A417 Missing Link
TR010056

6.4 Environmental Statement
Appendix 13.7 Hydrogeological Impact Assessment

Planning Act 2008

APFP Regulation 5(2)(a)
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6.4 Environmental Statement
Appendix 13.7 Hydrogeological Impact Assessment

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1 Introduction

1.1 Purpose of this document

1.1.1 The purpose of this document is to present the hydrogeological impact assessment (HIA) for the scheme supporting the Environmental Statement (ES). This HIA presents the baseline conditions of groundwater features and assesses potential impacts to groundwater flows, levels and quality from the scheme.

2 Methodology

2.1 Overview

2.1.1 The Cotswold region is an area of valued geological and environmental interest and importance. To understand the environmental risks of the scheme in the context of groundwater, a desktop study and review of ground investigation data was completed to understand the groundwater regime and the potential impact of the design elements.

2.1.2 The geological setting and ground conditions along the scheme are presented in ES Chapter 9 Geology and soils (Document Reference 6.2).

2.2 Ground investigations

2.2.1 Details of the completed intrusive ground investigations are presented in ES Chapter 9 Geology and soils (Document Reference 6.2). The following sections focus on the hydrogeological aspects of these investigations.

Phase 1 ground investigation

2.2.2 The Phase 1 ground investigation was completed between January and February 2019[1]. The scope of works included eight boreholes with standpipe installations in each and water level loggers were installed within four of these. The boreholes were positioned in four locations, including National Star College (DS/RC 408 and OH 407), Air Balloon public house (DS/RC 406 and OH 405), Barrow Wake (DS/RC 419 and DS/RC 404) and Ermin Way (Roman Road) (DS/RC 415 and OH 406). A summary of the monitoring installations is presented in Appendix A of this document.

2.2.3 Groundwater monitoring of the eight Phase 1 boreholes commenced in February 2019 and is currently on-going with a scheduled completion in August 2021. The locations are scheduled to provide continuous logging data and dip meter measurements on a monthly basis. It was not possible to take dip meter measurements between June 2019 and August 2019.

Phase 2A ground investigation

2.2.4 The Phase 2A ground investigation included the installation of 52 groundwater monitoring boreholes, where the proposed in-situ testing and monitoring of these boreholes included:

- 38 locations with monthly dip measurements
- 14 locations with water level loggers for continuous groundwater level monitoring and monthly dip measurements
- 7 variable head tests

2.2.5 The field works of the Phase 2A ground investigation was completed in October 2020. Groundwater level monitoring is still on-going with a scheduled completion in August 2021. The monitoring installation coverage to date is concentrated in land parcels where access has been granted.

2.2.6 Monitoring of the Phase 2A boreholes constructed early in the ground investigation programmed commenced at the end of May 2019 and is currently ongoing. Currently the available groundwater monitoring data comprises dip meter and water level loggers.

2.2.7 A total of 60 monitoring locations from Phase 1 and Phase 2A are included in this HIA to support the ES.

2.3 Baseline conditions scope

2.3.1 The locations of groundwater monitoring installations used to inform this baseline conditions review are presented in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3). Monitoring data received up until the 31 October 2020 has been considered in this assessment. The factual data is presented in ES Appendix 9.3 Ground investigation factual report (Document Reference 6.4).

2.3.2 Barometric loggers have been installed in the headworks of select borehole locations during the Phase 1 and Phase 2A. These locations include: DS/RC 408 at Air Balloon, CP 223 on Crickley Hill and DS/RC 220 between Shab Hill junction and Cowley junction.

2.3.3 Daily rainfall data has been acquired for the Ebsworth rainfall gauge (461800) from the Environment Agency (EA). The gauge is located approximately 5.4 km south-west of the scheme.

2.4 Designations and directives

Catchment Abstraction Management Strategy (CAMS)

2.4.1 The scheme is located within three CAMS areas as designated by the EA. These are listed below and presented in ES Figure 13.8 Catchment abstraction management strategy areas (Document Refence 6.3):

- The Severn Corridor[2] – up to approximately Ch 2+100, west of the groundwater divide.
- The Cotswolds[3] – between approximately Ch 2+100 and Ch 3+800, east of the groundwater divide.
- The Severn Vale[4] – from approximately Ch 3+800, west of the groundwater divide.

2.4.2 The availability of water for abstraction within the catchments is presented in Table 2.1. Generally, there is water available in the Severn Corridor catchment but limited to no water available within the Cotswolds and Severn Vale catchments.

Table 2.1 CAMS water resource availability summary

Flow type	Severn corridor	Cotswolds	Severn Vale
Q95 (lowest)	Limited water available	Water not available	Limited water available
Q70	Water available	Water not available	Limited water available
Q50	Water available	Water not available	Limited water available
Q30 (highest)	Water available	Restricted water available	Limited water available

EA designations

2.4.3 Aquifers within the study area that have been designated by the EA are listed in the following paragraphs and are presented in ES Figure 13.6 Aquifer designations (Document Refence 6.3).

2.4.4 The Cheltenham Sand and Gravel and alluvial deposits are designated by the EA as Secondary A aquifers. This designation indicates that the aquifers are 'permeable layers capable of supporting water supplies at a local rather than a strategic scale, and in some cases forming an important source of base flow to rivers'[5].

2.4.5 The Great Oolite Group (excluding the Fuller's Earth Formation) and Inferior Oolite Group are designated as Principal aquifers, described as "*permeable layers capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers*"[6].

2.4.6 The Fuller's Earth Formation is classified by the EA as an Unproductive aquifer associated with "*low permeability [and] negligible significance for water supply or river base flow*"[7].

2.4.7 In the study area, the BGS present the stratigraphy encompassing the upper parts of the Lias Group and the lower parts of the Inferior Oolite Formation as the 'Lias Group and Inferior Oolite (undifferentiated)'. Owing to this stratigraphy being combined, the Lias Group and Inferior Oolite (undifferentiated)' is designated by the EA as a Principal aquifer. Based on descriptions of the Lias Group[8], the Bridport Sand Formation is considered a minor aquifer. However, the site-specific information in this report is based upon ground investigation data from this scheme, thereby this provides a higher resolution to the EA mapping in the site area. As such the properties of the aquifers in this area are based on site specific information.

2.4.8 In the study area, the Charmouth Mudstone Formation is classified by the EA as a Secondary (undifferentiated) aquifer, described as "*both minor and non-aquifer in different locations due to the variable characteristics of the rock types*"[9].

Water Framework Directive (WFD)

2.4.9 The scheme is located over two river basin districts: the Severn to the west and the Thames to the east. The topographical catchment boundary along the Upper Cotswolds Plateau generally correlates to the groundwater divide between the Severn and Thames catchments[10]. These river basin districts are divided into three WFD groundwater bodies, where two are within the Severn Vale catchment and one is within the Thames catchment[11]. A summary of the WFD groundwater bodies is presented in Table 2.2 and ES Figure 13.4 WFD groundwater bodies (Document Refence 6.3).

2.4.10 The superficial deposit aquifers are not specifically designated as WFD groundwater bodies. However, it is anticipated they are hydraulically connected to the relevant underlying designated WFD groundwater bodies presented in Table 2.2.

2.4.11 The Severn Vale catchment is divided into the Severn Vale - Jurassic Limestone Cotswold Edge South (ID GB40901G305700) and the Severn Vale - Secondary Combined (ID GB40902G204900) groundwater bodies. These groundwater bodies locally drain towards the west into the River Frome and Norman's Brook, and their tributaries.

2.4.12 The Severn Vale - Jurassic Limestone Cotswold Edge South groundwater body generally correlates to areas of the Great Oolite Group, Inferior Oolite Group and Upper Lias Group, west of the groundwater divide.

2.4.13 The Severn Vale - Secondary Combined groundwater body includes areas underlain by the Charmouth Mudstone Formation at the base of the Lias Group at the western end of the scheme.

2.4.14 The Thames catchment includes the Burford Jurassic WFD groundwater body (ID GB40601G600400). The Burford Jurassic groundwater body generally correlates to the Great Oolite Group and the Inferior Oolite Group limestones that drain towards the south-east where the Inferior Oolite is confined by the Fuller's Earth Formation. The aquifers locally feed into the River Churn and its tributaries in the south-east.

2.4.15 The overall 2019 status of both the Jurassic Limestone Cotswolds Edge South and Secondary Combined groundwater bodies is 'good', however the Burford Jurassic is poor.

Table 2.2 Summary of WFD groundwater bodies[12]

	Burford Jurassic	Severn Vale – Jurassic limestone Cotswolds edge south	Severn Vale – secondary combined
Groundwater body ID	GB40601G600400	GB40901G305700	GB40902G204900
Operational catchment	Burford Jurassic	Severn Vale – Jurassic Limestone Cotswolds Edge South	Severn Vale – Secondary Combined
Management catchment	Thames GW	Severn England GW	Severn England GW
River basin district	Thames	Severn	Severn
Current overall status	Poor (2019)	Good (2019)	Good (2019)
Current quantitative status	Good (2019)	Good (2019)	Good (2019)
Current chemical status	Poor (2019) – poor nutrient management (diffuse sources) and private sewage treatments (point sources)	Good (2019)	Good (2019)
Quantitative objective	Good by 2027	Good by 2015	Good by 2015
Chemical objective	Good by 2027	Good by 2015	Good by 2015
Protected area	Drinking water protected area and nitrates directive.	Drinking water protected area and nitrates directive.	Drinking water protected area and nitrates directive.

3 Baseline

3.1 Regional geology

Superficial deposits

3.1.1 Superficial deposits are located on Crickley Hill (west of the Cotswold Escarpment crest), in the Churn Valley (near Shab Hill Farm) and in the Frome Valley (near Stockwell-Nettleton) (ES Figure 9.3 Geological map (Document Reference 6.3)).

Detailed descriptions of the superficial deposits are presented in ES Chapter 9 Geology and soils (Document Reference 6.2).

3.1.2 The superficial deposits comprise of[13,14]:

- Mass movement deposits – landslide deposits, cohesive material derived from limestone and mudstone parent materials.
- Alluvial deposits - clay, silt, sand and gravel
- Cheltenham sand and gravel - sand, quartzose, fine to medium grained, generally unbedded, with seams of poorly sorted predominantly limestone gravel, especially in the lower part

3.1.3 For the purposes of this scheme 'mass movement deposits' and 'head' are being used as a general terms for transported slope material derived from the underlying bedrock and transported to its current position as a result of a range of slope processes, including landslides, hillwash, and soil creep.

3.1.4 Mass movement deposits underlie the scheme on Crickley hill where the underlying Lias Group mudstones is the parent material reworked by slope processes.

3.1.5 Head deposits includes superficial deposits overlying the Great Oolite Group and the Inferior Oolite Group. Head deposits underlie the scheme within the valley at Shab Hill junction, which feeds into the River Churn. These deposits are also present in the valleys that feed into the River Frome, west of the scheme's southern end.

3.1.6 Alluvial deposits are present west of the scheme's southern end, in the Frome Valley.

3.1.7 Cheltenham Sand and Gravel underlie the western end of the scheme and extend towards the north west.

Bedrock geology

3.1.8 The scheme is underlain by three bedrock geological groups (Figure 1), where the Fuller's Earth Formation is laterally continuous in the A417 study area[15]. The bedrock geology underlying the scheme is presented in ES Figure 9.3 Geological map (Document Reference 6.2) and detailed descriptions of the bedrock units are presented in ES Appendix 9.2 Preliminary ground investigation report (Document Reference 6.4). Structurally these bedrock units generally dip between 2º and 5º towards the east and south-east. The bedrock groups include, from youngest to oldest:

- Great Oolite Group – Jurassic aged limestones and basal mudstone
- Inferior Oolite Group – Jurassic aged limestones
- Lias Group – Triassic aged mudstones with limestone and sandstone beds

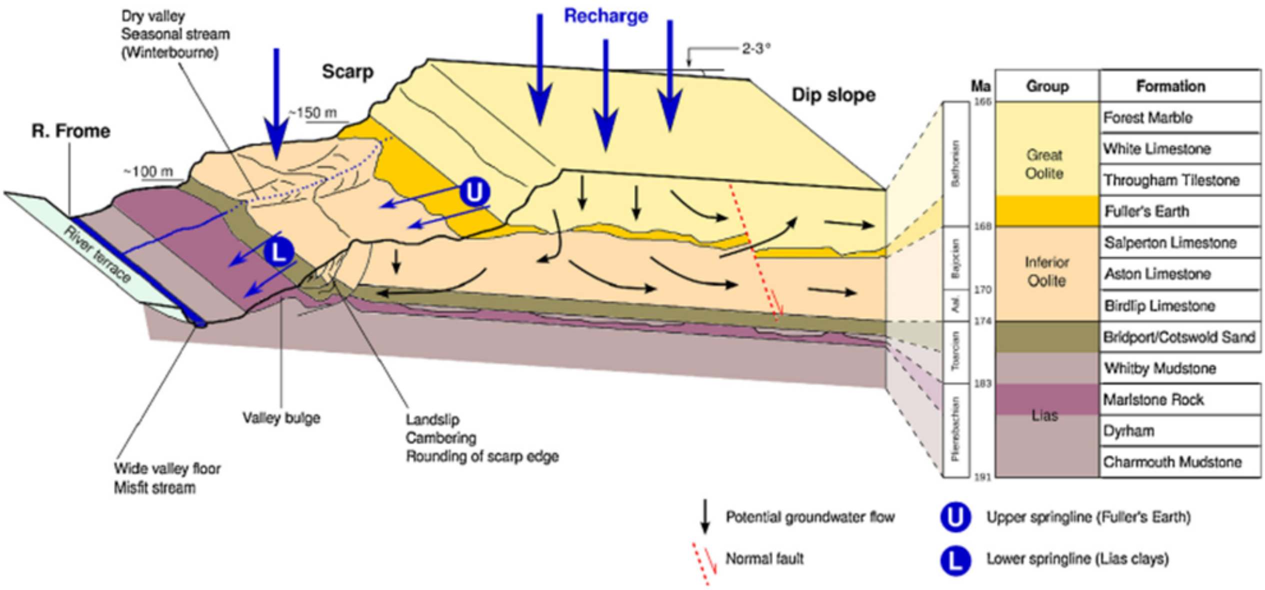

Figure 1 Idealised conceptual model of the hydrogeological processes in the mid-Cotswold area[16]

Great Oolite Group

3.1.9 The Great Oolite Group includes the White Limestone Formation, the Hampen Formation and the Fuller's Earth Formation. It underlies the scheme to the south of Shab Hill fault (ES Figure 9.3 Geological map (Document Reference 6.2)).

3.1.10 The White Limestone Formation, being the highest geological unit in the area, is only present on some hill tops. Where present, it has been eroded down to a thickness of less than 6 m. It is generally described as a weak to medium strong highly fractured bioclastic and ooidal limestone. The fractures are often stained and have a calcite precipitate.

3.1.11 The Hampen Formation generally comprises a weak bioclastic and ooidal limestone with frequent calcite veining (up to 3 mm) and closely spaced fractures. The fractures are generally undulating, rough, clean from infill and often stained orangish brown. The Hampen Formation is thickest in the downthrown fault block to the west of Shab Hill junction, where it has been encountered at depths up to 15 mbgl.

3.1.12 The Fuller's Earth Formation is a grey/brown mudstone with limestone beds (up to about 2m thick) at the base of the Great Oolite Group that is up to approximately 20 m thick in the site area. It generally has closely spaced undulating sub-horizontal fractures that are rarely infilled. The Fuller's Earth Formation is laterally persistent in the study area and is at ground surface south of Stockwell fault.

Inferior Oolite Group

3.1.13 The Inferior Oolite Group includes the Salperton Limestone Formation, the Aston Limestone Formation and the Birdlip Limestone Formation. The Inferior Oolite Group underlies the scheme from the crest of the Cotswold Escarpment to the northern side of the Shab Hill fault (ES Figure 9.3 Geological map (Document Reference 6.2)).

3.1.14 It is anticipated that the entire sequence of the Inferior Oolite Group would be encountered moving from the Cotswold Escarpment to the Shab Hill junction. The Salperton Formation (the uppermost formation) comprises a weak to moderately strong bioclastic to ooidal limestone with closely to medium spaced fractures. Fractures have been described as sub horizontal to around 20°, undulating, rough and stained.

3.1.15 The Aston Formation (underlying the Salperton Formation) comprises a moderately strong bioclastic to ooidal limestone with closely to medium spaced fractures. Fractures have been described as sub horizontal to around 40°, undulating, rough, stained and some are infilled with clay.

3.1.16 The Birdlip Limestone Formation (the lowermost formation), comprises a weak to moderately strong, predominantly bioclastic limestone. A range of fracture spacing has been recorded within the Birdlip Limestone but predominantly range from 50 mm to 200 mm. Fractures have been described as sub horizontal to 30° and sub vertical, undulating, rough and stained and some are clay infilled. The Inferior Oolite Group is underlain by the Lias Group mudstones and the surface boundary between these units is near the crest of the Cotswolds escarpment.

Lias Group

3.1.17 The Lias Group in the Cotswolds area comprises the Worcester Basin Formations. The Worcester Basin includes the Bridport Sand Formation, the Whitby Mudstone Formation, the Marlstone Rock Formation, the Dyrham Formation and the Charmouth Mudstone Formation. The Whitby Mudstone Formation, Dyrham Formation and Charmouth Mudstone Formation are the thicker formations within the Lias Group. Largely comprising mudstone and silty mudstone the formations are relatively impermeable.

3.1.18 The Bridport Sand Formation is typically described as an extremely weak siltstone and is often weathered to a very stiff sandy silt. In some locations the Bridport Sand Formation comprises beds of extremely weak fine sandstone, which during drilling was recovered as a slightly sandy clayey sandstone gravel. The fractures in the Bridport Sand Formation are very closely to medium spaced (20 – 600mm) and are rarely infilled.

3.1.19 The Whitby Mudstone Formation has been identified predominantly in the lower Crickley Hill valley, but it was also encountered in some holes as far northeast as the Air Balloon Roundabout. It is typically described as a firm to very stiff fissured dark brownish grey clay. It locally contains gravel and cobbles and is occasionally slightly sandy. The gravel is subangular to sub-rounded limestone, mudstone, siltstone and sandstone. The cobble is typically limestone. There are occasional bands of extremely weak to weak laminated grey mudstone or medium strong limestone. Fractures within the mudstone are closely to widely spaced planar smooth.

3.1.20 The Marlstone Rock Formation was encountered across the study area and was typically encountered as medium strong to strong limestone with rare to frequent shell fragments. Fractures are generally closely spaced, sub horizontal, undulating and smooth to rough with occasional orange staining.

3.1.21 The composition of the Dyrham Formation is varied. It is typically encountered as bands of either a weak light grey limestone, a very stiff thinly laminated sandy silty clay, a very stiff silt or an extremely weak mudstone.

3.1.22 The Charmouth Mudstone Formation presents as a stiff to very stiff mottled grey silty clay or an extremely weak to very weak laminated dark grey mudstone with very close to closely spaced undulating smooth fractures, locally stained orange.

3.1.23 The Lias Group is mostly overlain by other geological units in the area, however it does influence the geological and hydrogeological processes within the region. On the western side of the Cotswold escarpment the Lias Group is covered by a mantle of mass movement deposits and at the western end of the scheme by localised Cheltenham Sand and Gravel (ES Figure 9.3 Geological map (Document Reference 6.2)). To the east of the escarpment, the Lias Group is overlain by Inferior Oolite limestone.

Structural geology

3.1.24 The published geological faults in the region that the scheme is likely to intersect are the Shab Hill fault, the Shab Hill Barn fault and Stockwell fault. The faults typically strike north-west to south-east and are presented on ES Figure 9.3 Geological map (Document Reference 6.2).

