to change in	No	

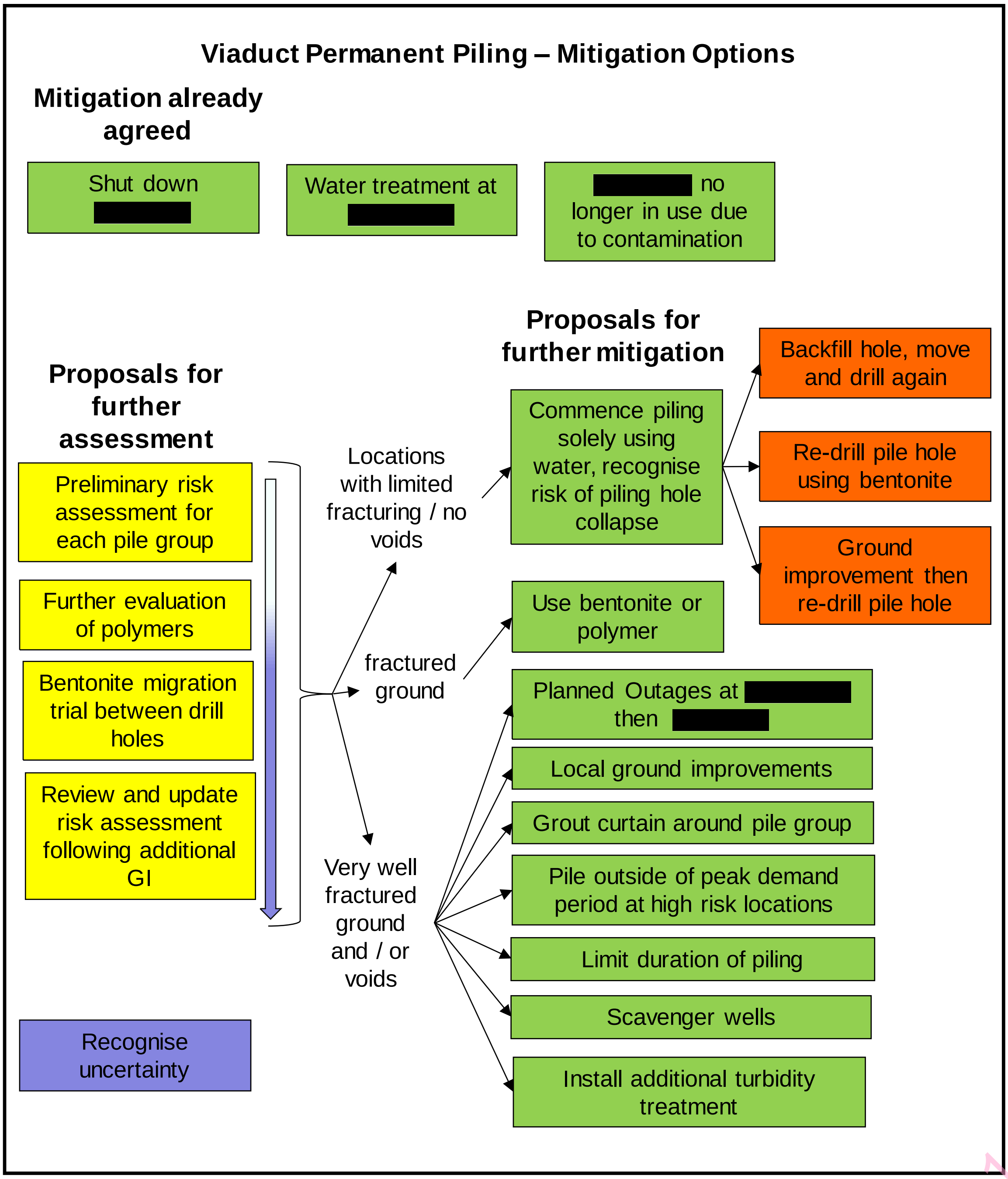
Technique	Advantages	Disadvantages	Consider further ?	Further work required
		friction, casing removal could change ground conditions.		
Grout curtain around pile group	Will prevent any migration of bentonite from within the curtain. Use of rapid setting grout required when forming curtain to prevent grout migration and/or use of grout thickeners to increase viscosity.	Very high cost, increased programme, installation of grout curtain could cause greater chalk turbidity than piling.	Yes	Review ground investigation and use consider this option only at very high risk locations where there are no other viable options.
Drill replacement abstraction borehole outside of zone of influence	Water source sufficient distance so as to not be affected by piling.	Identification of suitable locations, land ownership, long run in time to obtain consents / permits and to get authorisation to use for potable supply.	No	Option considered at Environmental Impact Assessment stage and ruled out.
Extend treatment at Affinity Water boreholes to treat higher levels of turbidity	Allow greater aquifer disturbance (e.g. multiple activities). If monitoring indicates a potential effect may address issue Allow extra levels of turbidity to be treated if monitoring indicates potential for impact	Additional cost Additional time to procure further treatment units (but infrastructure should already be in place)	Yes	Liaise with Affinity Water / HS2 regarding additional land take for this. Determine cost of additional units.