3.1.25 The position of published faults has been revised following review of the geomorphological, ground investigation and surface geophysics information (ES Appendix 9.2 Preliminary ground investigation report (Document Reference 6.4). This review also identified two additional faults underlying the scheme:

- The Churn Valley fault at Shab Hill Junction, striking north-west to south-east between the Shab Hill fault and the Shab Hill Barn fault.
- The Cally Hill fault, located at Ch 4+000 and striking north-east to south-west.

3.1.26 The revised positions of the faults have been adopted for the ES and are presented on ES Figure 9.3 Geological map (Document Reference 6.2).

3.1.27 The geological setting in conjunction with Quaternary glacial and interglacial processes has facilitated a number of processes, which create the geomorphological setting of the Cotswold region. The Cotswold escarpment is a pronounced feature in the region, which formed from mechanical stress relief in the rock mass during the Quaternary.

3.1.28 It is likely that cambering, valley-bulging, and both rotational and translational landslides occurred during the transitional periods in the Quaternary, facilitated by lateral stress relief during valley erosion and reduced effective stresses caused by increased pore water pressure initiated by the melting of ground-ice, as illustrated in Figure 2. Evidence of mass movement, such as landslides, cambering, gulls, and solifluction (soil creep due to freeze-thaw activity) are present along the Cotswold Escarpment at Crickley Hill. These deposits are collectively referred to as mass movement deposits.

3.1.29 Gulls and cambering within limestone formations have the potential to be further solutionally enlarged and where this has occurred they are included as karst features. Karst features, where present, are discussed in Section 3.2 Regional Hydrogeology.

3.1.30 Gulls mostly occur at the Cotswold escarpment edge. Further away from the Cotswold escarpment the only karst features recorded include the dry valley at Shab Hill and voids within the Inferior Oolite Group. Self & Boycott (2004) identified in the Stroud area that the tributaries of the River Frome have incised deeply through the Great Oolite Group limestones and into the Fuller's Earth Formation but no gull caves are known[17]. Similar conditions were found in the Great Oolite Group at the southern end of the scheme.

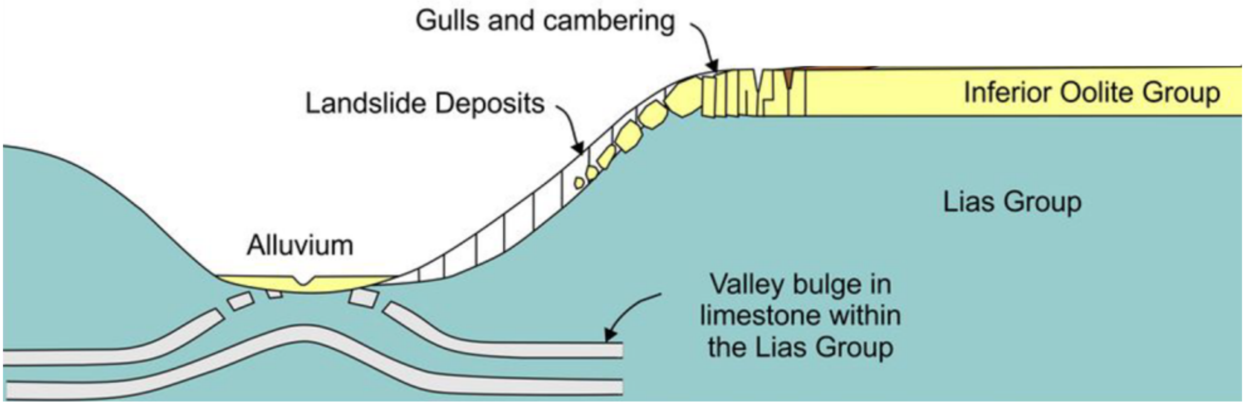

Figure 2 Schematic illustration of cambering, valley bulging and landslides (modified from Farrant et al., 2014) [18]

3.2 Regional hydrogeology

3.2.1 The hydrogeology of the Cotswold region is influenced by the complex relationship between aquifers, aquitards, periglacial geomorphology and surface water – groundwater interactions. An idealised model of the regional hydrogeological processes is presented in Figure 1. In the scheme area, 'head' deposits cover the Lias Group formations and the Fuller's Earth Formation is laterally continuous.

Superficial deposits

3.2.2 The superficial deposits comprise alluvial deposits, mass movement deposits, head deposits and the Cheltenham Sand and Gravel in discrete areas beneath and around the scheme. The alluvial, mass movement and head deposits are largely clay dominated with isolated lenses of sand and gravel. The mass movement deposits also include toppled limestone blocks and material from the underlying Lias Group. Groundwater flow through the superficial deposits will be locally variable and limited to more permeable zones. The mass movement and head deposits are not an EA designated aquifers, however groundwater within these deposits support groundwater-surface water interactions, including springs and seepages. Where springs are point flow groundwater emergences and seepages as diffuse groundwater emergences.

3.2.3 Groundwater flow through the superficial deposit aquifer is dominated by intergranular flow where the permeability will support it. Coarse grained units within the clay dominated deposits are likely to facilitate local zones of groundwater flow and will create zones of perched groundwater. These more permeable zones promote localised shallow groundwater flow which emerge as springs and seepages within the superficial deposits in the Crickley Hill area, which support flow in the tributary of Norman's Brook.

3.2.4 The superficial deposits are unconfined however within the clay dominated material localised confinement of water bearing, coarse grained units are likely. Groundwater levels are likely to be locally variable and shallow in the superficial deposit aquifer.

3.2.5 On the northern side of the A417 between approximately CH1+600 to CH1+700, historic counterfort drains are present within the mass movement deposits (Appendix A, Preliminary ground investigation report (ES Appendix 9.2 (Document Reference 6.4)). Based on the location of these drainage measures they are anticipated to locally control groundwater levels within the mass movement deposits by capturing flow that they intersect. On this basis groundwater levels in the mass movement deposits are artificially lowered at this location.

Great Oolite Group - limestone formations

3.2.6 The Great Oolite Group comprises of a sequence of limestone that locally is interbedded with mudstone. The Great Oolite Group forms the upper stratigraphy of the Cotswold plateau and often forms isolated outliers on hill tops. Owing to the Great Oolite Group forming the top of high ground it is unconfined but mudstone interbeds within the group locally confine limestone units. The limestone formations are underlain by the Fuller's Earth Formation, which is the lowest formation of the Great Oolite Group.

3.2.7 As detailed in section 3.1.10, the limestone units of the Great Oolite Group are thickest between the Shab Hill and Shab Hill Barn faults. At this location the limestones are dominant and generally not interbedded with mudstones. The base of the Great Oolite Group limestone formations at Shab Hill junction extends to 15 m below ground level. To the south of the Shab Hill Barn fault, limestone of the Great Oolite Group is present but has significantly increased interbedding with mudstone.

3.2.8 The underlying Fuller's Earth Formation forms a basal barrier to downward flow. Where mudstone is present in the limestone formations this will locally perch groundwater levels in the limestone units.

3.2.9 Groundwater flow in the Great Oolite Group limestone is largely dominated by secondary porosity with localised tertiary enhancement by karst processes. As such, the Great Oolite Group limestone formations can have a local high rate of transmissivity but otherwise has low primary matrix porosity storage capacity. Secondary porosity features include joints and bedding planes within the rock mass. Karst features identified in the Great Oolite Group include a dry valley at Shab Hill, a small number of shallow voids (<0.6m) are identified in the scheme GI program and several springs and seepages, which occur at the escarpment margins near the base of the Great Oolite Group and feed an unnamed tributary to the Churn and an unnamed tributary to the Frome.

3.2.10 The ground investigation drilling logs and downhole calliper identified shallow near surface voids (c.40cm in dimension) in borehole OH 413 at Shab Hill junction. Fractures with open fractures (with staining from groundwater flow) are identified in boreholes OH 411 and DS/RC/OH 400.

3.2.11 Between the Shab Hill Barn fault and Stockwell fault the Great Oolite Group dominantly comprises of mudstone units with minor limestone units. As a result, the effective horizontal hydraulic conductivity of the transition zone will only occur in limestone units where present and the vertical conductivity of the transition zone will be limited by the hydraulic conductivity of mudstone units.

3.2.12 Limestones that are locally confined by mudstone will have limited recharge, which will largely only occur where leakage via fracturing provides a pathway through overlying interbedded mudstone. Limestone units that are near surface and not confined will be directly recharged by rainfall.

Great Oolite Group – Fuller's Earth Formation

3.2.13 The Fuller's Earth Formation is a grey mudstone with thin limestone beds, which is the basal formation of the Great Oolite Group. In the study area the Fuller's

Earth Formation aquitard is laterally continuous below the Great Oolite Group limestones and above the Inferior Oolite Group.

3.2.14 South of the Stockwell fault and underlying Cowley junction, mudstone units become more dominant with fewer limestone units. The mudstone units will likely form a barrier to groundwater flow there may be localised confined groundwater flow associated with the minor limestone units.

Inferior Oolite Group

3.2.15 The Inferior Oolite Group forms the crest of the Cotswold escarpment and extends south-east from the escarpment (ES Figure 9.3 Geological map (Document Reference 6.2)). This limestone aquifer is largely unconfined, however in the southern portion of the scheme it is partially confined by the Fuller's Earth Formation mudstone aquitard.

3.2.16 Groundwater flow through the limestones is dominated by secondary (fracture) porosity pathways and tertiary (karstic) porosity features, so the aquifer may locally have a high fracture or karstic permeability even though the primary matrix porosity characteristically provides low storage capacity. Karst features identified in the Inferior Oolite Group include four limestone springs (springs 16, 17, 18 and 19) at Crickley Hill and a dry valley at Barrow Wake (G3).

3.2.17 Evidence from the ground investigation, including downhole geophysics and geological logging, indicates that voids are common within the Inferior Oolite Group. Voids identified by down the hole calliper and camera range from 10mm to 140mm in dimension, varying in shape from rounded to irregular and predominantly iron stained with occasional sandy clay infill. Voids were logged at varying depths but were predominantly present logged towards the base.

3.2.18 Stress relief along fractures, joints and bedding planes that occur in conjunction with cambering processes will be higher closer to the margins of the Cotswold escarpment. It is possible that these features may be locally enhanced by karst processes.

3.2.19 Is it likely that fissures and gulls along the escarpment form part of the flow paths for groundwater to feed springs and seepages identified in the Inferior Oolite Group. In cases where the base of the Inferior Oolite Group is covered by mass movement deposits then groundwater from the Inferior Oolite Group may drain into the superficial deposits where they are sufficiently permeable. Based on the interface between bedrock geology and superficial geology then this will only occur in the upper most superficial deposits in those locations where the mass movement deposits cover the Inferior Oolite Group.

3.2.20 A potential gull feature is observed in the downhole calliper and camera record within the Bridport Sand/Lias for borehole (DS/RC 301), which lies close to the escarpment edge.

Lias Group

3.2.21 The Whitby Mudstone Formation, Dyrham Formation and Charmouth Mudstone Formation are the thicker formations within the Lias Group and are the prime influence for the group's hydraulic properties. Largely comprising mudstone and silty mudstone the formations have relatively low permeabilities and function as aquitards.

3.2.22 The Bridport Sand Formation and Marlstone Rock Formation are relatively thinner geological units that have greater permeability and can influence more localised groundwater flow.

3.2.23 The Bridport Sand Formation, at the top of the Lias Group, can locally be hydraulically connected with the base of the Inferior Oolite Group where fracturing or more permeable lithological units are present. Groundwater flow through the Bridport Sand Formation is occurs due to secondary porosity features including bedding planes and joints to the local connectivity between Inferior Oolite Group and Lias Group Bridport Sand Formation these are considered as the same aquifer across the study area. As such, springs and seepages in the Bridport Sand Formation may be fed in part from the Inferior Oolite Group.

3.2.24 The Marlstone Rock Formation can be greatly affected by cambering[19]. The cambering processes will be more pronounced closer to the edge of the escarpment. Relatively higher hydraulic conductivity within the Marlstone Rock Formation, relative to the overlying Whitby Mudstone Formation, may promote a local flow zone.

Groundwater quality

3.2.25 Limestone aquifers are particularly vulnerable to contamination, which may originate from point or diffuse sources. In accordance with the Nitrate Pollution Prevention Regulations 2015, the EA have identified areas at risk of agricultural nitrate pollution and have designated these as nitrate vulnerable zones (NVZ)[20]. Waters are defined within the Nitrate Pollution Prevention Regulations 2015 as polluted if they contain or could contain, if preventative action is not taken, nitrate concentrations greater than 50mg/l[21].

3.2.26 The EA has designated the Upper Cotswold Plateau, limestone at the crest of the Cotswold escarpment and the northern side of Crickley Hill (approximately 220m north of the scheme at Crickley Hill) as an NVZ[22].

3.2.27 Bicarbonate rich groundwater is expected to be the dominant water type in the region given the presence of limestone[23]. The quality testing completed for the scheme is discussed in section 6. The geochemistry of waters in carbonate aquifers is particularly affected by residence times and mixing with recharge, older formation water and/or anthropogenic influences. Water types can typically be categorised by source, age and geological conditions including aquifer confinement. A schematic showing the conceptualisation of the Cotswold Plateau is shown in Figure 3, and described in the following paragraphs. Note, unlike the conceptual model presented in Figure 3 the Fuller’s Earth Formation is laterally continuous in the study area.

3.2.28 Groundwater close to recharge areas are typically oxidising and strongly pH buffered with calcium and bicarbonate (HCO_3^-) as dominant dissolved ions[24]. Recharge areas are particularly susceptible to high nitrate concentrations from agricultural pollution. This is anticipated to be most reflective of unconfined waters the scheme may encounter.

3.2.29 Regionally, as groundwater becomes more confined, down gradient of recharge areas, ion-exchange processes occur, with sodium and bicarbonate being the dominant ions in the groundwater[25]. The process of ion exchange causes dissolved calcium ions in the groundwater to attach or ‘adsorp’ onto the rock surface and, in exchange, sodium ions come off the rock surface and into the groundwater.

3.2.30 In more confined groundwaters, dissolved oxygen is reduced or absent, with conditions becoming more reducing, which is evidenced by redox-sensitive elements[26]. Lower nitrate levels can suggest that denitrification may be occurring[27], however this could also be affected by mixing with old formation waters deep within the aquifer that have low nitrate levels when entering the aquifer.

3.2.31 Mixing with older formation water deeper within the confined aquifer results in a sodium-chloride type groundwater. Isotope analysis suggests a residence time in the order of thousands of years for these waters[28].

3.2.32 Neumman et. al. (2003) concluded no significant differences in the chemistry of the Great and Inferior Oolite groundwaters can be observed[29].

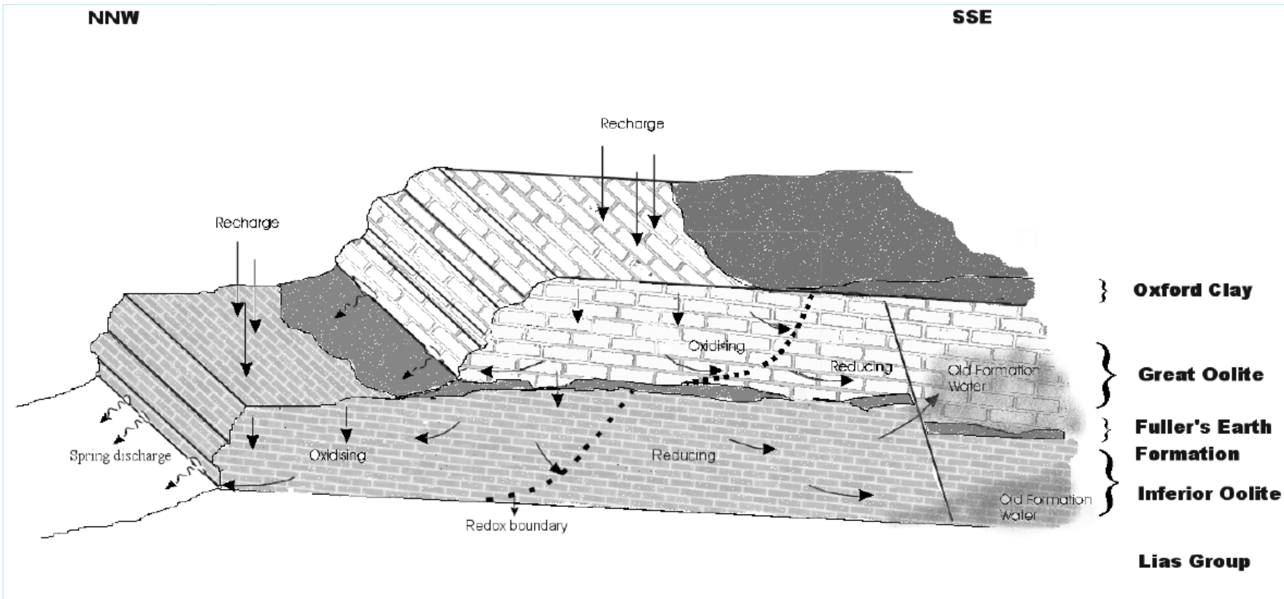

Figure 3 Conceptual model of redox conditions within the Cotswolds[30]

Recharge

3.2.33 The mean annual estimated recharge for the Cotswold area is 370mm per annum[31]. The amount of recharge can be wide ranging, as Morgan-Jones and Eggboro (1981) noted in the hydraulic years of 1975 and 1976 where recharge was 100mm and 630mm respectively.

3.2.34 The superficial deposit aquifers are recharged by a variety of mechanisms including rainfall infiltration, run off from low permeability mudstones and groundwater draining from limestone aquifers higher in the landscape. It is possible that limestone inclusions within mudstone formations and the Marlstone Rock Formation could also be locally, hydraulically linked to the superficial deposit aquifer. In the Churn and Frome valleys, the superficial deposits may be leaking into the underlying Inferior Oolite Group.

3.2.35 The Great Oolite Group limestone is recharged directly by rainfall. The underlying Fuller's Earth Formation perches the groundwater within the Great Oolite Group limestones and limits the connection with the underlying Inferior Oolite Group except where a fault is present. Springs and seepages emerging from the base of the Great Oolite limestones at the boundary with the Fuller's Earth Formation boundary have the potential to recharge the Inferior Oolite limestones downgradient.

3.2.36 Recharge of the Inferior Oolite limestone in the scheme area is from rainfall where exposed. Maurice et. al. (2008) suggest leakage via the Fuller's Earth Formation due to faulting, which locally connects the Great Oolite Group and the Inferior Oolite Group[32]. However, this may only occur during the wetter months of the year when drainage from the unconfined Great Oolite aquifer reduces the elevation of the water table such that the saturated zone of the aquifer thins to an extent that transmissivity is greatly reduced[33].

3.2.37 The future baseline conditions from the UK Climate Projections 2018 (UKCP18) indicates that the study area may undergo climatic changes including higher temperatures, increase in heat waves, reduced precipitation in summer and increased precipitation in winter.

3.2.38 The future baseline conditions are likely to reduce the amount of recharge to the groundwater aquifers which may have impacts upon groundwater dependent features near the scheme and cause some perennial features to become seasonal. Abstractions, springs, seepages, groundwater fed watercourses, areas of flooded ground and Bushley Muzzard SSSI are likely to be particularly sensitive to these impacts. Groundwater quality is also likely to be affected by a reduction in the flushing of aquifers, which may increase the residence time of groundwater within them.

Abstractions

3.2.39 The Baunton public water supply abstraction (approximately 12km south-east of the scheme) and associated source protection zone (SPZ) is located within the Thames groundwater catchment. The Baunton abstraction takes groundwater from the Inferior Oolite aquifer and its associated SPZ3 (corresponding to the total catchment area) is intersected by part of the scheme between Shab Hill junction and Cowley junction.

3.2.40 Land east of Cowley junction, and extending south along the scheme, is located within SPZ3. The southern end of the scheme is approximately 2.8km from SPZ2 and 3.4km from SPZ1 in the south-east (ES Figure 13.5 Hydrogeological study area and features (Document reference 6.3)).