Technique	Advantages	Disadvantages	Consider further ?	Further work required
Alternate shutdown of [redacted] and [redacted] to match construction that is scheduled in closest proximity to each abstraction	Closest borehole to work will cease operation reducing risk of an unplanned outage (i.e. [redacted] would shut first whilst work at north end of viaduct and Northern Embankment is completed, then [redacted] would re-start and [redacted] would shut down). Significant improvement to construction programme	Assumes that there is no rapid flowpath to the abstraction borehole from areas not adjacent to the abstraction and does not provide mitigation in this instance. Will only provide a partial solution to the problem.	Yes	Discuss options / potential with Affinity Water
Shut down [redacted] abstraction	No reliance on water going into supply from this source	Could change flow characteristics at [redacted] risks to [redacted] stability on re-start.	Yes	Outage is already programmed, consider effects on groundwater levels due to rebound and effects at [redacted]

8.5 Mitigation route map managing turbidity

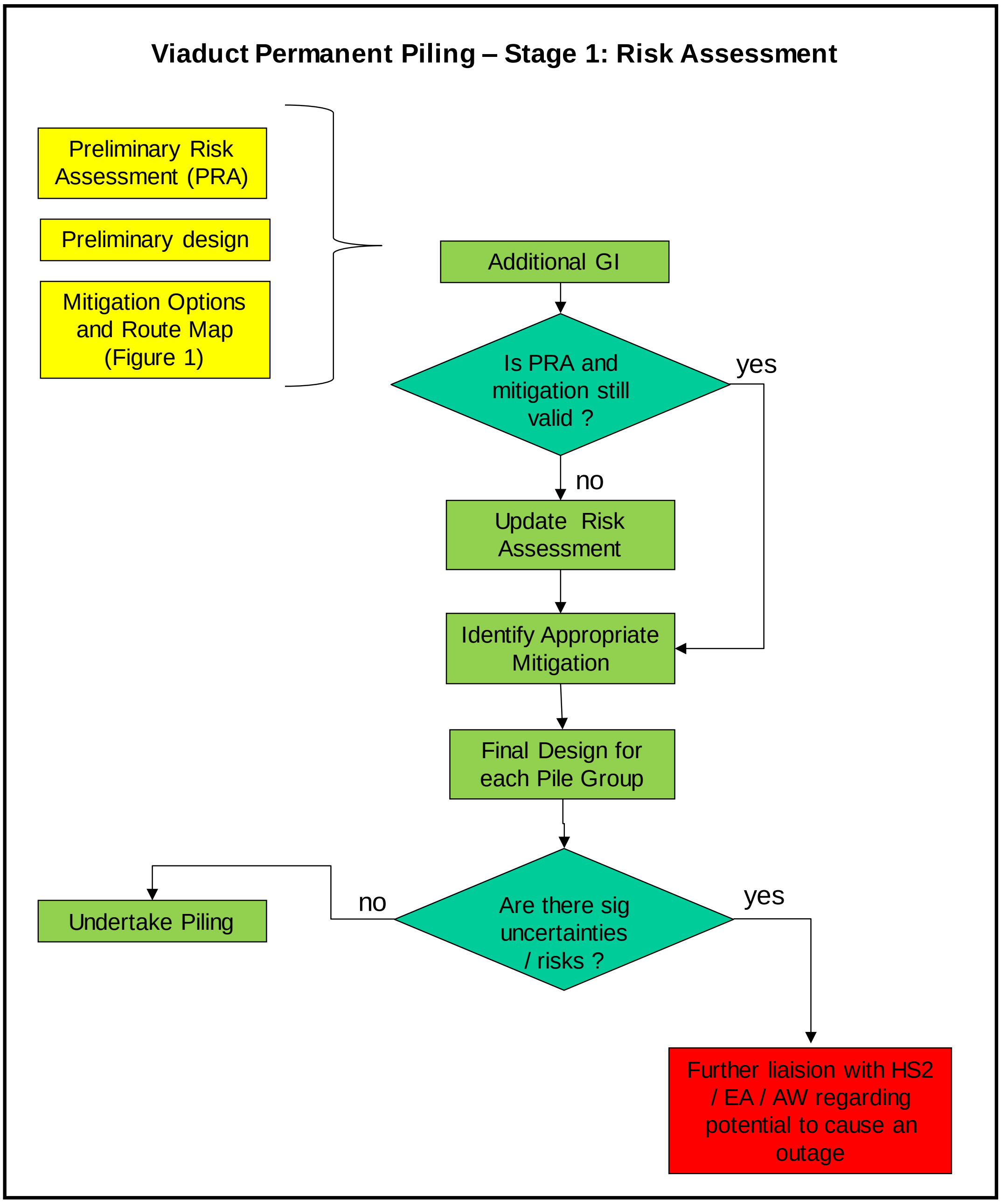
8.5.1 There is no single option that will mitigate all risks to Affinity Water abstractions whilst allowing the construction of the viaduct to continue to a reasonable cost and within a reasonable programme. However, as indicated above there are a series of options, with those considered viable at this stage shown schematically in Figure 5.