3.2.41 There are no further recorded licensed abstractions known within 1km of the scheme.

3.2.42 The water feature survey identified 16 potentially unlicensed abstractions, boreholes and wells near the scheme (refer to Appendix 13.11 Water features survey (Document Reference 6.4)). Many of these features were either not in use or details on their usage and groundwater source were not able to be obtained. The locations of these are presented on ES Figure 13.5 Hydrogeological study area and features (Document reference 6.3).

Consented discharge

3.2.43 To date there have been nine consented discharges of treated sewage or unspecified combined sewage and trade effluent to land and underground strata recorded within 1km of the scheme[34]. Of these, three discharge licenses are still active and are located at Air Balloon public house, Crickley Hill and the Birdlip wastewater treatment works approximately 1km west of the scheme. The consented discharge locations are presented on ES Figure 13.5 Hydrogeological study area and features (Document reference 6.3).

3.2.44 These consented groundwater discharges are existing potential point sources of pollution to the underlying aquifers.

Table 3.1 Consented groundwater discharge licences within 1km of the scheme

Site Name	Site type	Receiving water	License status	Effluent description
Air balloon public house	Food and beverage services	To ground	Revoked	Sewage discharges – final / treated effluent - not water company
Air balloon public house	Wastewater treatment works (not water company)	Underground strata (soakaway)	Active	Sewage & trade combined - unspecified
Air balloon public house	Food and beverage services	Underground strata	Revoked	Sewage & trade combined - unspecified
Air balloon public house	Wastewater treatment works (not water company)	Underground strata (soakaway)	Revoked	Sewage & trade combined - unspecified
Birdlip wastewater treatment works	Wastewater / sewage treatment works (water company)	Groundwater into infiltration system	Active	Sewage discharges – final / treated effluent - water company
Crickley cottages	Domestic property (single) (incl. farmhouse)	Underground strata	Active	Sewage discharges – final / treated effluent - not water company
Hardings barn	Domestic property (single) (incl. farmhouse)	Inferior oolite	Revoked	Sewage discharges – final / treated effluent - not water company
Hardings barn	Domestic property (single)	Inferior oolite	Revoked	Sewage discharges – final / treated effluent - not water company
Ullenwood manor	Dentist / hospital / nursing home (medical) / human health	Land	Revoked	Sewage discharges – final / treated effluent - not water company

Surface water

3.2.45 Details on surface water features and hydromorphological characteristics of the scheme are presented in ES Chapter 13 Road drainage and water environment (Document Reference 6.2). The scheme is located within two surface water catchments: the Severn River catchment (21,000km^2) and the Thames River catchment (16,200km^2). The Severn River discharges in the Bristol Channel and the Thames discharges into the North Sea. Surface water resources near scheme are managed by the Severn River Basin District River Basin Management Plan[35] and the Thames River Basin District River Basin Management Plans[36].

3.2.46 In the scheme area, the Severn and Thames catchment divide is set back from the Cotswold escarpment where the Severn catchment is located to the west and the Thames catchment is to the east. As a result, the scheme interacts with the headwaters of these respective surface water subcatchments, in the form of localised tributaries. The Severn River Catchment includes the Norman's Brook and Horsebere Brook subcatchments, whilst the Thames River catchment includes the River Churn and River Frome subcatchments.

3.2.47 The tributary of Norman's Brook is located on the southern side of the A417 along the Cotswold escarpment. The brook is groundwater dependent (gaining) along much of its reach. The tributary headwater, near the crest of the escarpment, is reliant on discharge from the upper Inferior Oolite Group aquifer. Further downstream the tributary becomes more reliant on groundwater discharge from the mass movement deposits springs and seepages.

3.2.48 The surface water catchments and watercourses are presented on ES Figure 13.5 Hydrogeological study area and features (Document reference 6.3).

3.3 Local geology

3.3.1 The review of the local geology is based on published geology and past ground investigation information and preliminary interpretation of available Phase 2A borehole records. Visual representation of the conceptual models as described in the following sections is shown on ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3). The locations of the cross sections are shown on ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3). Further details of the geological conditions are presented in the Preliminary ground investigation report (ES Appendix 9.2 (Document Reference 6.4)). The geological information provided in this section is used as a basis for the local hydrogeology, which is presented in Sections 4 to 9.

Ch 0+000 to 0+500, Crickley Hill approach

3.3.2 Along the scheme alignment, the existing ground profile at the Crickley Hill approach gently rises from approximately 96mAOD to 114mAOD. The ground conditions comprise Cheltenham Sand and Gravel, thickening towards the west, underlain by Charmouth Mudstone Formation bedrock.

Ch 0+500 to 1+700, Crickley Hill escarpment

3.3.3 The existing ground profile along the scheme alignment at Crickley Hill rises from approximately 114mAOD to 212mAOD, generally following the low point in the embayment adjacent to the tributary of Norman’s Brook.

3.3.4 The ground conditions on the escarpment are dominated by cohesive mass movement deposits. The mass movement deposits are thinner at the crest of the escarpment and thicken towards the scheme. However due to the variety of landslipping processes occurring across the escarpment, the thickness of mass movement deposits is variable.

3.3.5 Overlying the mass movement deposits are areas of localised made ground at Crickley Hill tractors and some localised alluvium is expected along the tributary of Norman’s Brook.

3.3.6 The mantle of mass movement deposits over the escarpment is underlain by the Lias Group. The top of the Lias Group in this area dips towards the tributary of Norman’s Brook. Norman’s Brook is fed by multiple springs and seepages from permeable units within the dominantly cohesive mass movement deposits. At the headwater of the tributary of Norman’s Brook are seasonal limestone springs, which are located at the contact between the Bridport Sand Formation and the Inferior Oolite Group.

Ch 1+700 to Ch 3+000, cutting

3.3.7 Within the cutting from Ch 1+700 to Ch 3+000 cutting section, the existing ground cuts into the crest of the Inferior Oolite Group limestone, rising from approximately 212mAOD to 228mAOD between Ch 1+700 and Ch 1+900. From Ch 1+900 the existing ground level becomes less steep on the Upper Cotswold Plateau, which includes rolling hills up to 274mAOD.

3.3.8 The ground conditions include small localised areas of made ground, underlain by Inferior Oolite Group limestone up to approximately 35m depth. The Inferior Oolite Group limestone is underlain by the Bridport Sand Formation.

3.3.9 The Shab Hill Barn fault intersects the scheme at Ch 1+925, striking in a north-west to south-east direction. Four limestone springs (springs 16,17, 18 and 19 in the water features survey) are located along the Shab Hill Barn fault near the contact between Inferior Oolite Group limestone and the underlying Lias Group Bridport Sand.

Ch 3+000 to Ch 3+500, Shab Hill junction

3.3.10 The Shab Hill junction area is within the Upper Cotswold Plateau area, with low gradient rolling hills between approximately 274mAOD to 280mAOD. The plateau is intersected by a steep sided dry valley at Ch 3+140, which travels in a generally easterly direction. The steep valley sides (up to 12 degrees) are up to approximately 30m high at the eastern side of the proposed Shab Hill junction and the valley continues to deepen towards the headwaters of the River Churn.

3.3.11 The scheme is intersected by the Shab Hill fault at Ch 2+950 and the Shab Hill Barn fault at Ch 3+500, both striking in a north-west to south-east direction. A third fault, the Churn Valley fault, has been interpreted to lie between these faults, striking in a similar direction at Ch 3+200.

3.3.12 North of the Shab Hill fault the scheme is underlain by Inferior Oolite Group. Between the Shab Hill fault and Shab Hill Barn fault the scheme is underlain by the Great Oolite Group comprising the Great Oolite Group limestone formations and the Fuller’s Earth Formation, which is underlain by the Inferior Oolite Group.

Ch 3+500 to Ch 5+760, Shab Hill junction to Cowley junction

3.3.13 In the Stockwell-Nettleton area, the scheme roughly follows the ridgeline of the Upper Cotswold Plateau. The existing topography features rolling hills running in a relatively north-south direction and ranging in elevation from 260mAOD to 286mAOD.

3.3.14 The scheme is underlain by the Great Oolite Group comprising the Great Oolite limestone and the Fuller’s Earth Formation. The Great Oolite Group is underlain by Inferior Oolite Limestone over Lias Group.

3.3.15 The Stockwell fault intersects the scheme at Ch 4+800 and strikes in a north-west to south-east direction. A second fault, the Calley Hill fault, has been interpreted between the Shab Hill Barn fault and Stockwell fault, intersecting the scheme at Ch 4+000 and striking north-east to south-west.

4 Groundwater monitoring programme

4.1 Monitoring

4.1.1 Groundwater monitoring is being undertaken as part of the Phase 2A investigations. Refer to ES Chapter 9 Geology and soils (Document Reference 6.2) for details of the completed intrusive investigations. In summary this provides for:

- Weekly monitoring required for duration of Phase 2A fieldwork period.
- Monthly monitoring required for 12 months post Phase 2A field work period.
- Installation of data loggers in selected installations (set to take readings at 15mins intervals) with monthly downloads and dip meter verification at Diver data logger locations required for 12 months post Phase 2A field work period.
- The Contractor may be asked to extend both the monthly monitoring of standpipes and the monthly data logger reading interval beyond the 12 month post fieldwork period, or to amend the frequencies.

4.1.2 The groundwater monitoring boreholes have been selected at locations where specific design elements are proposed or where water receptors have been identified. Together, these locations provide a spatial network of groundwater monitoring across the study area so that hydraulic gradients and directions of flow can be identified. Water quality testing was also completed at selected locations and is discussed further in Section 6. The location of all groundwater monitoring locations is presented in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3).

4.1.3 The design of each monitoring installation is presented in Appendix A of this document.

4.1.4 Monitoring data comprises manual dips and logger data, presented in ES Appendix 9.3 Ground investigation factual report (Document Reference 6.4). The hydrographs for each monitoring well are presented in Appendix B of this document and discussed in section 5. Logger data provides a high frequency of data recording that allows correlation with rainfall/recharge events and provides a reflection of groundwater responses.

4.1.5 Spring and surface water monitoring commenced in August 2020 at the tributary of Norman's Brook, the unnamed tributary to River Churn and the unnamed tributary to River Frome, which are the three groundwater fed subcatchments that drain from the study area. The monitoring in each subcatchment comprises of a fixed logging station, which also has manual measurements for QA and calibration purposes. Each tributary has a second surface water monitoring location which is a manual monitoring location. Each tributary also has manual measurements at selected springs (ES Figure 13.15 Water environment monitoring locations (Document Reference 6.3)).

4.1.6 At the tributary of Norman's Brook the dataset for the recording station SW2 is supplemented by a downstream manual monitoring station SW1 and at upstream springs GW1 (81), GW2 (81), GW3 (G231) and GW4 (confluence of 66 and 67) where manual measurement is taken (water feature survey ID given in brackets).

4.1.7 At the unnamed tributary of the River Frome the dataset is supplemented by an upstream manual monitoring station (SW3) and upstream springs GW5 (G25) and GW6 (111) where manual measurements are taken.

4.1.8 At the unnamed tributary of the River Churn the dataset is supplemented by an upstream manual monitoring station (SW5) and springs GW7 (downstream of G99) and GW8 (G4) where manual measurements are taken.

4.1.9 The logging surface water monitoring stations provide a record of the stream flows which provide the cumulative groundwater discharges and baseflow contribution for each subcatchment. Further details about the surface water monitoring programme are presented in ES Chapter 13 Road Drainage and Water Environment (Document Reference 6.3).

4.2 Aquifer testing

4.2.1 Water quality samples have been collected as part of this programme and the results of these are presented in Appendix C of this document and discussed in section 6.

4.2.2 Hydraulic testing results from the monitoring wells are included in ES Appendix 9.3 Ground investigation factual report (Document Reference 6.4) and are discussed in section 7.

4.3 Quality assurance

4.3.1 Review and validation of the monitoring data has been completed in consultation with the monitoring contractor. Auto-sampling events are presented on the hydrographs included in Appendix B of this document and are labelled on the contractor's hydrographs provided in ES Appendix 9.3 Ground investigation factual report (Document Reference 6.4).

4.3.2 One hydrograph shows an uncharacteristic response to recharge, CP 223. An unexplained recharge response was recorded between February 2020 to April 2020, where the recorded groundwater level is increasing over this time as rainfall rates are decreasing. The logger and manual dips recorded over this time and until October 2020 are consistent, indicating the measurements are accurate. However, the response is considered unusual and may be due to unique conditions at this location.

4.3.3 Manual dips recorded at or below the response zone base have been excluded from the summaries provided in Section 5 and hydrographs in Appendix B.

5 Groundwater level monitoring results

5.1 Superficial Aquifer - Mass movement deposits, Crickley Hill

Overview

5.1.1 The locations of groundwater monitoring wells are shown in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3). A summary of the response zone strata is presented in Appendix A and the range of observed groundwater levels is presented in Table 5.1.

5.1.2 The hydrographs for groundwater monitoring within the mass movement deposits of Crickley Hill are presented in Appendix B, Figure B-1 to Figure B-7. Within the Crickley Hill area there are a total of 16 groundwater monitoring locations within the mass movement deposits. Monitoring at these locations has progressively started since the 17 May 2019. The distribution of monitoring locations includes:

- Four between Ch 0+500 and Ch 1+000 in the lower slopes of Crickley Hill
- Nine between Ch 1+000 and Ch 1+400 in the mid slopes of Crickley Hill
- Two between Ch 1+400 and Ch 1+700 in the upper slopes of Crickley Hill

Table 5.1 Summary of groundwater monitoring in superficial mass movement deposits at Crickley Hill

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Ch 0+500 to Ch 1+000 (southern side of A417) – Lower Crickley Hill					
CP 102	Mass movement deposits - silty clay	Data logger	0.15 - 2.19 (1.20)	125.36 - 127.40 (126.35)	2.04
CP 104A	Mass movement deposits - sand	Data logger	8.52 - 10.76 (10.06)	137.24 - 139.48 (137.94)	2.24
CP 200	Mass movement deposits - sand and gravel	Data logger	2.49 - 3.16 (2.90)	126.54 - 127.21 (126.8)	0.67
CP 202	Mass movement deposits - clay	Data logger	-0.24 - 0.97 (0.37)	134.73 - 135.94 (135.33)	1.22

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Ch 1+000 to Ch 1+400 (northern side of A417) – Mid Crickley Hill					
CP 210 (s)	Mass movement deposits – silty clay	38	1.78 [1]	172.52 [1]	-
CP 211	Mass movement deposits - gravel	37	Dry	Dry	-
CP 215 (s)	Mass movement deposits - clay	42	1.51 - 2.10 (1.81)	183.95 - 184.54 (184.24)	0.59
DS/RC 205	Mass movement deposits - gravelly clay	39	7.05 - 8.90 (8.33)	158.25 - 160.10 (158.82)	1.85
Ch 1+000 to Ch 1+400 (southern side of A417) - Mid Crickley Hill					
CP 105	Mass movement deposits - silt and gravel	48	1.97 - 5.05 (3.65)	164.85 - 167.93 (166.25)	3.08
CP 206	Mass movement deposits - clay	Data logger	1.76 - 5.74 (3.97)	157.11 - 161.09 (158.88)	3.97
CP 216	Mass movement deposits - gravelly silty clay	Data logger	0.21 - 1.89 [1] (1.22)	171.61 - 173.29 [1] (172.28)	1.69
CP 204 (s)	Mass movement deposits - clay	20	7.80 - 9.80 [1] (8.74)	169.10 - 171.10 [1] (170.16)	2.00
CP 212 (s)	Mass movement deposits - gravel and clay	Data logger	7.39 - 8.80 (8.39)	182.80 - 184.21 (183.21)	1.40
Ch 1+400 to Ch 1+700 (southern side of A417) - Upper Crickley Hill					
DS/RC/OH 107	Mass movement deposits - sands and gravels	41	1.95 - 2.77 (2.07)	189.13 - 189.95 (189.83)	0.82
Ch 1+400 to Ch 1+700 (northern side of A417) - Upper Crickley Hill					
DS/RC 229	Mass movement deposits – silt	23	5.20 - 5.94 (5.63)	194.51 - 195.25 (194.82)	0.74

Note: 1. Groundwater level falls below response zone base

Ch 0+500 to Ch 1+000 – Lower Crickley Hill

5.1.3 The groundwater monitoring locations in the lower slopes of Crickley Hill are located on the southern side of the A417 next to tributary of Norman's Brook. The hydrographs for these locations are presented on Figure B-1 (Appendix B). Within this domain, relatively shallow (< 3.2 mbgl) groundwater levels were recorded in CP 102, CP 200 and CP 202. Deeper groundwater levels were recorded in CP 104A (average 10 mbgl).

5.1.4 The shallow wells CP 102, CP 200 and CP 202 are located within silty and clayey mass movement deposits. The hydrographs show a gradual seasonal response at each location. CP 102 is responsive to larger rainfall events, whilst CP 200 and CP 202 show minimal response to rainfall.

5.1.5 CP 104A monitors the groundwater level within a confined or semi-confined sand layer. The groundwater response at CP 104A also shows a seasonal response (up to 3m), indicating that the sand layer is connected to recharge.

Ch 1+000 to Ch 1+400 (northern side of A417) – Mid Crickley Hill

5.1.6 In the mid-slope region of Crickley Hill between Ch 1+000 and Ch 1+400, there are four groundwater monitoring locations. The hydrographs for these locations are presented on Figure B-2 and Figure B-3 (Appendix B). Relatively shallow groundwater levels (< 2.1 mbgl) were recorded in CP 215(s), whilst other shallower response zones in CP 210(s) (2.5 to 5.5 mbgl) and CP 211 (1.1 to 3.3 mbgl) are mostly dry. Deeper groundwater levels were recorded in DS/RC 205 up to 8.9 mbgl.

5.1.7 CP 210(s) and CP211 are both monitoring within shallow, coarse-grained mass movement deposits. The monitoring to date indicates these deposits are mostly unsaturated. This may be limited by the frequency of recordings and the rate groundwater levels may respond to rainfall.

5.1.8 CP 215 (s) is monitoring within a bed of clay dominated mass movement deposits. The location shows a slight response to rainfall, however there is no distinct seasonality to this location.

5.1.9 DS/RC 205 is monitoring within gravelly clay mass movement deposits at depth. A seasonal variation (up to 1.9m) was observed at this location and water levels are responsive to larger rainfall events during wetter months.

Ch 1+000 to Ch 1+400 (southern side of A417) - Mid Crickley Hill

5.1.10 Between Ch 1+000 and Ch 1+400 on the southern side of the A417, there are five groundwater monitoring locations. The hydrographs for these locations are presented on Figure B-4 and Figure B-5 (Appendix B). Similar to other areas of Crickley Hill, relatively shallow groundwater levels were recorded (0.2 to 5.3 mbgl) near Norman's Brook. Deeper groundwater levels, between 7.3 and 11.6 mbgl, were recorded at CP 212(s) which is located approximately halfway up the southern escarpment slope.

5.1.11 CP 105, CP 206 and CP 216 are located on the southern side of Norman's Brook. CP 105 is monitoring within silt and gravel deposits and CP 206 is monitoring within clay. CP105 and CP206 show a similarly large seasonal variation (between 3.1 m and 4 m) in groundwater levels. Both locations are highly responsive to rainfall, particularly over wetter months, indicating they receive direct recharge. The response zone for CP 216 is within gravelly silty clay material and shows comparatively smaller seasonal variation and responsiveness to rainfall.

5.1.12 CP 204(s) is located mid-way up the Crickley Hill escarpment and has response zone within clay. Manual dips taken at this location have been largely dry, apart from July 2020. The variation in readings suggests the location may respond rapidly to rainfall events.

5.1.13 CP 212(s) is monitoring within gravel and clay mass movement deposits. The monitoring results show seasonal variation in water levels which is responsive to rainfall over winter months. Over drier, summer months the groundwater level is relatively consistent at approximately 183 mAOD within the gravels.

Ch 1+400 to Ch 1+700 (southern side of A417) - Upper Crickley Hill

5.1.14 Within the upper slopes of Crickley Hill on the southern side of A417 there is one monitoring location within the mass movement deposits, DS/RC/OH 107, which is monitoring within sands and gravels. The hydrograph for this location is presented on Figure B-6 (Appendix B). No seasonal variation or responsiveness to rainfall was observed at this location, indicating the location doesn't receive direct recharge.

Ch 1+400 to Ch 1+700 (northern side of A417) - Upper Crickley Hill

5.1.15 Within the upper slopes of Crickley Hill on the northern side of A417 there is one monitoring location within silt mass movement deposits, DS/RC 229. The hydrograph for this location is presented on Figure B-7 (Appendix B). Monitoring at this location commenced in March 2020, the monitoring suggests there is a seasonal variation at this location, however responsiveness to rainfall was not observed.

5.2 Great Oolite Group - Limestones

Overview

5.2.1 The locations of groundwater monitoring wells are shown in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3). A summary of the response zone strata is presented in Appendix A and the range of observed groundwater levels is presented in Table 5.2.

5.2.2 The hydrographs for groundwater monitoring within the Group Oolite Group limestones are presented in Appendix B, Figure B-8 to Figure B-11. Across the scheme there are 7 monitoring locations within the Great Oolite Group limestones. Monitoring at these locations has progressively started since the 3rd October 2019. The distribution of monitoring locations includes:

- three between Ch 3+000 and Ch 3+500 at Shab Hill junction
- three between Ch 3+500 and Ch 5+000 between Shab Hill junction and Cowley junction
- one near the Bushley Muzzard SSSI

5.2.3 A summary of the response zone strata is presented in Appendix A and the range of observed groundwater levels is presented in Table 10.

Table 5.2 Summary of groundwater monitoring in Great Oolite Group limestones

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Ch 3+000 to Ch 3+500 - Shab Hill junction					
OH 413	Great Oolite (Limestone)	42	Dry [1]	Dry [1]	-
DS/RC 311	Great Oolite (Limestone)	22	39.04 - 39.40 [1] (39.30)	215.80 - 216.16 [1] (215.90)	0.36
DS/RC 312	Great Oolite (Limestone)	18	12.71 - 12.96 (12.87)	269.19 - 269.44 (269.28)	0.25
Ch 3+500 to Ch 5+000 - Shab Hill junction to Cowley junction					
DS/RC 218	Great Oolite (Interbedded limestone, mudstone and siltstone)	42	1.50 - 8.91 (6.14)	276.74 - 284.15 (279.51)	7.41
DS/RC 317	Great Oolite (Limestone)	Data logger	0.56 - 3.92 (3.11)	270.98 - 274.34 (271.79)	3.36

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
DS/RC 401	Great Oolite (Interbedded limestone and mudstone)	31	5.80 - 8.05 [1] (7.27)	265.05 - 267.30 [1] (266.44)	2.58
Bushley Muzzard SSSI					
DS/RC 420	Great Oolite (Interbedded limestone, mudstone and sandstone)	N/A[1]	1.54 - 3.50 [1] (2.20)	274.09 - 275.56 [1] (275.01)	1.47

Note: 1. Groundwater level falls below response zone base

Ch 3+000 to Ch 3+500 - Shab Hill junction

5.2.4 Three monitoring locations are located at Shab Hill junction within the Great Oolite Group limestones, OH 413, DS/RC 311 and DS/RC 312. The response zones for OH 413 and DS/RC 312 extend to the base of the limestones, whilst DS/RC 311 terminates above the base of the limestones. The hydrographs for these locations are presented on Figure B-8 and Figure B-9 (Appendix B).

5.2.5 The monitoring results indicate the aquifer has a deep unsaturated zone. The water levels in DS/RC 312 are consistently between 1.6 and 1.8m above the base of the aquifer. This observation is in line with the expectation that the Great Oolite Group at Shab Hill junction is a well drained limestone, unlike the section south to Cowley junction which is largely mudstone.

5.2.6 DS/RC 311 shows a seasonal response where relatively steady water levels were recorded between April 2020 to June 2020, then the location was dry up until October 2020. Groundwater levels at this location do not show responsiveness to rainfall and may be controlled by the adjacent fault acting as a groundwater flow path.

Ch 3+500 to Ch 5+000 - Shab Hill junction to Cowley junction

5.2.7 Between Ch 3+500 and Ch 5+000 there are 3 monitoring locations: DS/RC 218, DS/RC 317 and DS/RC 401. These installations are monitoring within the transition zone of the Great Oolite Group which includes mudstones with interbedded limestone. The hydrographs for these locations are presented in Figure B-10 (Appendix B).

5.2.8 A large seasonal variation was observed in DS/RC 218. Over the wetter, winter months the location was responsive to rainfall indicating the location receives direct recharge most likely by fracture flow. Over summer month the recorded groundwater level was consistently within the deepest limestone bed in the formation and not responsive to rainfall.

5.2.9 Groundwater levels within DS/RC 317 were also responsive to rainfall events over wetter, winter months, but unresponsive over summer months. DS/RC 401 showed a seasonal response in groundwater levels and minor response to rainfall, indicating the location is more likely to receive indirect recharge.

Bushley Muzzard SSSI

5.2.10 DS/RC 420 is located north-west of the Bushley Muzzard SSSI and is monitoring within shallow, interbedded limestones and mudstones above the Fuller's Earth

Formation. The hydrograph for this location is presented on Figure B-11 (Appendix B). A seasonal response was observed where groundwater levels were responsive to rainfall events over winter months. Over summer months the aquifer is largely unsaturated and isn't responsive to rainfall events.

5.3 Great Oolite Group – Fuller's Earth Formation

Overview

5.3.1 There are three groundwater monitoring locations within the Fuller's Earth Formation. The maps showing the locations of these wells are presented in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3) and the hydrographs for these groundwater monitoring locations are presented in Appendix B, Figure B-12 to Figure B-14. Monitoring at the location commenced on the 4th February 2019. The groundwater monitoring network for the Fuller's Earth Formation may be divided into the following specific areas:

- two between Ch 3+500 and Ch 5+000 between Shab Hill junction and Cowley junction
- one at Ermin Way, west of the Bushley Muzzard SSSI

5.3.2 Table 5.3 provides a summary of the range of groundwater levels recorded, the number of manual measurements and whether a water level data logger was used. A summary of the response zone interval is presented in Appendix A, Table A.1.

5.3.3 The following sections provide a description of the groundwater level data recorded for each area and provides an interpretation of these fluctuations based on seasonal recharge and responses to rainfall events.

Table 5.3 Summary of groundwater monitoring in Fuller's Earth Formation

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Ch 3+500 to Ch 5+000 - Shab Hill junction to Cowley junction					
DS/RC 220	Fuller's Earth Formation (transition)	Data logger	1.27 - 3.70 (2.19)	275.15 - 277.58 (276.66)	2.43
DS/RC 403	Fuller's Earth Formation (transition)	25	3.40 - 5.36 (4.57)	242.29 - 244.25 (243.08)	1.96
Ermin Way					
OH 416	Fuller's Earth Formation (weathered)	Data logger	1.48 - 3.55 (2.31)	283.3 - 285.37 (284.54)	2.07

Ch 3+500 to Ch 5+000 - Shab Hill junction to Cowley junction

5.3.4 The response zones in DS/RC 220 and DS/RC 403 are within the Fuller's Earth Formation transition zone, mostly comprising mudstones with occasional limestone beds. The hydrographs for these locations are presented on Figure B-12 and Figure B-13 (Appendix B).

5.3.5 A seasonal response was observed at DS/RC 220 where groundwater levels were also responsive to larger rainfall events, indicating the location likely receives indirect recharge. Over the summer period the groundwater levels showed little to no response to rainfall events. Monitoring at DS/RC 403 commenced in March 2020 and shows little response to rainfall events over the following months, indicating the location also likely receives indirect recharge.

Ermin Way

5.3.6 One groundwater monitoring borehole (OH 416) is located adjacent to Ermin Way (Roman Road). The hydrograph for this location is presented on Figure B-14 (Appendix B). The location shows a seasonal response, where groundwater levels are higher over winter months and only show minor, rapid fluctuations in levels over this period due to rainfall. Over summer months the location is responsive to rainfall events, where these fluctuations are small and rapid, indicating the location receives direct recharge.

5.4 Inferior Oolite Group

Overview

5.4.1 There are a total of 23 groundwater monitoring locations within the Inferior Oolite Group limestones. The maps showing the locations of these wells are presented in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3) and the hydrographs for these groundwater monitoring locations are presented in Appendix B, Figure B-15 to Figure B-22. Monitoring at these locations has progressively started since the 5 February 2019. The groundwater monitoring network for the Inferior Oolite Group may be divided into the following specific areas:

- ten between Ch 1+700 and Ch 2+250 at Air Balloon
- one between Ch 2+250 and Ch 2+270 at Air Balloon
- two near Barrow Wake
- one near the proposed B4070
- five between Ch 3+000 and Ch 3+500 at Shab Hill junction
- two between Ch 3+500 and Ch 4+575 between Shab Hill junction and Cowley junction
- one at Ermin Way

5.4.2 Table 5.4 provides a summary the range of groundwater levels recorded, the number of manual measurements and whether a water level data logger was used. A summary of the response zone interval is presented in Appendix A, Table A.1.

5.4.3 The following sections provide a description of the groundwater level data recorded for each area and provides an interpretation of these fluctuations based on seasonal recharge and responses to rainfall events.

Table 5.4 Summary of groundwater monitoring in Inferior Oolite Group

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Ch 1+700 to Ch 2+250 - cutting					
DS/RC 109	Inferior Oolite (Limestone)	33	Dry	Dry	-
DS/RC 301	Inferior Oolite (Limestone, Bridport Sand)	33	26.13 - 28.72 [1] (26.87)	205.48 - 208.07 [1] (207.33)	2.59
DS/RC 302	Inferior Oolite (Limestone)	28	23.95 - 25.80 [1] (25.20)	208.70 - 210.55 [1] (209.30)	1.85

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
DS/RC 319	Inferior Oolite (Limestone)	30	19.31 - 20.00 [1] (19.74)	211.85 - 212.29 [1] (212.16)	1.09
DS/RC 325	Inferior Oolite (Limestone)	25	21.81 - 24.36 (23.07)	208.89 - 211.44 (210.18)	2.55
DS/RC 406	Inferior Oolite (Birdlip Limestone)	Data logger	27.77 - 31.98 (31.03)	206.67 - 210.88 (207.62)	4.20
DS/RC 418	Inferior Oolite (Limestone)	27	55.96 - 57.48 [1] (56.55)	214.77 - 216.29 [1] (215.70)	1.52
DS/RC/OH 110	Inferior Oolite (Limestone)	27	29.52 - 33.50 [1] (31.14)	206.50 - 210.48 [1] (208.86)	3.98
OH 405	Inferior Oolite (Limestone)	43	Dry	Dry	-
OH 407	Inferior Oolite (Limestone)	37	Dry	Dry	-
Ch 2+250 to Ch 2+750 - cutting					
DS/RC/OH 308	Inferior Oolite (Limestone)	25	54.25 - 57.45 [1] (55.85)	213.9 - 217.10 [1] (215.5)	3.20
Barrow Wake					
DS/RC 404	Inferior Oolite (Birdlip Limestone)	45	33.28 - 33.45 [1] (33.4)	235.55 - 235.72 [1] (235.6)	0.17
DS/RC/OH 414	Inferior Oolite (Limestone)	40	55.03 - 58.94 [1] (57.46)	215.66 - 219.57 [1] (217.14)	3.91
B4070 realignment					
DS/RC 314	Inferior Oolite (Limestone)	43	14.85 - 14.97 [1] (14.90)	278.15 - 278.25 [1] (278.20)	0.12
Ch 3+000 to Ch 3+500 - Shab Hill junction					
DS/RC 310	Inferior Oolite (Limestone)	20	Dry	Dry	-
DS/RC 315	Inferior Oolite (Limestone)	25	42.75 - 48.70 (45.11)	198.20 - 204.15 (201.79)	5.95
DS/RC 315A	Inferior Oolite (Limestone)	15	46.55 - 51.24 [1] (50.2)	195.76 - 200.45 [1] (196.8)	4.69
DS/RC/OH 412	Inferior Oolite (Limestone)	39	28.20 - 28.95 [1] (28.81)	221.35 - 222.10 [1] (221.49)	0.75
OH 411	Inferior Oolite (Limestone)	13	79.75 - 83.98 [1] (82.18)	196.52 - 200.75 [1] (198.32)	4.23
Ch 3+500 to Ch 4+575 - Shab Hill junction to Cowley junction					
DS/RC/OH 400	Inferior Oolite (Limestone)	35	70.72 - 71.89 [1] (71.33)	196.06 - 197.23 [1] (196.62)	1.17
OH 417	Inferior Oolite (Limestone)	41	68.00 - 70.80 [1] (69.79)	204.85 - 207.65 [1] (205.86)	2.80
Ermin Way					
DS/RC 415	Inferior Oolite (Salperton, Aston and Birdlip Limestone Formations)	43	Dry	Dry	-

Note: 2. Groundwater level falls below response zone base

Cutting Ch1+700 to Ch2+250

5.4.4 A total of 12 groundwater monitoring boreholes are located at Air Balloon. Most of the monitoring response zones extend to the base of the Inferior Oolite Group except for DS/RC 325, DS/RC 408, OH 405 and OH 407, which terminate above the base. The hydrographs for these locations are presented on Figure B-15 (Appendix B). Monitoring shows that there is a deep unsaturated zone in this area, where water levels are up to 6m above the aquifer base.

5.4.5 Four locations were consistently dipped 'dry' over the monitoring period, including DS/RC 109, OH 405 and OH 407. DS/RC 109 is located near the crest of the Cotswold escarpment and includes voids near the base of the response zone, which in combination results in 'dry' readings. Groundwater flow is likely to be 'flashy' at this location, meaning the groundwater levels change rapidly as flow travels through the aquifer.

5.4.6 A seasonal response was observed in the remaining monitoring locations. DS/RC 301, DS/RC 319 and DS/RC 418 recorded steady groundwater levels over the winter period indicating they are unlikely to receive direct recharge. DS/RC 302, DS/RC 319 and DS/RC 406 showed flashy responses over the wetter, winter period where the amplitude and response pattern is similar across the locations indicating they may be connected by a flow path that receives direct recharge.

5.4.7 Over drier summer months, groundwater levels were only recorded in DS/RC 325, DS/RC 406, DS/RC 408 and DS/RC/OH 110, located on the eastern side of the Shab Hill fault where the top of the underlying Lias Group is lower than surrounding areas.

Cutting Ch 2+250 to Ch 2+800

5.4.8 Within the eastern extent of the cutting there is one monitoring locations available, DS/RC/OH 308. The hydrograph for this location is presented on Figure B-16 (Appendix B). The location is mostly dry throughout the year with seasonal, flashy readings recorded during wetter winter months. It is likely this location receives direct recharge and remains largely dry as the top of the Lias Group is higher in this location compared to the western end of the proposed cutting between Ch 1+700 and Ch 2+250 allowing the water to drain away.

Barrow Wake

5.4.9 Two groundwater monitoring boreholes, DS/RC 404 and DS/RC/OH 414, are located adjacent to the proposed B4070 realignment. The hydrographs for these locations are presented on Figure B-17 and Figure B-18 (Appendix B). Seasonal groundwater levels were recorded in each monitoring location. At DS/RC 404, located near the crest of the Cotswold escarpment, the location is mostly dry with similar groundwater levels recorded over the winter months at approximately 235.6 mAOD (1.5m above the aquifer base). It's likely this location receives indirect recharge from the groundwater flowing through the aquifer to the escarpment where it drains.

5.4.10 DS/RC/OH 414 is set further back from the escarpment and adjacent to the Shab Hill Barn fault. Similar to other monitoring locations in the Inferior Oolite Group, there is a deep unsaturated zone and water levels are up to 5.4m above the aquifer base. Over the wetter, winter months DS/RC/OH 414 recorded very rapid and flashy water levels in response to rainfall events indicating the location receives direct recharge.

B4070 realignment

5.4.11 One groundwater monitoring borehole, DS/RC 314, is located adjacent to the proposed B4070 realignment and the base of the aquifer is at an unknown depth below the response zone. The hydrograph for this location is presented on Figure B-19 (Appendix B). Water levels recorded are very close to the base of the response zone and may be indicative of water pooling in the borehole end cap.

Ch 3+000 to Ch 3+500 - Shab Hill junction

5.4.12 Five groundwater monitoring boreholes, DS/RC 310, DS/RC 315, DS/RC 315A, DS/RC/OH 412 and OH 411, are located at Shab Hill junction. The hydrographs for these locations are presented on Figure B-20 and Figure B-21 (Appendix B). The monitoring response zones extend to the base of the aquifer with the exception of DS/RC 310 and DS/RC 412. In this area the Inferior Oolite Group is overlain by the Great Oolite Group and superficial head deposits.

5.4.13 A seasonal response was observed in DS/RC 315 and DS/RC 315A, where the results showed a deep, unsaturated zone and groundwater levels up to 10.7 m above the base of the aquifer. Over the wetter, winter months the location had a delayed response to rainfall events and over the summer months the water levels were not responsive to rainfall events and some dry readings were recorded. The location likely receives indirect recharge from the overlying head deposits.

5.4.14 DS/RC/OH 412 shows the water level lies near the base of the aquifer unit and doesn’t respond to rainfall events. Water levels in this location are consistent with a 70° incipient fracture logged at 28.8mbgl, which is likely to be a flow path.

5.4.15 Monitoring at OH 411 commenced in June 2020 and data received up until October 2020 suggests this location has a seasonal groundwater response.

Ch 3+500 to Ch 4+575 - Shab Hill junction to Cowley junction

5.4.16 Two groundwater monitoring boreholes, OH 417 and DS/RC/OH 400, are located adjacent to the proposed cuttings between Shab Hill junction and Cowley junction. The hydrographs for these locations are presented on Figure B-22 (Appendix B). In this area the Inferior Oolite Group is at surface along the valley sides and overlain by the Great Oolite Group along the ridgeline.

5.4.17 The groundwater monitoring record for these boreholes indicates there is a deep, unsaturated zone and water levels are near the base of the aquifer. Water levels are seasonal and ‘dry’ readings were recorded later in the summer months. The water levels were not responsive to rainfall indicating recharge in the area is from indirect sources like leakage from the overlying Great Oolite Group and interflows from where the aquifer is recharged directly.

Ermin Way

5.4.18 One monitoring location, DS/RC 415, is monitoring within the Inferior Oolite Group at Ermin Way (Roman Road), north-west of Bushley Muzzard SSSI. The base of the response zone (49mbgl) is above the base of the aquifer, which was not proved during the ground investigation. Monitoring at this location commence in February 2019 and has consistently dipped dry since indicating there is a deep, unsaturated zone and water levels are likely near the base of the aquifer.

5.5 Lias Group – Bridport Sand Formation

Overview

5.5.1 There is a total of two groundwater monitoring locations within the Bridport Sand Formation. The maps showing the locations of these wells are presented in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3) and the hydrographs for these groundwater monitoring locations are presented in Appendix B, Figure B-25 and Figure B-29. Monitoring at these locations has progressively started since the January 2019. The groundwater monitoring network for the Lias Group within Crickley Hill may be divided into the following specific areas:

- one at Air Balloon
- one at Barrow Wake

5.5.2 Table 5.5 provides a summary the range of groundwater levels recorded, the number of manual measurements and whether a water level data logger was used. A summary of the response zone interval is presented in Appendix A, Table A.1.

5.5.3 The sections below provide a description of the groundwater level data recorded for each area and provides an interpretation of these fluctuations based on seasonal recharge and responses to rainfall events.