Figure 5 Mitigation route map – planning stage



8.5.2 In order to identify which mitigation options are required at which pile group a risk assessment approach is proposed. A preliminary risk assessment would be prepared that would identify those locations along the viaduct where there is the greatest risk of causing an outage at an Affinity Water supply. This is effectively the risk assessment summarised in Table 1. The risk assessment is being be used at the planning stage to design the work and in particular to identify those locations that would benefit from a particular approach. This process is shown schematically in Figure 6.

Figure 6 Risk assessment approach



8.5.3 During the construction stage of the works (Stage 2), the management tool which is shown in Figure 7, would be used to ensure that the ground conditions are taken into account and the mitigation is amended accordingly to limit the potential for bentonite turbidity. The piling approach would be selected based on Stage 1 and this design would be implemented for construction. Monitoring would then be used to determine if the piling is causing an unexpected effects and whether additional mitigation is required.

8.5.4 The management regime shows that if insufficient or inappropriate mitigation is undertaken, either at design or construction stage, or if an appropriate technique cannot be identified, this could result in shut down of the [redacted] public water supply borehole. The implications of this would vary with the season and the duration of the shut down.

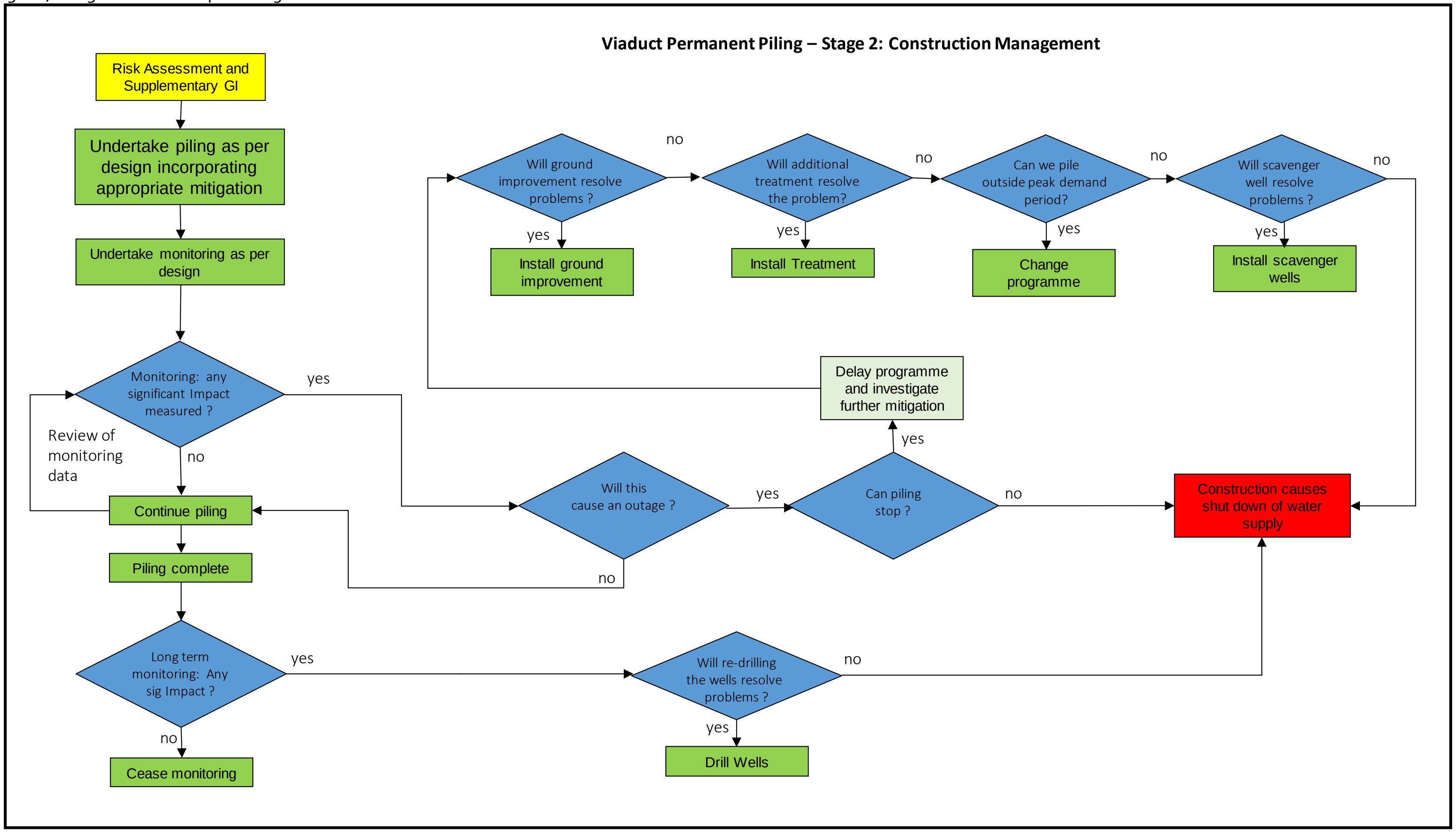
8.5.5 Outside of perk demand period it may be possible to provide sufficient water from other sources, whereas if it happened during the peak demand period it could lead to a water shortage and implementation of an emergency drought order to reduce water consumption. Supplies to non-critical users may be suspended, and this could include HS2 Section C1 if the water supply for construction is provided by Affinity Water. In extreme circumstances it could require the provision of bottled drinking water, or supply by tanker or bowser from other sources.

8.5.6 If the effect was short term over hours or 1 to 2 days then even during peak demand period it is likely that sufficient water from other sources could be provided until the water was suitable to be put back into supply again. If it was a very short term event due to a specific short duration construction activity then there would be no requirement to cease the activity unless there was an indication that its effect would continue.

8.5.7 In the event of the [redacted] abstraction being shut down due to ongoing activities being undertaken by Align then the construction activities would cease and the cause of the shut down would be evaluated and its implications considered. This may mean a complete change in approach to the construction activity or cessation of work until the peak demand period is over and alternate supplies can be put in place.

8.5.8 If [redacted] is taken out of supply it may be necessary to keep pumping to waste to flush any contaminants through the aquifer, or there may be a requirement for scavenger wells to remove contamination, or possibly additional treatment installed at [redacted] At this stage, and based on the risk assessment in this report, the likelihood of the complete closure of [redacted] is assessed as very low and the need for additional mitigation is unlikely.

Figure 7 Mitigation route map – during construction



8.6 Recommended approach for managing bentonite / polymer turbidity at each pile group

8.6.1 The risk identified for piling at each pier identified in Table 1 has been used to prepare a preliminary mitigation approach to manage bentonite / polymer turbidity on the basis that the [redacted] supply is shut down. This is summarised in Table 6. As additional ground investigation information is obtained the approach to the mitigation would be reviewed and if necessary modified. The mitigation route map for construction (Figure 7) would then be followed and if monitoring indicates an effect further mitigation would be implemented as appropriate.

8.6.2 In all cases the proposed approach would be reviewed following acquisition of additional ground investigation data.

Table 6 Mitigation option route proposed for pile group at each pier

Viaduct Piers	Essential Mitigation	Comments
1-19	None	Distant from [redacted] and down gradient. [redacted].
19-36	None, but monitoring to be undertaken to check on groundwater quality. If there is a need for mitigation follow mitigation route map (Figure 7).	Distant from [redacted] and down gradient.
37-46	Turbidity treatment at [redacted] Requirements for ground treatment pre-piling to be based on additional GI. If practicable and effective, do not use bentonite or polymer to stabilise the formation. Monitoring to determine need for further mitigation (Figure 8). Build flexibility into programme to allow piling to cease in the event of a risk of outage to [redacted]	Piling in this area represents a very high risk to [redacted] If a planned outage at [redacted] can be implemented whilst still pumping at [redacted] then this option would only apply to piles at Piers 37-42. Bentonite migration trial / piling trial in Colne valley will help to establish the actual level of risk.