Table 5.5 Summary of groundwater monitoring in Lias Group – Bridport Sand Formation

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Air Balloon					
DS/RC 408	Lias Group (Bridport Sand)	Data logger	21.23 - 22.77 (21.82)	209.73 - 211.27 (210.68)	1.54
Barrow Wake					
DS/RC 419	Lias Group (Bridport Sand)	Data logger	35.61 - 39.93 (38.00)	228.97 - 233.29 (230.90)	4.32

Note: 1. Continuous monitoring data available

Air Balloon

5.5.4 One groundwater monitoring well (DS/RC 408) is located within the proposed Air Balloon cutting. The hydrograph for this location is presented on Figure B-23 (Appendix B). In this area the Bridport Sand Formation is overlain by the Inferior Oolite Group. A seasonal response was recorded at this location where groundwater levels were not responsive to rainfall events. The location likely receives recharge from the overlying Inferior Oolite Group.

Barrow Wake

5.5.5 One groundwater monitoring well (DS/RC 419) is located near Barrow Wake. The hydrograph for this location is presented on Figure B-24 (Appendix B). In this area the Bridport Sand Formation has a thin, fractured mudstone bed (0.95 m thick) at the top of the formation which is overlain by the Inferior Oolite Group. A seasonal response was recorded at this location and groundwater levels are responsive to rainfall events, indicating the location has a strong hydraulic connection to the overlying Inferior Oolite Group.

5.6 Lias Group – undifferentiated mudstones

Overview

5.6.1 There is a total of eight groundwater monitoring locations within the Lias Group undifferentiated mudstones. The maps showing the locations of these wells are presented in ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3) and the hydrographs for these groundwater monitoring locations are presented in Appendix B, Figure B-25 to Figure B-28. Monitoring at these locations has progressively started since May 2019. The groundwater monitoring network for the Lias Group within Crickley Hill may be divided into the following specific areas:

- Six between Ch 1+000 and Ch 1+400 in the mid-slopes of Crickley Hill
- One at Air Balloon
- One in the upper slopes of Crickley Hill

5.6.2 Table 5.6 provides a summary the range of groundwater levels recorded, the number of manual measurements and whether a water level data logger was used. A summary of the response zone interval is presented in Appendix A, Table A.1.

5.6.3 The sections below provide a description of the groundwater level data recorded for each area and provides an interpretation of these fluctuations based on seasonal recharge and responses to rainfall events.

Table 5.6 Summary of groundwater monitoring in Lias Group undifferentiated mudstones

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Ch 1+000 to Ch 1+400 (northern side of A417) – Mid Crickley Hill					
CP 210 (d)	Lias Group (weathered, mudstone)	38	13.72 - 16.40 (15.33)	157.90 - 160.58 (158.97)	2.68
CP 215 (d)	Lias Group (weathered CLAY)	47	12.85 - 15.38 (14.08)	170.67 - 173.20 (171.97)	2.53
Ch 1+000 to Ch 1+400 (southern side of A417) – Mid Crickley Hill					
CP 106	Lias Group (mudstone)	35	14.98 - 16.39 (15.84)	169.86 - 171.27 (170.41)	1.41
CP 204 (d)	Lias Group (weathered clay)	17	10.06 - 12.70 (11.88)	166.20 - 168.84 (167.02)	2.64
CP 212 (d)	Lias Group (mudstone)	Data logger	17.76 - 19.59 (18.52)	172.01 - 173.84 (173.08)	1.83
CP 223	Lias Group (mudstone/ sandstone)	Data logger	19.58 - 22.27 (21.42)	157.46 - 162.44 (158.33)	4.98
Ch 1+400 to Ch 1+700 (southern side of A417) - upper Crickley Hill					
DS/RC 108	Lias Group (weathered sandy silty CLAY, weathered limestone)	48	1.76 - 3.79 (2.48)	189.81 - 191.84 (191.12)	2.03
Air Balloon					
DS/RC/OH 304	Lias Group (mudstone)	26	21.50 - 24.64 (23.32)	207.16 - 210.30 (208.48)	3.14

Location	Formation	No. dips	GWL range (average) (mbgl)	GWL range (average) (mAOD)	Observed range (m)
Southern Crest of Crickley Hill					
DS/RC 224	Lias Group (mudstone/ limestone)	Data logger	19.87 - 35.73 [1] (22.44)	191.12 - 206.98 [1] (204.41)	15.86

Note: 2. Groundwater level falls below response zone base

Ch 1+000 to Ch1+400 (northern side of A417) – Mid Crickley Hill

5.6.4 Two groundwater monitoring boreholes, CP 210(d) and CP 215(d), are located on the northern side of the A417, in the mid-slopes of Crickley Hill. The hydrographs for these locations are presented on Figure B-25 and Figure B-26 (Appendix B). In this area the Lias Group is overlain by superficial mass movement deposits.

5.6.5 A seasonal response was observed in both monitoring location. Over the winter months, a delayed response to rainfall was recorded indicated the locations receive indirect recharge. Over the drier, summer months the groundwater levels were only responsive to large rainfall events.

Ch 1+000 to Ch 1+400 (southern side of A417) – Mid Crickley Hill

5.6.6 Three groundwater monitoring boreholes, CP 204(d), CP 212(d) and CP 223, are located on the northern side of the A417, in the mid-slopes of Crickley Hill. The hydrographs for these locations are presented on Figure B-27 (Appendix B). In this area the Lias Group is overlain by superficial mass movement deposits.

5.6.7 A seasonal response was observed at the monitoring boreholes. Logger data at CP 204(d), CP 212(d) and CP 223 showed small, rapid fluctuations to rainfall inputs.

Air Balloon

5.6.8 One groundwater monitoring location within the Lias Group is present at Air Balloon, DS/RC/OH 304. The hydrograph for this location is presented on Figure B-28 (Appendix B). Monitoring commenced at this location in March 2020, which indicate the location is likely to have seasonal groundwater levels that aren't responsive to rainfall events. This shows the location receives indirect recharge from the overlying Inferior Oolite Group.

Southern Crest of Crickley Hill

5.6.9 One groundwater monitoring borehole, DS/RC 224, is located near the southern crest of the Cotswold escarpment. The hydrograph for this location is presented on Figure B-29 (Appendix B). In this area the Lias Group is overlain by superficial mass movement deposits.

5.6.10 The groundwater monitoring record for this borehole has been affected by a slow response in water levels following installation and sampling events. The water table responds to rainfall events, however seasonal variation is masked by the changes in water level due to sampling.

5.7 Hydraulic gradient and groundwater flow

Crickley Hill

5.7.1 Within the Crickley Hill area, groundwater flow paths in the mass movement deposits and Lias Group typically follow the topographical slopes and generally flow towards surface water features such as the tributary of Norman's Brook and the unnamed tributaries that flow into this watercourse. To the south of the Norman's Brook tributary the hydraulic gradient is generally towards the north and north west. Conversely, to the north of the Norman's Brook tributary the hydraulic gradient is to the south and south west.

Air Balloon

5.7.2 The Cotswold escarpment forms a groundwater divide between the River Severn catchment and the River Thames catchment (to the west and south-east of the divide respectively). This divide is set back from the escarpment crest and is likely to cause divergent flow to the west and east within the Inferior Oolite aquifer near Air Balloon. At present there is a lack of groundwater monitoring data to confirm where this divergence is occurring.

5.7.3 Based on the monitoring data available, groundwater within the Inferior Oolite Group generally drains towards the Cotswold escarpment crest. The Existing A417 cutting through Air Balloon creates a local drainage point in the aquifer.

Shab Hill junction

5.7.4 Groundwater flow within the Great Oolite Group and Inferior Oolite Group in the Shab Hill junction area is likely to be heavily influenced by the three faults interpreted across the area. Generally, groundwater flow from the junction is likely to be towards the east into the Churn headwaters. The groundwater divide is likely to be west of Shab Hill Junction, where groundwater flows towards the Cotswold escarpment.

Shab Hill junction to Cowley junction

5.7.5 South of Shab Hill junction, towards Cowley junction, the groundwater divide in the overlying Great Oolite Group likely runs along the ridgeline. As a result, divergent flows to the south-west and south-east are likely in the Great Oolite limestone aquifer in this area. Incised valleys in this area are likely to induce locally steeper groundwater gradients within the Great Oolite Group. In the underlying Inferior Oolite Group groundwater flows are towards the south east.

5.8 Hydraulic relationships between aquifer units

5.8.1 Faults are providing some groundwater flow pathways between the same bedrock aquifers in the region. In Air Balloon similar responses in groundwater levels were recorded either side of the Shab Hill fault, indicating a strong hydraulic connection. This may be a localised area of connectivity across the fault as the fault conditions are likely to vary vertically and along the length.

5.8.2 Additionally, the throw induced by the faults vertically offsets the geological formations either side of the fault. It is anticipated that in the Great Oolite limestone aquifer, the Stockwell fault, Churn Valley fault, Cally Hill fault and Shab Hill Barn fault may facilitate downward leakage into the underlying Inferior Oolite aquifer. As previously discussed, this leakage may be more prominent during wetter periods when there is sufficient saturated zone within the Great Oolite limestone aquifer[37].

5.8.3 The Bridport Sand Formation at the top of the Lias Group is assumed to be hydraulically connected to the base of the Inferior Oolite Group aquifer and is recharged via these limestones.

5.8.4 It is possible that thin but potentially laterally extensive beds of limestone within mudstone formations and the Marlstone Rock Formation could also be locally, hydraulically linked to the superficial deposit aquifer. In the Churn and Frome valleys, the superficial deposits may be slowly leaking into the underlying Inferior Oolite limestones at a relatively constant rate.

6 Groundwater quality

6.1.1 During the Phase 1 ground investigation, groundwater samples were taken from the Birdlip Limestone of the Inferior Oolite aquifer (DS/RC 406) and Bridport Sand Formation (DS/RC 419) on the 14th February 2019. Sampling from Phase 2A boreholes has progressively been completed since the 11th November 2019. A summary of the groundwater quality testing results is presented in Appendix C.

6.1.2 The composition of water samples from each geological formation is relatively similar where bicarbonate waters are the most common. Calcium is the dominant cation however some samples had higher concentrations of potassium and sodium. Samples with higher potassium and sodium concentrations were from the mass movement deposits, Inferior Oolite Group and Lias Group mudstone.

6.1.3 Water samples were typically fresh (<1,560 µS/cm), however some slightly saline to moderately saline waters were sampled from Lias Group mudstones and mass movement deposit samples. The highest EC reading was 5,600 µS/cm in DS/RC 224, located at the crest of the Crickley Hill escarpment where the Inferior Oolite Group and Lias Group mudstone are included in the response zone.

6.1.4 Exceedance of UK Drinking Water Standards occurred in the following samples:

- Sulphate as SO_4^{2-} – 392mg/l in CP 104 (mass movement deposits)
- Nitrite as NO2 – 1,600µg/l in DS/RC 110 (Inferior Oolite Group), 6,300 to 12,000µg/l in DS/RC 224, 750µg/l in CP 206 (mass movement deposits), 650µg/l in DS/RC 403 (Fuller's Earth Formation)
- Manganese – 27 exceedances primarily from mass movement deposits and Inferior Oolite group samples, where the maximum recorded concentration was 1,300µg/l in CP 206
- Sodium – 240mg/l in DS/RC 110 (Inferior Oolite Group), 260 to 270mg/l in DS/RC 224 (Lias Group mudstone and Inferior Oolite Group)
- Arsenic – 10.2µg/l in CP 200 (mass movement deposits)

7 Aquifer testing

7.1.1 Aquifer testing was conducted during the Phase 1 and Phase 2A ground investigations to estimate the hydraulic conductivity (K) of selected bedrock formations. A combination of constant head and rising head tests were used depending upon saturated aquifer thickness[38]. A summary of the testing results is presented in Table 7.1 and test reports are included in ES Appendix 9.3 Ground investigation factual report (Document Reference 6.4).

Table 7.1 Summary of field testing results[39]

Location	Test interval	Test lithology	K (m/s)
OH 416	3.0 – 5.0mbgl 283.85 – 281.85mAOD	Weathered Fuller's Earth Formation – Great Oolite Group	$2x10^{-7}$
DS/RC 220	3.0 – 13.0mbgl 275.85 - 265.85mAOD	Fuller's Earth Formation – Great Oolite Group	$1.3 x10^{-7}$

Location	Test interval	Test lithology	K (m/s)
DS/RC 404	23.0 – 34.0mbgl 246.0 – 235.0mAOD	Birdlip Limestone Formation - Inferior Oolite Group	$4.6x10^{-5}$ to $7.2x10^{-5}$
DS/RC 406	20.5 – 35.0mbgl 218.15 – 203.65mAOD	Birdlip Limestone Formation - Inferior Oolite Group	$2x10^{-6}$
OH 405	11.0 – 18.0mbgl 228.5 – 221.5mAOD	Inferior Oolite Group	$5.7x10^{-5}$
OH 407	6.0 – 15.5mbgl 225.75 – 216.25mAOD	Inferior Oolite Group	$4.2x10^{-5}$ to $7.0x10^{-5}$
DS/RC 419	36.0 – 42.0mbgl 232.9 – 226.9mAOD	Bridport Sand Formation – Lias Group	$3.2x10^{-6}$
DS/RC 408	20.0 – 24.0mbgl 212.5 – 208.5mAOD	Bridport Sand Formation – Lias Group	$1.1x10^{-5}$

7.1.2 A summary published hydraulic conductivity of the bedrock formations in the Cotswold area is presented in Table 7.2.

Table 7.2 Summary of published hydraulic conductivities for bedrock in the Cotswolds

Parameter	K range (m/s)	K suggested mean (m/s)
Bridport Sand Formation	$8x10^{-8}$ – $4x10^{-6}$	-
Lias Group	$1x10^{-11}$ – $4x10^{-6}$	-
Inferior Oolite Group	$3x10^{-11}$ – $5.8x10^{-3}$	$1.1x10^{-9}$ and $5.8x10^{-9}$
Fuller's Earth Formation	$6.9x10^{-6}$	$2.3x10^{-7}$
Great Oolite Group limestone	$2.2x10^{-11}$ – $2.2x10^{-5}$	$1.1x10^{-9}$

7.1.3 The aquifer properties presented in Table 10 and Table 11 provide an overview of those K values recorded in the study area and the regional context. These data are used in developing the Hydrogeological conceptual model in Section 8 and Potential impacts to groundwater features in Section 10. The limestone formations of the Inferior Oolite Group and the Great Oolite Group have the potential for karst processes to locally increase permeability. The K values presented do not include karst, which has the potential for conduit flow which is of a significantly higher scale. Where karst has the potential to be encountered as part of the proposed road development then this is dealt with specifically on a location by location basis.

8 Groundwater conceptual model

8.1 Overview

8.1.1 Three aquifers and two aquitards have been considered in the development of the groundwater conceptual models. The aquifers include the superficial deposits, the limestones of the Great Oolite Group and the Inferior Oolite Group. The Fuller's Earth Formation and Lias Group mudstones are low permeability strata that form barriers to flow causing perched groundwater in overlying aquifers. These barriers can influence flow direction but also create ponding where structural controls are present. The groundwater characteristics of the aquifer units are presented below, whilst a summary of the hydrogeological units are presented in Table 8.1. The local groundwater regimes for each section of the proposed road development are presented in Section 8.2.

Superficial deposits

8.1.2 The superficial deposits comprise mass movement deposits and head deposits which form areas in the lower ground on the western and eastern approaches to the scheme. The mass movement and head deposits are dominantly clay but include sand and gravel lenses, which are locally recharged and often associated with springs and seepages. A number of the springs and seepages are tufa forming. Due to the localised nature of the water occurrence in the mass movement and head deposits it is not possible to develop groundwater contours.

Inferior Oolite Group

8.1.3 Groundwater contours have been developed for the Inferior Oolite Group and Great Oolite Group based on seasonal minimum and seasonal maximum groundwater levels. These contours are presented in (all Document Reference 6.3):

- ES Figure 13.11 Groundwater contours – Inferior Oolite Group, seasonal minimum levels.
- ES Figure 13.12 Groundwater contours – Inferior Oolite Group, seasonal maximum levels.
- ES Figure 13.13 Groundwater contours – Great Oolite Group, seasonal minimum levels.
- ES Figure 13.14 Groundwater contours – Great Oolite Group, seasonal maximum levels.

8.1.4 The seasonal minimum groundwater levels within the Inferior Oolite Group are presented in ES Figure 13.11 Groundwater contours – Inferior Oolite Group, seasonal minimum levels (Document Reference 6.3). The minimum groundwater levels were recorded over summer months and these show that wide areas of the aquifer are fully drained extensive periods of time. Summer groundwater levels were only recorded at Air Balloon, east of the Shab Hill fault, where the top of the Lias Group is down faulted into a graben structure. In this area the Inferior Oolite Group is lower in elevation and bound by the Lias Group, which causes groundwater levels in the Inferior Oolite Group to pond.

8.1.5 The seasonal maximum groundwater levels of the Inferior Oolite Group area presented in ES Figure 13.12 Groundwater contours – Inferior Oolite Group, seasonal maximum levels (Document Reference 6.3). The maximum groundwater levels were recorded over winter months. Within the Air Balloon area groundwater flow is towards the Existing A417 cutting. Between the Shab Hill junction and Cowley junction, south of the Shab Hill Barn fault groundwater flow is towards the south east.

8.1.6 From the monitoring results it is clear that the Air Balloon area is on the western side of the groundwater divide and the Shab Hill junction to Cowley junction area is on the eastern side of the groundwater divide. The monitoring data indicate that the groundwater divide is likely to vary seasonally.

Great Oolite Group

8.1.7 The Great Oolite Group is crossed by the scheme from Shab Hill junction southwards. In this area the groundwater levels are strongly controlled by faulting with groundwater being isolated to fault blocks and the faults themselves allowing leakage to the Inferior Oolite Group underlying the Fuller’s Earth Formation.

8.1.8 The seasonal minimum groundwater levels within the Great Oolite Group are presented in ES Figure 13.13 Groundwater contours – Great Oolite Group, seasonal minimum levels (Document Reference 6.3). During the summer months groundwater levels were only recorded on the northern side of the Stockwell fault. On the southern side of the Stockwell fault the aquifer is dry. Summer groundwater levels on the northern side of the fault indicate a southward groundwater flow to the fault.

8.1.9 The seasonal maximum levels presented on ES Figure 13.14 Groundwater contours – Great Oolite Group, seasonal maximum levels (Document Reference 6.3) show groundwater flow is largely to the south and south-west and groundwater levels were recorded within the Great Oolite Group underlying Cowley junction as well.

Table 8.1 Summary of hydrogeological units

Age	Group	Formation	EA designation	Description	Thickness	Hydrogeological properties
Quaternary	-	Cheltenham Sand and Gravel	Secondary A aquifer	Fine to medium grained sand, seams of limestone gravel	0m to 2m	• Groundwater flow through relatively high permeability, intergranular matrix. • Directly recharged.
		Superficial deposits (alluvium, mass movement deposits and head deposits)	Alluvium – Secondary A aquifer Mass movement deposits and head deposits – no aquifer designation	Largely cohesive material with non-cohesive lenses	0m to 23m	• Variable hydraulic conductivity. Groundwater flow through intergranular matrix. • Directly recharged. • Seasonal groundwater levels. • Localised springs/seepages were more permeable zones are present such as sand and gravel lenses or toppled limestone blocks. • Springs/seepages may be tufa forming if the permeable zones occur in limestone dominant material.
Middle Jurassic	Great Oolite Group (168 - 165Ma)	White Limestone Formation	Principal aquifer	Limestone aquifer with clay beds	10m to 20m	• Highly fractured. Potential for karst enhancement in limestone between Shab Hill Barn fault and Shab Hill fault. • Iron staining and calcite precipitate on fractures. • Deep unsaturated zone. • Seasonal groundwater levels where aquifer is largely dry during summer months.
		Hampen Formation		Sandy and ooidal limestone aquifer with clay and marl beds		
		Througham Formation		Interbedded calcareous sandstone, variably oolitic limestone and calcareous mudstone and siltstone	0m to 10m	• Large anisotropy in hydraulic conductivity. • Where non-limestones dominate such as in the area south of the Shab Hill Barn fault then unlikely to develop karst • Seasonal groundwater levels.
		Fuller's Earth Formation	Unproductive aquifer	Mudstone aquitard with limestone beds	0m to 15m	• Sub-horizontal fracturing. • Relatively low permeability. • Forms an underlying barrier to groundwater flow in the Great Oolite limestones.