Viaduct Piers	Essential Mitigation	Comments
	Consider higher level of treatment at [redacted] / lower volume of water to be treated. Consider if pre-drilled and licensed scavenger wells are required.	
47-58	Planned outage at [redacted] prior to outage at [redacted] [redacted] If practicable programme as many piles as possible outside peak demand period, especially any identified by additional GI as representing a significant risk.	Piling in this area represents a very high risk to [redacted] so planning an outage for [redacted] whilst continuing pumping at [redacted] but with no construction work within the area of risk to [redacted] could significantly reduce this risk. If a planned outage at [redacted] can be implemented whilst still pumping at [redacted] then this option would also apply to piles [redacted]
South Embankment	None	Downgradient and too far from [redacted] to represent a risk of chalk turbidity risk. [redacted]
North Embankment	Turbidity treatment at [redacted]	Embankment is close to [redacted] with limited and shallow VCC. Could increase chalk turbidity due to large number of pilesto be placed. Construct during planned outage at [redacted] (as for [redacted]).
Sheet piles	None	Shallow and installed into clay, long term risk very low.
Tube piles	None	Installed through silt and clay, potential to create a pathway limited, no long term degradation.

9 Conclusions

9.1.1 The risks from piling at the viaduct include those from chalk turbidity, bentonite turbidity, cement / concrete, creation of preferential pathways, aquifer destabilisation and changes to flow paths / reduction in yield. This assessment has concluded that:

- the risks from chalk turbidity are significant and will primarily be managed by installing treatment facilities at the [redacted] Affinity Water supply, in addition to an agreed 2 year outage at [redacted]
- the 2 year outage at [redacted] will be flexible and in the early stages, it will likely be replaced with an outage at [redacted] whilst piling at the northern end of the viaduct is undertaken;
- the risks from bentonite / polymer turbidity are significant and will be managed using a route map approach with a range of mitigation options available to be implemented, including the installation of turbidity treatment at [redacted] and the planned 2 year outage at [redacted]
- the route map approach to managing bentonite / polymer turbidity will also allow chalk turbidity to be managed and the options may be appropriate if chalk turbidity is higher than predicted;
- the risks from cement / concrete are not significant assuming that rapid set materials are used and that cement is not pumped into flowing (turbulent) water;
- the risks of creating preferential vertical pathways are very low and mitigation is not required;
- the risks of aquifer de-stabilisation are low but uncertain, and if there is a collapse at [redacted] it could result in changes in flow routes through the aquifer which could in turn increase the proportion of lake water pumped from [redacted] which would increase manganese;
- installing steel well screen in the [redacted] abstraction boreholes should be considered in order to mitigate the potential for collapse of the boreholes;
- extensive monitoring would be required prior to and during the recommissioning of the [redacted] supply to determine if there have been any effects from construction of the viaduct;
- if there is a long term increase in manganese or other substances it may be necessary to re-drill the [redacted] abstraction boreholes if collapse has caused the increase, or if it is due to other HS2 construction factors then water treatment may be required at [redacted]

- the likelihood of the piles across the valley causing a significant reduction in yield at [redacted] or [redacted] are very low and further mitigation is not required, but there could be localised changes in the source of the abstracted water which could increase manganese concentrations and require mitigation (as above); and
- in the unlikely event of [redacted] being shut down alternative temporary water sources and/or emergency drought order may be required whilst construction work ceases and the supply is re-instigated.

9.1.2 Further investigation and monitoring would be beneficial in helping to refine the risk assessment, including cross-well geophysics to identify solution cavities and installation of data loggers in monitoring wells to determine if changes in abstraction from Affinity Water PWS can be identified. These changes could include specific changes induced by Affinity Water to look at connectivity between observation boreholes and PWS. Monitoring details are provided in a separate monitoring position statement that has been prepared by Align on behalf of HS2 and which details all of the proposed groundwater monitoring along Section C1.

Appendix 1 Schematic drawings illustrating typical pile installation process

Appendix 2 Turbidity risk assessment pre-mitigation