Age	Group	Formation	EA designation	Description	Thickness	Hydrogeological properties
	Inferior Oolite Group (175 - 168Ma)	Salperton Limestone	Principal aquifer	Shelly, ooidal limestone aquifer	0m to 40m	• Fractured with camber developed gulls near the escarpment margins. • Potential for karst enhancement. • Frequent, iron stained voids towards base of aquifer. • Deep unsaturated zone. • Seasonal groundwater levels, where aquifer is largely dry during summer. • Directly recharged where outcropping but often capped by Fuller's Earth Formation which prevents recharge. • Possible indirect recharge by leakage from overlying Great Oolite Group where faulting allows. • Springs occur in the Inferior Oolite Group near Air Balloon associated with the Shab Hill Barn fault.
		Aston Limestone		Shelly, sandy limestone aquifer		
		Birdlip Limestone		Ooidal, sometimes sandy limestone aquifer with sandy clay layers		
Lower Jurassic	Lias Group (200 - 175Ma)	Bridport Sand Formation	Principal aquifer (see paragraph 2.4.7)	Sandy mudstone and fine grained sandstone – minor aquifer	0m to 10m	• Discontinuous presence within the study area. • Hydraulic connection with base of Inferior Oolite Group. • Fracture dominated flow. • Seasonal groundwater table. • Indirectly recharged.
		Whitby Mudstone Formation (WMF)		Mudstone aquitard with limestone beds at base	12m to 98m[40]	• Relatively low permeability. • Potential to form a spring line with overlying Inferior Oolite Group and Bridport Sand. • Fissured clays in weathered zone.
		Marlstone Rock Formation (within the WMF)		Ferruginous, ooidal limestone and sandstone – minor aquifer	0m to 5m[41]	• Fracture dominated flow. • Recharged via leakage from overlying formations.
		Dyrham Formation		Silty mudstone and siltstone aquitard	15m to 54m[42]	• Relatively impermeable.
		Charmouth Mudstone Formation	Secondary Aquifer (Undifferentiated)	Mudstone aquitard with thin beds and nodules of limestone	120m to 284m[43]	• Relatively impermeable. • Localised zones of iron staining on fractures.

8.2 Ch 0+000 to Ch 1+700, Crickley Hill

8.2.1 A summary of the groundwater conceptual model elements within Ch 0+000 and Ch 1+700 are presented in Table 8.2 and Table 8.3. Representative cross sections have been developed for the following chainage are presented in Section A-A’, Section B-B’ and Section C-C’ of ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3). The locations of the cross sections are shown on ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3).

Table 8.2 Ch 0+000 to Ch 0+500 Crickley Hill approach conceptual model elements

Model element	Description
Surface topography	Low gradient slope towards the west, between approximately 96mAOD and 114mAOD
WFD groundwater catchment	Severn Vale – Secondary combined
Main groundwater bodies	Superficial: Localised Cheltenham Sand and Gravel underlie the Existing A417 and are connected to mass movement deposits (up-gradient) between Ch 0+350 and Ch 0+500 Bedrock: Lias Group mudstones aquitard (Charmouth Mudstone Formation and Dyrham Formation)
Groundwater flow direction	Regional: west, north-west through superficial deposits Localised: towards the tributary of Norman’s Brook
Approximate groundwater level at scheme	Unknown, to be confirmed from on-going ground investigations
Approximate maximum groundwater level	Ground surface. Mapped potential for groundwater flooding to occur at surface.
Approximate groundwater level variation	Unknown, to be confirmed from on-going ground investigations
Surface water bodies	Tributary of Norman’s Brook runs approximately parallel to the southern side of the Existing A417 between Ch 0+250 to Ch +500 and. The tributary is culverted under the Existing A417 around Ch 0+500, where it flows in a south to north direction and joins Norman’s Brook.
Springs	There are no springs/seepages in the sand and gravel deposits. Whilst springs/seepages are associated with permeable zones in the mass movement deposits none have been identified in this chainage domain.
Recharge	Rainfall and superficial deposits upgradient
Drainage	Road drainage along Existing A417

Table 8.3 Ch 0+500 to Ch 1+700 Crickley Hill escarpment conceptual model elements

Model element	Description
Surface topography	Escarpment slope with areas of hummocky ground, between approximately 114mAOD to 270mAOD. Locally the escarpment creates an embayment that the Existing A417 runs up. The slopes either side of the Existing A417 dip to the south-west (northern side) and the north-west (southern side).
WFD groundwater catchment	West of Ch 0+850: Severn Vale – Secondary combined

Model element	Description
	East of Ch 0+850: Severn Vale – Jurassic limestone Cotswold south edge
Main groundwater bodies	Superficial: Mass movement deposits and localised alluvium associated with the tributary of Norman's Brook Bedrock: Lias Group mudstones aquitard below superficial deposits (Dyrham Formation and Whitby Mudstone Formation) with a band of Marlstone Rock Formation at approximately 160-165mAOD and localised Bridport Sand Formation at approximately 212mAOD. Inferior Oolite limestone aquifer exposed at escarpment crest.
Groundwater flow direction	Regional: West, north-west through superficial deposits Localised: Towards the tributary of Norman's Brook, generally following the topographical slope
Regional faults	Shab Hill Barn fault at approximately Ch 1+600
Approximate groundwater level at scheme	Typically, between 2m and 3.3m below ground level, with some groundwater levels up to 11m below ground level
Approximate maximum groundwater level	Ground surface, due to prevalence of springs/seepages
Approximate groundwater level variation	Seasonal variations between 0.6m and 4.0m and responsive to rainfall inputs
Surface water bodies	Tributary of Norman's Brook runs approximately parallel to the southern side of the Existing A417
Springs	Springs occur in more permeable units of the cohesive dominated mass movement deposits, such as sand or gravel and remnants of limestone rock topples. Mass movement deposit springs in the valley floor will be perennial whilst those higher in valley sides are more likely to be seasonal. A collection of springs (springs 16, 17, 18 and 19) occur near the base of the Inferior Oolite limestone where the Shab Hill Barn fault cross cuts the escarpment. These limestone springs are seasonal and based on the groundwater levels recorded locally will have a flashy response to storm events. A modified spring, S01 lies on the northern side of the Existing A417 as part of a drainage trench that cuts into the Bridport Sand Formation. This cut and the modified spring will locally manage groundwater by lowering the water table to the base of the trench.
Recharge	Rainfall and groundwater draining from Inferior Oolite limestone and Bridport Sand Formation upgradient
Drainage	Road drainage along Existing A417, which may locally lower groundwater levels

8.3 Ch 1+700 to Ch 2+800, Air Balloon

8.3.1 A summary of the conceptual groundwater model elements within Ch 1+700 and Ch 2+800 is presented in Table 3-22. Representative cross sections have been developed for the following chainage are presented in Section D-D' and Section E-E' of ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3). The locations of the cross sections are shown on ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3).

Table 8.4 Ch 1+700 to Ch 2+800 Air Balloon conceptual model elements

Model element	Description
Surface topography	Moderate slopes (210mAOD to 270mAOD) dipping south-east and north-west towards the current A417 west of Air Balloon roundabout and crest of embayment. From approximately Ch 2+500 the slope gradient decreases and the ground level is approximately 274mAOD.
WFD groundwater catchment	West of Ch 1+950: Severn Vale – Jurassic limestone Cotswold south edge East of Ch 1+950: Burford Jurassic A groundwater divide exists close to these catchment boundaries
Main groundwater bodies	Superficial: None Bedrock: Inferior Oolite limestones over Bridport Sand Formation
Groundwater flow direction	Regional: West within Severn Vale catchment and East within the Burford Jurassic Locally: towards the escarpment edge and towards the Existing A417 cuttings where winter groundwater levels are likely intercepted by the existing road drainage network
Approximate groundwater level at scheme	Deep unsaturated zone to 210mAOD
Approximate maximum groundwater level	212.3mAOD
Approximate groundwater level variation	Seasonal groundwater levels (up to 4.2m), largely dry over summer months
Regional faults	Shab Hill fault at approximately Ch 1+925
Surface water bodies	Pond 50m northwest of Air Balloon roundabout
Springs	A collection of limestone springs (springs 16, 17, 18 and 19) occur near the base of the Inferior Oolite limestone where the Shab Hill Barn fault cross cuts the escarpment. These limestone springs are seasonal and based on the groundwater levels recorded locally will have a flashy response to storm events. A modified spring, S01 lies on the northern side of the Existing A417 as part of a drainage trench that cuts into the Bridport Sand Formation. This cut and the modified spring will locally manage groundwater by lowering the water table to the base of the trench.
Recharge	Rainfall

8.4 Ch 2+800 to Ch 3+500, Shab Hill junction

8.4.1 A summary of the conceptual groundwater model elements within Ch 2+800 and Ch 3+500 is presented in Table 3-23. Representative cross sections have been developed for the following chainage are presented in Section F-F’ and Section G-G’ of ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3). The locations of the cross sections are shown on ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3).

Table 8.5 Ch 2+800 to Ch 3+500 Shab Hill junction conceptual model elements

Model element	Description
Surface topography	Low gradient slopes between 272mAOD and 280mAOD. A dry valley starts on the western side of the proposed Shab Hill junction and extends and incises to the east, toward the River Churn.

Model element	Description
WFD groundwater catchment	Burford Jurassic
Main groundwater bodies	Superficial: head deposits. Bedrock: Great Oolite limestones over Fuller's Earth Formation, underlain by Inferior Oolite limestone.
Groundwater flow direction	Regional: South east Locally: draining towards faults and over Fuller's Earth Formation
Approximate groundwater level at scheme	269mAOD at western side of junction and 215.9mAOD in dry valley, within Great Oolite limestone 200mAOD within underlying Inferior Oolite limestone.
Approximate maximum groundwater level	Up to 269.4mAOD in Great Oolite limestone 222mAOD within underlying Inferior Oolite limestone
Approximate groundwater level variation	Deep unsaturated zones in both the Great Oolite Group limestone and the Inferior Oolite Group limestone.
Regional faults	Shab Hill fault at approximately Ch 3+000 Churn Valley fault at Ch 3+200 Shab Hill Barn fault at approximately CH3+450
Surface water bodies	Unnamed tributary to River Churn lies to the east of Shab Hill junction
Springs	Springs/seepages occur east of Shab Hill junction at the base of the Great Oolite Group limestone formations where the underlying Fuller's Earth Formation forms a barrier to flow and perches groundwater.
Recharge	Great Oolite Group limestone formations are directly recharged by rainfall. Recharge to the underlying Inferior Oolite limestone is prevented by Fuller's Earth Formation cap but may be locally recharged where faulting permits.

8.5 Ch 3+500 to Ch 5+760, Shab Hill junction to Cowley junction

8.5.1 A summary of the conceptual groundwater model elements within Ch 3+500 and Ch 5+760 is presented in Table 3-24. Representative cross sections have been developed for the following chainage are presented in Section H-H' and Section I-I' of ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3). The locations of the cross sections are shown on ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3).

Table 8.6 CH3+500 to CH5+760 conceptual model elements

Model element	Description
Surface topography	The scheme roughly follows the ridgeline of rolling, low gradient hills between approximately 260mAOD and 282mAOD. Incised valleys associated with water courses are located to the east and west of the scheme.
WFD groundwater catchment	The scheme runs approximately along the groundwater divide. East of the scheme: generally, Burford Jurassic West of the scheme: generally, Severn Vale – Jurassic limestone Cotswold edge north
Main groundwater bodies	Superficial: no aquifer Bedrock: Great Oolite Group over Fuller's Earth Formation, underlain by Inferior Oolite Group. Great Oolite Group is dominantly mudstone with minor limestone units.

Model element	Description
Groundwater flow direction	Regional: West within Severn Vale catchment and East within the Burford Jurassic catchment
Approximate groundwater level at scheme	From Ch 3+600 to Ch 5+000, decreasing from 279.5mAOD to 267.3mAOD in Great Oolite Group. 200mAOD in underlying Inferior Oolite Group, with deep unsaturated zone
Approximate maximum groundwater level	From Ch 3+600 to Ch 4+500, decreasing from 284.5mAOD to 273.1mAOD in Great Oolite limestone 207.7mAOD in underlying Inferior Oolite limestone
Approximate groundwater level variation	Seasonal groundwater levels, responsive to rainfall, with 2.6 to 7.4m variation in Great Oolite Group Seasonal groundwater levels (up to 2.8m), largely dry during summer months in underlying Inferior Oolite Group
Regional faults	Shab Hill Barn fault at approximately Ch 3+450 Cally Hill fault at approximately Ch 4+000 Stockwell Farm fault at approximately Ch 4+800
Surface water bodies	Unnamed tributaries to the River Frome are located on the western side of the scheme and flow towards the south. Tributaries of the River Churn are located on the eastern side of the scheme and flow towards the east
Springs	Springs/seepages occur in thin superficial deposit, which overlies the Great Oolite Group. The springs are seasonal, with multiple small springs west of Cowley junction. These comprise of: • West springs/seepages on the western side of the unnamed tributary to the River Frome, which include tufa springs at Bushley Muzzard SSSI. • East springs/seepages on the eastern side of the unnamed tributary to the River Frome
Recharge	Great Oolite limestone is recharged by rainfall. Inferior Oolite limestone is indirectly recharged by leakage from overlying superficial deposits and Great Oolite Group, fault flow paths and interflow from where the aquifer is at ground surface and directly recharged.
Groundwater dependent terrestrial ecosystems	Bushley Muzzard is located on the western side of the unnamed tributary of the River Frome, which lies west of the scheme southern end.
Source protection zone	Source protection zone 3 for the Baunton abstraction is located on the eastern side of the scheme and intersects the mainline between Ch 4+400 and Ch 5+000. The Baunton abstraction is taking water from the Inferior Oolite Group, which is hydraulically disconnected from the scheme in this area.

8.6 Hydraulic parameters

8.6.1 The proposed hydraulic parameters are based on a combination of field tests and published data is presented in Table 8.7. Notably for the limestone aquifers, particularly the Inferior Oolite Group, the saturated zone is very thin (and locally absent), hydraulic testing is limited. Additionally, the K range presented in Table 8.7 for the Inferior Oolite Group are representative for fracture flow. Where there is the potential for karst conduit, this has been accounted for in the impact assessment.

Table 8.7 Proposed hydraulic parameters

Unit	Description	K, minimum (m/s)	K, maximum (m/s)
Engineered fill	Granular, gravelly sand	$5.0x10^{-5}$	$5.0x10^{-4}$
Alluvium	Clay, sandy clay	$1.0x10^{-8}$	$1.0x10^{-6}$
Mass movement and head deposits	Clay, sand/gravel lenses	$1.0x10^{-8}$	$1.0x10^{-4}$
Cheltenham Sand and Gravel	Sand and gravel	$1.0x10^{-4}$	$1.0x10^{-2}$
Great Oolite Group	Fractured limestone	$2.0x10^{-6}$	$2.0x10^{-4}$
	Fractured mudstone	$2.0x10^{-8}$	$2.0x10^{-7}$
Inferior Oolite Group	Fractured limestone	$1.0x10^{-6}$	$1.0x10^{-4}$
	Massive limestone	$3.0x10^{-11}$	$3.0x10^{-9}$
Lias Group	Bridport Sand Formation	$1.0x10^{-7}$	$1.0x10^{-5}$
	Mudstone	$1.0x10^{-11}$	$1.0x10^{-7}$

9 Groundwater related features

9.1 Groundwater aquifers

9.1.1 The main aquifers likely to be impacted by the scheme include the superficial deposit Secondary A aquifers, and the Great Oolite and Inferior Oolite Principal aquifers.

9.2 Abstractions

9.2.1 The SPZ3 associated with the Baunton abstraction, abstracting water from the Inferior Oolite aquifer, intersects part of the scheme near Stockwell. The proposed works in these areas are primarily within the Great Oolite aquifer. Where there are works proposed within SPZ3 and within the mapped area of the Inferior Oolite aquifer, the proposed works comprise above ground elements.

9.2.2 Due to the Fuller’s Earth aquitard separating the Great Oolite limestone aquifer and the Inferior Oolite aquifer, it is unlikely that changes in groundwater flow and levels from the proposed cuttings in this area will have a significant impact upon the abstraction. Additionally, the impact of above ground elements within the SPZ3 and underlain by the mapped area of Inferior Oolite aquifer are likely to be negligible.

9.2.3 Two unlicensed abstractions identified during the water feature survey are used for drinking water supply. The first unlicensed abstraction is a piped spring for shared between a private dwelling and Crickley Hill Tractors both at Grove Farm, which is likely to be sourced from the Inferior Oolite Group. The second unlicensed abstraction is a spring at Bushley Muzzard SSSI to supply Watercombe Farm, which is likely to be sourced from the Great Oolite Group.

9.3 Environmentally sensitive sites

9.3.1 Two SSSI are located near the scheme: the Crickley Hill and Barrow Wake SSSI and Bushley Muzzard SSSI. These are represented on ES Figure 13.5 Hydrogeological study area and features (Document Reference 6.3).

9.3.2 The Crickley Hill and Barrow Wake SSSI is designated for its calcareous grassland, broadleaved woodland and nationally important rock exposures[44]. Based on nearby groundwater monitoring data there is deep unsaturated zone below the SSSI. The ecological surveys completed for the scheme did not identify the presence of groundwater dependent habitats. [45][46]

9.3.3 Bushley Muzzard SSSI is species-rich wet grassland supplied by localised springs and seepages[47]. It has been identified as supporting a groundwater dependent habitat. The SSSI is located on the western side of the valley forming the River Frome headwaters. Underlying the SSSI is the Great Oolite Group and Fuller's Earth Formation, where groundwater levels within the Great Oolite Group aquifer are seasonal and directly recharged by rainfall. Springs are present at the geological contact, which contribute to the marshland conditions of the SSSI. These springs support fen-meadow (M22) vegetation, which may be sensitive changes in local groundwater condition[48]. The spring catchments are on the opposite side of the valley to the scheme, which is located on the eastern side of the valley.

9.4 Surface water bodies

9.4.1 The Cotswold escarpment forms a surface water divide between the River Severn catchment and the River Thames catchment (to the east and south-east of the divide). To the west of the divide, the land within the scheme drains to the River Severn and its tributaries, including Norman's Brook, Horsbere Brook and the River Frome (ES Figure 13.5 Hydrogeological study area and features (Document Reference 6.3)). To the east and south-east, the land within the scheme drains to the River Churn, a tributary of the Thames.

9.4.2 Several watercourses in the study area, such as Norman's Brook, are fed by springs. Some of these streams have losing and gaining reaches meaning that stream flow can be seasonal. As a result, these surface water courses are dependent on groundwater and sensitive to changes in groundwater levels and flows.

9.5 Springs

9.5.1 Groundwater springs are ubiquitous within the Cotswolds escarpment region (ES Figure 13.5 Hydrogeological study area and features (Document Reference 6.3)). Springs in the study area feed the tributary of Norman's Brook headwaters, an unnamed tributary of the River Frome and an unnamed tributary of the River Churn. These springs are associated with either superficial deposits or limestone formations of the Inferior Oolite Group and the Great Oolite Group. Springs recorded in the study area are presented on ES Figure 13.9 Groundwater monitoring locations (Document Reference 6.3).

9.5.2 Many of the springs (both superficial and limestone) are seasonal features that dry out in response to lower groundwater levels within the respective source aquifer or are linked to storm events.

9.5.3 Mapped limestone springs in the region correlate to bedrock formations and boundaries or structural features including:

- The Great Oolite limestones and the Fuller's Earth Formation
- The Inferior Oolite Group (in spatially limited connection with Bridport Sand) and Lias Group mudstone

- Shab Hill Barn fault
- Cally Hill fault

9.5.4 Limestone springs 16, 17, 18 and 19 at Crickley Hill form the headwaters to the tributary of Norman's Brook and are located at the base of the Inferior Oolite Group/top of Bridport Sand Formation, which is locally overlain by thin mass movement deposits. The groundwater levels in the area (borehole DS/RC301) generally have a flashy response, which is a reflection of them being rapid pathway in the aquifer from storm events providing rapid recharge and through put followed by quick draining and returning to low or even dry conditions. The limestone springs close to the edge of the escarpment, are often linked to fissures, faults or gull features.

9.5.5 Spring and seepages emerging from superficial deposits, such as those that feed Norman's Brook at a lower elevation than limestone springs 16, 17, 18 and 19, include a combination of seasonal and perennial springs. In the case of the superficial springs that feed Norman's Brook these are fed from permeable units within the cohesive dominated mass movement deposits. Whereas the cohesive deposits are derived from failure and weathering of the Lias Group the permeable units derive from topple failures and weathering of the Inferior Oolite Group. As such the permeable units are a source for $CaCO_3$, which will harden the recharge waters and result in springs with relatively high $CaCO_3$ concentrations. Where the emergent conditions are suitable tufa may precipitate, which is presented in more detail in Section 9.6 below.

9.5.6 Springs that feed the unnamed tributary to the Frome and unnamed tributary to the River Churn are both those derived from limestone bedrock and superficial deposits. Springs are characterised as being from superficial deposits where the drift is considered think enough. Otherwise these are characterised as limestone springs emerging from a thin veneer of drift.

9.5.7 The seasonality of springs is determined from the record of water features survey and interpretation of site photographs/aerial photographs.

9.6 Superficial carbonate precipitates

9.6.1 Superficial carbonate precipitates are terrestrial deposits[49] which form a variety of environments and are commonly found in areas with limestone bedrock. Common names for terrestrial carbonate deposits, 'tufa' and 'travertine', are often used interchangeably within karst literature. The naming convention adopted by Ford & Williams (2007) has been applied to this assessment where:

- Tufa refers to grainy deposits accreting to algal filaments, plant stem and roots at springs, along riverbanks, lake edges, etc[50].

9.6.2 Based on the definition of tufa in Ford & Williams (2007), the sites identified in the Water Feature Survey are considered potential tufa formations until additional geomorphology and ecology surveys can be completed.

9.6.3 Carbonate deposits typically forms due to the precipitation of calcium carbonate, when carbon dioxide degasses from supersaturated carbonate waters:

$$\boldsymbol{Ca^{2+} + 2HCO^{3-} \Leftrightarrow CaCO_3 + CO_2 + H_2O}$$

9.6.4 Several factors can influence the rate of carbon dioxide degassing and accretion of calcite precipitate, which includes but is not limited to temperature change and groundwater flow rates. Microbial activity can also increase the reaction rate and promote the formation of precipitate.

9.6.5 The classification of these deposits is based on three main criteria: geochemical – precipitation processes and carbon dioxide geochemistry; fabric; and morphology[51]. Tufa formations are of importance due to the potential of protected flora growing at the formation location.

9.6.6 The identified tufa deposits have been surveyed by a specialist ecologist with respect to tufa habitats. The report is presented in ES Appendix 8.24 Assessment of tufaceous vegetation (Document Reference 6.4).

9.6.7 The tufa deposits identified in the Biodiversity Chapter include those identified along the tributary of Norman's Brook during the Water Feature Survey (ES Figure 13.5 Hydrogeological study area and features (Document Reference 6.3) and ES Appendix 13.11 Water feature survey). Based on the geological setting it is anticipated that tufa is precipitating from groundwater seeping from mass movement deposits, which includes limestone parent material. The high permeability units of the mass movement deposits allow significant contact of groundwater with the limestone rock fragments, which allows the groundwater to become hard relatively quickly. Recharge, such as rainfall precipitation, which is slightly acidic and can dissolve calcium carbonate and other ions is often referred to as 'attacking'[52].

9.7 Dry valleys

9.7.1 Dry valleys in limestone terrains are glaciofluvial karst features. Such valleys originally formed by periglacial streams that incised into the limestone bedrock, often creating steep sided gorges and ravines. Subsequently, the streams drained elsewhere, often being lost to ground as losing streams[53]. Dry valleys are relic topographical features, but seasonal streams may flow episodically[54,55].

9.7.2 Two dry valleys are recorded in the water feature survey, one at Shab Hill junction (G183 and G184) and one at Barrow Wake dry valley (G3) where the revised position of the Shab Hill Barn fault is located (ES Figure 13.5 Hydrogeological study area and features (Document Reference 6.3).

9.7.3 At Shab Hill the head of dry valley begins approximately 240m south west of Shab Hill junction. This stretch of the valley is approximately 60m wide and up to 12m deep and a seepage (G146) has been mapped on the left-hand valley side. From Shab Hill junction the dry valley runs in an east-south-east direction where the valley sides gradually become less steep and the valley becomes wider towards the tributary of the River Churn. Two seepages and one groundwater spring (G180, G145 and G181 respectively) have been mapped on the northern valley side of the valley in this section.

9.7.4 There is a dry valley mapped at Barrow Wake (G3), which extends to the north west from the crest of the escarpment towards Crickley Hill Tractors. The dry valley is approximately 150m in length and approximately 150m wide. The dry valley coincides with the revised position of the Shab Hill Barn fault with a cluster of springs at the base of the dry valley (springs 16, 17, 18 and 19), which form the headwaters to the tributary of Norman's Brook. The dry valley is likely to have been guided in its development due to the Shab Hill Barn fault and the resultant valley has formed due to a combination of these geomorphological features. During the Water Features Survey, flow gauging in the upper reach of Norman's

Brook identified that the spring fed watercourse had flows during April 2018 and March 2019 but dry in July 2018 and February 2019.

10 Potential impacts to groundwater features

10.1 Overview

10.1.1 This section assesses potential impacts to groundwater features from interaction with design elements of the scheme. The HIA focuses cuttings, ground stabilisation measures and embankments for both flow and drawdown impacts. The methodology of the assessment is provided below and is followed by a detailed assessment for each design element.

10.2 Methodology

Flow impacts

10.2.1 Groundwater flow impacts have been assessed qualitatively, particularly with cuttings, ground stabilisation and embankments. The cutting depth have been considered relative to the highest groundwater levels recorded or where conceptually the structure is likely to intercept groundwater. The horizontal extent of structures including pile spacing has been considered in the context of the aquifer extent and nearby groundwater features.

Drawdown impacts

10.2.2 Quantitative dewatering calculations have been completed for below ground works likely to intercept groundwater to determine the magnitude of drawdown effects and predict flow rates either during construction or operational phases of the scheme. Drawdown levels are based on the maximum measured groundwater level for the period of monitoring up to October 2020. The winter of 2019 and 2020 is reported by the Met office to be the 5th wettest on record, with February 2020 being the wettest February on record, with up to three times the expected average. On this basis the winter of 2019/20 includes one of the wettest winters on record and groundwater responses are expected to include high peak winter events.

10.2.3 Initially the design elements were qualitatively assessed using maximum groundwater monitoring levels and conceptual models to determine if the excavation is likely to encounter groundwater. The qualitative assessment compared the lowest relevant element level and the highest groundwater level, both in mAOD. If the groundwater level is below the lowest design element level, it is assumed that dewatering is not required and therefore a quantitative assessment has not been completed.

10.2.4 Potential drawdowns in bulk permeability are assessed using the Sichardt equation. However, for each cutting in limestone there is a further assessment for the situation that karst is encountered.

10.2.5 The Sichardt equation assumes the aquifer is unconfined, infinite horizontal extent, constant thickness, homogenous and isotropic with respect to hydrogeological parameters.

$$R_0 = C(H - h)\sqrt{K}$$

Where:

R_0 = Radius of influence (m)

C = Empirical correlation factor (taken as 2000 as design elements are linear)

H = Piezometric level in the aquifer (mAOD) i.e. maximum groundwater level anticipated

h = Target drawdown level (mAOD) i.e. 1m below the cutting, or lowest design element level

K = Hydraulic conductivity (m/s)

10.2.6 The inflow rates have been calculated using the Mansur & Kaufman[56] formulae for one-sided and two-sided trenches depending on the cut geometry and groundwater flow direction. A one-sided trench analysis has been completed where only one side of the road is in cut or where substantial flows are not anticipated into one side of the cut, for example, where one side of the cut is close to a hydraulic boundary such as the Fuller's Earth Formation. Otherwise a two-sided trench analysis has been completed.

$$Q = 0.73 + 0.27\frac{(H - h_w)}{H}\frac{(K - L)}{2R_0}(H^2 - {h_w}^2)$$ One-sided trench inflow

$$Q = 0.73 + 0.27\frac{(H - h_w)}{H}\frac{(K - L)}{R_0}(H^2 - {h_w}^2)$$ Two-sided trench inflow

Where:

Q = Flow rate (m^3/day)

h_w = Height of drawdown level above the base of the aquifer

L = Length of the element (m) i.e. cutting length like to intersect groundwater

10.2.7 The equations above represent steady-state conditions and are likely to represent the groundwater conditions to a point where the groundwater level stabilises due to passive dewatering at the cutting location.

10.2.8 A conservative approach has been taken to the drawdown assessment where the drawdown has been calculated using a combination of:

- Maximum cutting height within the aquifer.
- Maximum groundwater elevation.
- Drawdown required is to 1m below the finished road level or the base of the aquifer, whichever is higher.
- The highest bulk hydraulic conductivity value for the strata or where formations are horizontally interbedded the effective horizontal hydraulic conductivity (determined by the weighted arithmetic mean).

10.3 Detailed assessment

10.3.1 Detailed assessments have been undertaken to assess the potential quantitative impacts from proposed cuttings in accordance with the methodology presented in Section 10.2.

10.3.2 Conservative hydraulic conductivity values to provide a conservative estimate of the drawdown radius of influence (reference Table 8.7). The radius of influence represents a 'reasonable worst-case' and is based on conservative inputs derived from available field or desk study data and published research literature relevant to the study area

10.3.3 Cuttings are assumed to be open and passive drainage is installed 1m below the finished road level at the toe of the cutting.

Ground stabilisation measures

10.3.4 ES Chapter 2 The project (Document Reference 6.2) describes the ground stabilisation measures considered to be required to manage the risk of slope movement and instability. The proposed slope drainage would comprise shallow inclined perforated drainage pipes which would be installed by drilling into the slope from the highway verge, with any groundwater flows channelled into drainage.

10.3.5 Refer to ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3) for the general arrangement at the location and sections C-C' and D-D' in ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3) for the hydrogeological conceptualisation.

10.3.6 As the shallow inclined perforated drains would be installed into cohesive dominated superficial deposits, the induced drawdown is likely to be localised and limited in extent to the zone of the horizontal drains. However, those drains that intercept sand and gravel or areas where toppled limestone blocks are present would drain groundwater from these isolated pockets. Two springs are identified in the water features survey in the area of the land drains, these are G206 and 83.

10.3.7 All intercepted groundwater would be carried from the horizontal drains to a surface water discharge point, within the same receiving water that the groundwater would naturally have discharged to (see ES Appendix 13.10 Drainage (both Document Reference 6.4) respectively). Dewatering and discharge arrangements would need to be made with the EA prior to construction.

Embankments

10.3.8 Where the placement of embankments is over or adjacent to spring/seepage locations there is potential that the drainage measure to carry the flows to receiving waters may change the characteristics of the groundwater emergence. This is particularly relevant for tufa springs where tufa deposition is related to the physio-chemical properties of the groundwater at the point of emergence. However, it is noted that although the characteristics of the spring will be modified, the characteristics of recharge and storage of groundwater as flows through the superficial deposits will not be modified by the embankments and on this basis the impact will be to spring characteristics such as hydraulic gradient, width and depth rather than water quality and overall flow rate.

10.3.9 The list of springs and seepage locations that have the potential to be impacted by embankment placement are presented in Table 10.1.

Table 10.1 Summary of potential impacts to springs

Feature type	Quantity	Feature ID	Potential Impact
CH 0+900 to CH1+500 – Crickley Hill			
Seepage from superficial deposits contributing to the tributary of Norman's Brook	3	80, G20, G151	Embankment placement over spring
Modified spring from superficial deposits contributing to the tributary of Norman's Brook	2	61, G17	Embankment placement over spring
Tufa spring from superficial deposits contributing to the tributary of Norman's Brook	3	69, 81, G231	Embankment placement over spring
Perennial spring from superficial deposits contributing to the tributary of Norman's Brook	3	78, 72, G2	Embankment placement over spring
Seasonal spring from superficial deposits contributing to Norman's Brook	1	G152	Embankment placement over spring
CH3+100 – Shab Hill junction			
Seepage from superficial deposits overlying the Great Oolite Group that feed headwater of unnamed tributary of the River Churn	1	G146	Embankment placement over spring
CH4+000 – Cuttings between Shab Hill junction and Cowley junction			
Seepage from superficial deposits feeding headwater unnamed tributary of the River Churn (East)	1	G174	Embankment placement over spring

Cutting from Ch 1+700 to Ch 2+800

10.3.10 Refer to ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3) for the general arrangement at the location and sections C-C' and D-D' in ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3) for the hydrogeological conceptualisations. The cutting will be excavated into the Inferior Oolite Group. Springs 16,17, 18 and 19) are located 100m south of and 10m lower than the cutting.

10.3.11 Based on the groundwater level data available, the maximum winter groundwater level would not intercept the cut face but may rise above the drainage trench invert level at the most western end of the cutting only. Drawdown from the road drainage trench invert is within the Inferior Oolite Group and is limited to the west by the Lias Group geological boundary. In the case that karst conduits are intercepted by the drainage trench then these have the potential to intersect peak groundwater table during the winter high and in these cases this water would be intercepted by the drainage system. Due to the potential high connectivity of karst pathways in the Inferior Oolite Group if karst was encountered then this has the potential of lowering the seasonal peak groundwater table and spring flows but will not impact on groundwater levels and spring flows at any other time of the year.

10.3.12 In the non-karst scenario, based on a maximum hydraulic conductivity of $2x10^{-4}$ m/s and using the recorded winter peak groundwater levels, the maximum radius of influence calculated from the cutting is 32 m, which will not impact on springs 16, 17, 18 and 19. This is based on a conservative vertical drawdown of 1.2 m in the cutting. The drawdown from the cutting are shown in ES Figure 13.16 Groundwater impact assessment (Document Reference 6.3).

10.3.13 The baseline assessment identifies that groundwater intersected by the drainage trench is part of the Severn Vale groundwater catchment that drains westward supporting base flow in the tributary of Norman’s Brook. Groundwater captured within the drainage trench will be carried downstream of the cutting and will feed back into the realigned tributary of Norman’s Brook. There would be no net loss of groundwater to the tributary of Norman’s Brook as groundwater intercepted by the cutting would be routed back to it.

10.3.14 Dewatering and discharge arrangements would need to be made with the EA prior to construction.

10.3.15 A summary of the non-karst detailed assessment is presented in Table 10.2.

Table 10.2 Cutting from Ch 1+700 to Ch 2+800 detailed assessment summary

Section chainage	1+700
Ground conditions	Inferior Oolite limestone
Drawdown required (m)	5
Hydraulic conductivity (m/s)	$2x10^{-4}$
Radius of influence (m)	32
Design element length within water bearing unit (m)	50
Maximum inflow (m^3/day)	127

B4070 link road cutting

10.3.16 Refer to ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3) for the general arrangement at the location and section G-G’ in ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3) for the hydrogeological conceptualisation. The cutting has a maximum depth of 7 mbgl and cuts through the base of the Great Oolite Group and into the underlying Fuller’s Earth Formation. The Fuller’s Earth Formation is a hydraulic barrier to groundwater flow and the extent of drawdown would be slight where the cutting intersects this formation. However, drawdown would occur where the cutting intersects the Great Oolite Group limestone formations. East of the B4070 link road cutting lies the Shab Hill dry valley feature, which during peak winter storm events has been noted to develop flow.

10.3.17 The cutting is located along the ridgeline of the Cotswold plateau and within the headwater of the catchment. Based on the groundwater level data available, the maximum winter groundwater level would not intercept the cut face but may rise into the drainage trench invert level. In the case that karst conduits are intercepted by the drainage trench then these have the potential to intersect peak groundwater table during the winter high and in these cases this water would be intercepted by the drainage system. Due to the potential high connectivity of karst pathways in the Great Oolite Group at Shab Hill, if karst was encountered then this has the potential of lowering the seasonal peak groundwater table and potentially reducing emergent groundwater flows in the dry valley (spring G146) but will not impact on groundwater levels nor groundwater emergences at any other time of the year.

10.3.18 In the non-karst scenario, the estimated radius of influence encroaches onto the Shab Hill dry valley feature. On this basis there is a potential for a seasonal impact to groundwater emergences in the dry valley (spring G146) from the cutting due to a small reduction in the catchment size.

10.3.19 Based on a maximum hydraulic conductivity of $2x10^{-4}$m/s and the winter peak groundwater levels, the maximum radius of influence calculated from the cutting is 18m. The calculated radius of influence is shown in ES Figure 13.16 Groundwater impact assessment (Document Reference 6.3).

10.3.20 All intercepted groundwater would be carried from the cutting to a surface water discharge point, within the same receiving water that the groundwater would naturally have discharged to (see ES Appendix 13.10 Drainage (both Document Reference 6.4)). Dewatering and discharge arrangements would need to be made with the EA prior to construction.

10.3.21 A summary of the detailed assessment is presented in Table 10.3.

Table 10.3 B4070 link road cutting detailed assessment summary

Section chainage	3+040
Ground conditions	Great Oolite limestone Fuller's Earth Formation
Drawdown required (m)	0.65
Hydraulic conductivity (m/s)	$2x10^{-4}$
Radius of influence (m)	18
Design element length within water bearing unit (m)	100
Maximum inflow (m^3/day)	542

Shab Hill junction to Cowley junction cuttings

10.3.22 Refer to ES Figure 13.17 Groundwater conceptual model locations (Document Reference 6.3) for the general arrangement at the location and sections H-H' and I-I' in ES Figure 13.10 Groundwater conceptual model (Document Reference 6.3) for the hydrogeological conceptualisations. The cuttings are in the Great Oolite Group and Fuller's Earth Formation.

10.3.23 The cuttings are located along the ridgeline of the Cotswold plateau and within the headwater of the catchment. The recorded seasonal fluctuation of the groundwater table indicates that the cutting would be dry in the summer, however will intercept the winter groundwater table. The drawdown from the cutting is within the transition of Great Oolite Group limestones in the Fuller's Earth Formation. The ground conditions comprise interbedded mudstone with limestone units, where the mudstone layers become thicker with depth.

10.3.24 Based on the geological assessment that the transition lithology in this section of the scheme is mudstone dominant with minor limestone the risk of karst is significantly reduced and on that basis the drawdown calculation are assessed for the non-karst scenario only.

10.3.25 Based on a maximum hydraulic conductivity of $4.3x10^{-5}$ m/s and the peak winter groundwater levels, the maximum lateral radius of influence calculated from the deepest cutting is 81 m. The calculated radius of influence is shown in ES Figure 13.16 Groundwater impact assessment (Document Reference 6.3).

10.3.26 The calculated radius of influence for the cuttings does not extend as far as any groundwater features but has the potential to reduce the catchment area of spring on the Eastern side of the unnamed tributary to the River Frome. Those springs that lie on the western side of the unnamed tributary to the River Frome, which include Bushley Muzzard SSSI lies in a separate groundwater subcatchment that is isolated from the scheme by the valley of the tributary.

10.3.27 All intercepted groundwater will be carried from the cutting to a surface water discharge point, within the same receiving water that the groundwater would naturally have discharged to (see ES Appendix 13.10 Drainage (Document Reference 6.4)). Dewatering and discharge arrangements would need to be made with the EA prior to construction.

10.3.28 A summary of the detailed assessment is presented in Table 10.4.

Table 10.4 Shab Hill junction to Cowley junction cuttings detailed assessment summary

Section chainage	3+740	4+200	5+000
Ground conditions	Great Oolite Group interbedded mudstones and limestones Fuller's Earth Formation		
Drawdown required (m)	6.2	8.6	1.4
Hydraulic conductivity (m/s)	$1.2x10^{-4}$	$8.4x10^{-5}$	$7.4x10^{-5}$
Radius of influence (m)	81	40	26
Design element length within water bearing unit (m)	210	360	560
Maximum inflow (m^3/day)	310	1340	780

Cowley junction east cutting

10.3.29 The cutting is in the transition of the Great Oolite Group limestone formations and Fuller Earth Formation. The Fuller's Earth Formation is a hydraulic barrier to groundwater flow and limits the extent of drawdown. However, drawdown would occur where groundwater levels within Great Oolite Group are intercepted. As with the previous section, the Great Oolite Group formations at this location are dominantly mudstone with minor limestone units.

10.3.30 The cutting is located along the ridgeline of the Cotswold plateau and within the catchment headwaters. The recorded seasonal fluctuation of the groundwater table indicates that the cutting would be dry in the summer, however, would likely intercept the winter groundwater table. The drawdown from the cutting is within the basal unit of the Great Oolite Group, which comprises limestones interbeds transitioning into Fuller's Earth Formation with minor limestone units.

10.3.31 Based on the geological assessment that the transition lithology in this section of the proposed road development is mudstone dominant with minor limestone the risk of karst is significantly reduced and on that basis the drawdown calculation are assessed for the non-karst scenario only.

10.3.32 Based on a maximum hydraulic conductivity of $7.4x10^{-5}$ m/s and peak winter groundwater levels, the maximum lateral radius of influence is 16m, which is calculated from the deepest part of the cutting. The calculated radius of influence for the cuttings does not intercept and groundwater dependent features but has potential to reduce the winter flows in springs on the western margin of the outlier due to slight reduction in catchment extent. The calculated radius of influence is shown in ES Figure 13.16 Groundwater impact assessment (Document Reference 6.3).

10.3.33 All intercepted groundwater would be carried from the cutting to a surface water discharge point, within the same receiving water that the groundwater would naturally have discharged to (see ES Appendix 13.10 Drainage (both Document Reference 6.4). Dewatering and discharge arrangements would need to be made with the EA prior to construction.

10.3.34 A summary of the detailed assessment is presented in Table 10.5.

Table 10.5 Cowley junction east cutting detailed assessment summary

Section chainage	0+00
Ground conditions	Great Oolite interbedded mudstones and limestones Fuller's Earth Formation
Drawdown required (m)	0.9
Hydraulic conductivity (m/s)	$7.4x10^{-5}$
Radius of influence (m)	16
Design element length within water bearing unit (m)	120
Maximum inflow (m^3/day)	225

10.4 Summary of impacts

10.4.1 The detailed assessment of design elements of the proposed road development is assessed in Section 10.3. These are summarised as localised drawdown impacts related to drainage measures and cuttings in bedrock that intersect the groundwater table with potential impacts to springs/seepages and impacts from embankment placement over springs. Both types of impacts are summarised in Table 10.6.

Table 10.6 Summary of potential impacts to springs

Feature type	Quantity	Feature ID	Potential Impact
Ch 0+900 to Ch 1+500 – Crickley Hill			
Seepage from superficial deposits contributing to the tributary of Norman's Brook	3	80, G20, G151	Embankment placement over spring
Modified spring from superficial deposits contributing to the tributary of Norman's Brook	2	61, G17	Embankment placement over spring
Tufa spring from superficial deposits contributing to the tributary of Norman's Brook	3	69, 81, G231	Embankment placement over spring
Perennial spring from superficial deposits contributing to the tributary of Norman's Brook	3	78, 72, G2	Embankment placement over spring
Seasonal spring from superficial deposits contributing to Norman's Brook	1	G152	Embankment placement over spring

Feature type	Quantity	Feature ID	Potential Impact
Spring/seepage from superficial deposits contributing to Norman's Brook	2	G206 and 83	Drawdown from ground stabilisation
Ch 1+700 to Ch 3+000 cutting			
Seasonal limestone springs emerging from the Inferior Oolite Group/Bridport Sand Formation that feed the headwater of the tributary of Norman's Brook	4	16, 17, 18 and 19	Reduction in peak winter flow if cutting intersects karst in drainage invert
Ch 3+100 – Shab Hill junction			
Seepage from superficial deposits overlying the Great Oolite Group that feed headwater of unnamed tributary of the River Churn	1	G146	Embankment placement over spring and potential reduction in peak winter spring flow
Ch 4+000 – Cuttings between Shab Hill junction and Cowley junction			
Seepage from superficial deposits feeding headwater unnamed tributary of the River Churn (East)	1	G174	Embankment placement over spring
Seepage from superficial deposits feeding headwater unnamed tributary of the River Frome (East)	7	G150, G147, G173, G100, G221, G219 and G220	Reduction in peak winter spring/seepage flow

Combined effects

10.4.2 The potential impacts outlined above for cuttings occur within three aquifer types and within three subcatchments.

10.4.3 Those cutting impacts identified at CH1+700 to CH3+000 – cutting are specific to the Inferior Oolite Group which feeds headwaters to Norman's Brook.

10.4.4 Those cutting impacts identified at CH3+100 – Shab Hill junction are specific to the Great Oolite Group which feeds headwaters to an unnamed tributary of the River Churn.

10.4.5 Those cutting impacts identified at CH4+000 – Cuttings between Shab Hill junction and Cowley junction are specific to the Great Oolite Group which feeds headwaters to an unnamed tributary of the River Frome.

10.4.6 Based on the above, there is no cumulative impact between the three cuttings identified either to aquifer units or receiving surface waters.

10.4.7 The tributary of Norman's Brook has potential impacts from groundwater interception at CH1+700 to CH3+000 and interception of groundwater in superficial deposits from ground stabilisation measures. As the potential impacts are from separate aquifer units these will not have cumulative impacts on either groundwater body. Both design elements do however discharge to the tributary of Norman's Brook. As all groundwater will still be received by the natural receiving water there will be no net change in the total water quantities. Where groundwater interception occurs then the top of the groundwater table may be intercepted and seasonally decant into drainage inverts and cuttings. This has the potential to shorten the pathway from ground to stream, which may allow a component of groundwater to enter the tributary more rapidly.

11 Conclusions

11.1.1 The purpose of this HIA is to present the current information available to inform the baseline conditions of the site and assess how the scheme is likely to impact the groundwater regime with respect to levels, flow and quality. The assessment has focussed on groundwater features including: superficial aquifers, bedrock aquifers, groundwater abstractions, groundwater discharges, environmentally sensitive sites, surface watercourses, springs/seepages, terrestrial carbonate deposits (tufa) and karst dry valleys. Potential groundwater impacts from design elements of the scheme are summarised below.

11.1.2 Based on the detailed assessment, the proposed horizontal drains along Crickley Hill would cause localised lowering in the mass movement deposits. As the mass movement deposits are cohesive dominated, the drawdown extent would be limited to the immediate locale of the drains. However, in the case that high permeability zones, such as sand and gravel or zones of granular material associated with toppled limestone blocks, occur within the extent of drawdown then these would also be drained.

11.1.3 Based on the detailed assessment of the B4070 link road cutting, the drawdown extent has the potential to impact on groundwater levels below a dry valley. Based on this assessment during peak groundwater heads there is a potential that groundwater emergence in the floor of the dry valley would be reduced during the winter.

11.1.4 Cuttings along the scheme have the potential to intersect groundwater. The drawdown assessment has been undertaken using high permeability values and peak groundwater level conditions and as such as considered conservative. Based on the seasonal fluctuation of groundwater levels recorded along the scheme drawdowns are seasonal, occurring during the winter. Based on the monitoring data, summer groundwater levels will not be impacted but when groundwater levels rise to their highest groundwater levels during the winter then the top of the groundwater may be intercepted by drainage inverts and cuttings. The drainage design is managed so that all intercepted groundwater remains within the catchment of the respective receiving water.

Appendix A Standpipe installations

Table A.1 Summary of groundwater monitoring installations

Location	Ground investigation	Easting	Northing	Top of hole (mAOD)	Depth of hole (mbgl)	Response zone (mbgl)	Response zone (mAOD)
CP 102	Phase 2A	392080.9	215724.9	127.55	20.00	3.0 - 5.5	124.55 - 122.05
CP 104A	Phase 2A	392525.2	215641.5	148.00	16.76	14.7 - 15.8	133.3 - 132.2
CP 105	Phase 2A	392765	215682	169.90	30.00	3.0 - 9.5	166.9 - 160.4
CP 106	Phase 2A	392949	215756	186.25	35.50	19.0 – 30.0	167.25 - 156.25
CP 200	Phase 2A	392242.9	215743.3	129.70	14.50	8.5 - 12	121.2 - 117.7
CP 202	Phase 2A	392408.8	215671.5	135.70	20.00	3.7 - 5.7	132.0 – 130.0
CP 204 (d)	Phase 2A	392647.4	215541.1	178.90	25.00	12.5 - 13.9	166.4 – 165.0
CP 204 (s)	Phase 2A	392647.4	215541.1	178.90	25.00	8.5 - 9.9	170.4 – 169.0
CP 206	Phase 2A	392655	215664	162.85	19.70	10.0 – 16.0	152.85 - 146.85
CP 210 (d)	Phase 2A	392672.4	215777.0	174.30	25.00	13.0 – 17.0	161.3 - 157.3
CP 210 (s)	Phase 2A	392672.4	215777.0	174.30	25.00	2.5 - 5.5	171.8 - 168.8
CP 211	Phase 2A	392674.1	215809.4	183.45	35.00	1.1 - 3.3	182.35 - 180.15
CP 212 (d)	Phase 2A	392814	215558	191.60	24.50	18.5 - 24.5	173.1 - 167.1
CP 212 (s)	Phase 2A	392814	215558	191.60	24.50	8.0 - 13.9	183.6 - 177.7
CP 215 (d)	Phase 2A	392806.0	215804.5	186.05	25.00	14.5 - 15.5	171.55 - 170.55
CP 215 (s)	Phase 2A	392806.0	215804.5	186.05	25.00	2.0 – 3.0	184.05 - 183.05
CP 216	Phase 2A	392833	215701	173.50	25.60	2.0 – 7.0	171.5 - 166.5
CP 223	Phase 2A	392596	215474	179.75	25.50	19 - 22.6	160.75 - 157.15
DS/RC 109	Phase 2A	393208	215995.1	233.00	105.00	2.5 - 20	230.5 – 213.0
DS/RC 205	Phase 2A	392612.4	215766.3	167.15	30.00	9.5 - 11.7	157.65 - 155.45
DS/RC 218	Phase 2A	394126	214739	285.65	25.00	2.0 – 15.0	283.65 - 270.65
DS/RC 220	Phase 2A	394379	214500.9	278.85	31.30	3.0 – 13.0	275.85 - 265.85
DS/RC 229	Phase 2A	392895.9	215874.1	200.45	25.00	4.5 – 8.0	195.95 - 192.45
DS/RC 301	Phase 2A	393184.6	215961.8	234.20	105.05	7.4 - 28.5	226.8 - 205.7

Location	Ground investigation	Easting	Northing	Top of hole (mAOD)	Depth of hole (mbgl)	Response zone (mbgl)	Response zone (mAOD)
DS/RC 302	Phase 2A	393329	216018	234.50	35.20	15.0 – 26.0	219.5 - 208.5
DS/RC 310	Phase 2A	394101.2	215210.8	250.90	30.20	2.0 – 30.0	248.9 - 220.9
DS/RC 311	Phase 2A	394015.5	215259	255.20	40.00	11.5 – 40.0	243.7 - 215.2
DS/RC 312	Phase 2A	393779.7	215300.8	282.15	25.10	1.0 – 14.0	281.15 - 268.15
DS/RC 314	Phase 2A	393256	215193.1	293.10	15.00	2.0 – 15.0	291.1 - 278.1
DS/RC 315	Phase 2A	394194	215201.1	246.90	90.65	4.4 - 52.7	242.5 - 194.2
DS/RC 315A	Phase 2A	394194	215200	247.00	54.50	4.4 - 52.9	242.6 - 194.1
DS/RC 317	Phase 2A	394717.9	214126.8	274.90	30.00	1.0 - 3.8	273.9 - 271.1
DS/RC 319	Phase 2A	393406.8	216148.4	231.60	65.20	2.9 - 20	228.7 - 211.6
DS/RC 325	Phase 2A	393329.2	216103.9	233.25	40.60	3.8 - 25.1	229.45 - 208.15
DS/RC 401	Phase 2A	394825.4	213679.2	273.10	20.00	4.8 - 8.2	268.3 - 264.9
DS/RC 403	Phase 2A	394937.6	213164.4	247.65	20.00	4.0 - 20.6	243.65 - 227.05
DS/RC 404	Phase 1	393207	215566	269.00	100.50	23.0 - 33.5	246 - 235.5
DS/RC 406	Phase 1	393384	216009	238.65	60.00	20.5 - 34	218.15 - 204.65
DS/RC 408	Phase 1	393605	216240	232.50	75.20	20.0 - 23.5	212.5 - 209
DS/RC 415	Phase 1	393527	213994	287.20	51.00	25.5 – 49.0	261.7 - 238.2
DS/RC 418	Phase 2A	393131.8	216418.8	272.25	61.50	27.0 – 58.0	245.25 - 214.25
DS/RC 419	Phase 1	393213	215564	268.90	60.20	36.0 - 41.5	232.9 - 227.4
DS/RC 420	Phase 2A	393950	213950	277.10	30.00	0.8 - 3.2	276.3 - 273.9
DS/RC/OH 110	Phase 2A	393441	216054	240.00	60.20	23.0 – 34.5	217.0 – 205.5
DS/RC/OH 304	Phase 2A	393248.8	216080.1	231.85	60.20	26.1 - 53.7	205.75 - 178.15
DS/RC/OH 308	Phase 2A	393999.2	215766.9	271.35	70.40	1.5 - 58.5	269.85 - 212.85
DS/RC/OH 400	Phase 2A	394666.1	213848.1	267.95	90.30	13.3 - 76	254.65 - 191.95
DS/RC/OH 412	Phase 2A	394240.9	215146.1	250.30	30.00	13.2 - 29.5	237.1 - 220.8
DS/RC/OH 414	Phase 2A	393481.8	215560.7	274.60	90.00	28.3 - 59.3	246.3 - 215.3
DS/RC/OH 107	Phase 2A	393057	215838	191.90	30.20	2.0 - 5.5	189.9 - 186.4

Location	Ground investigation	Easting	Northing	Top of hole (mAOD)	Depth of hole (mbgl)	Response zone (mbgl)	Response zone (mAOD)
DS/RC 108	Phase 2A	393083	215863	193.60	49.50	8.0 – 16.0	185.6 - 177.6
DS/RC 224	Phase 2A	392857	215346	226.85	80.50	49.0 – 70.0	177.85 - 156.85
OH 405	Phase 1	393388	215997	239.50	40.00	11.0 – 17.0	228.5 - 222.5
OH 407	Phase 1	393596	216246	231.75	55.55	6.0 – 15.0	225.75 - 216.75
OH 411	Phase 2A	393819	215306	280.50	100.95	22 - 85.7	258.5 - 194.8
OH 413	Phase 2A	394312.1	214960.1	270.65	100.00	2.7 - 15.7	267.95 - 254.95
OH 416	Phase 1	393538	213990	286.85	5.00	3.0 - 4.5	283.85 - 282.35
OH 417	Phase 2A	394178	214888.9	275.65	90.00	5.5 - 70.9	270.15 - 204.75
OH 416	Phase 1	393538	213990	286.85	5.00	3.0 - 4.5	283.85 - 282.35
OH 417	Phase 2A	394178	214888.9	275.65	90.00	5.5 - 70.9	270.15 - 204.75

Appendix B Groundwater monitoring results

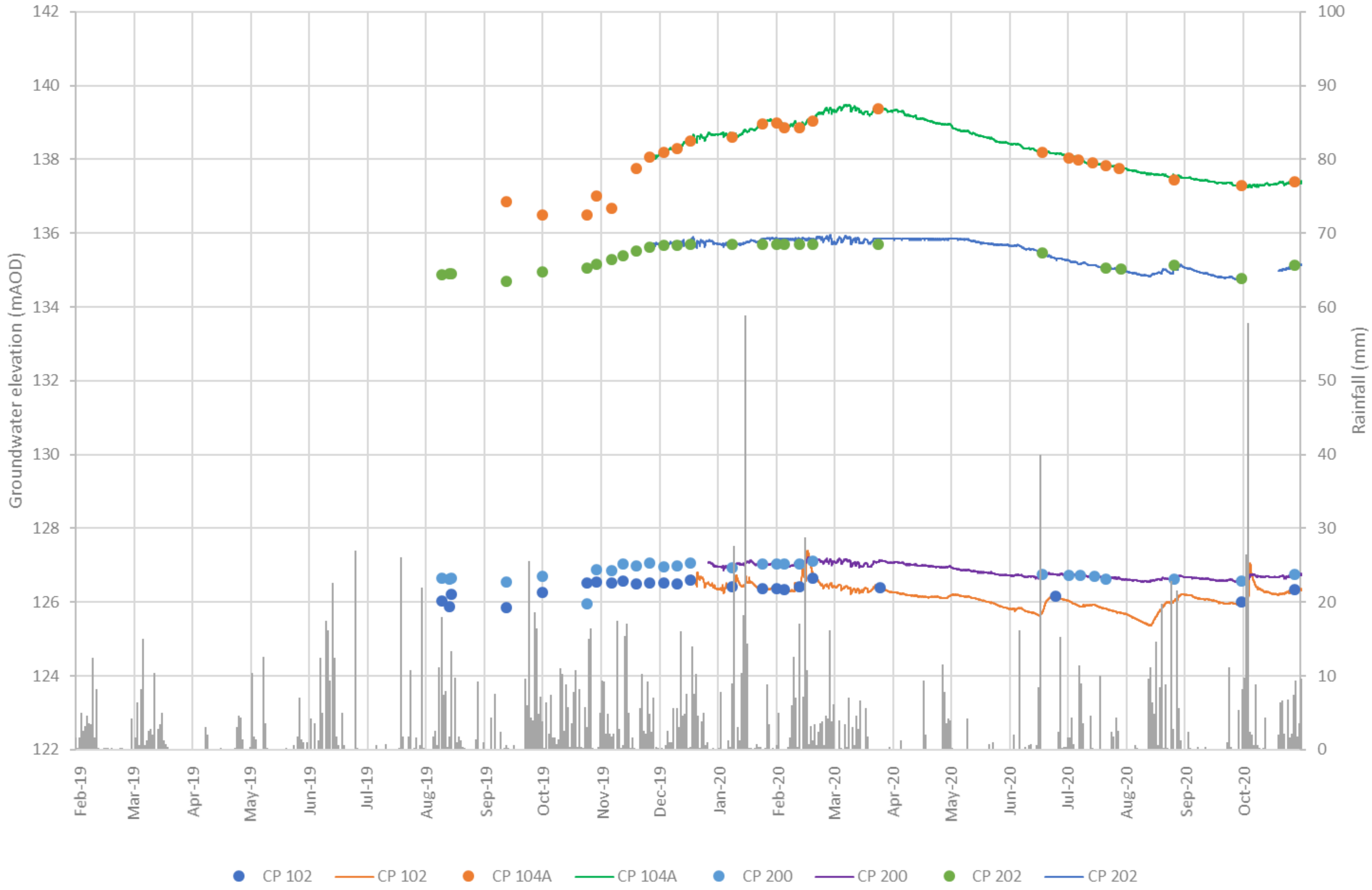

Figure B-1 Mass movement deposits groundwater monitoring – CH0+500 to CH1+000, lower Crickley Hill

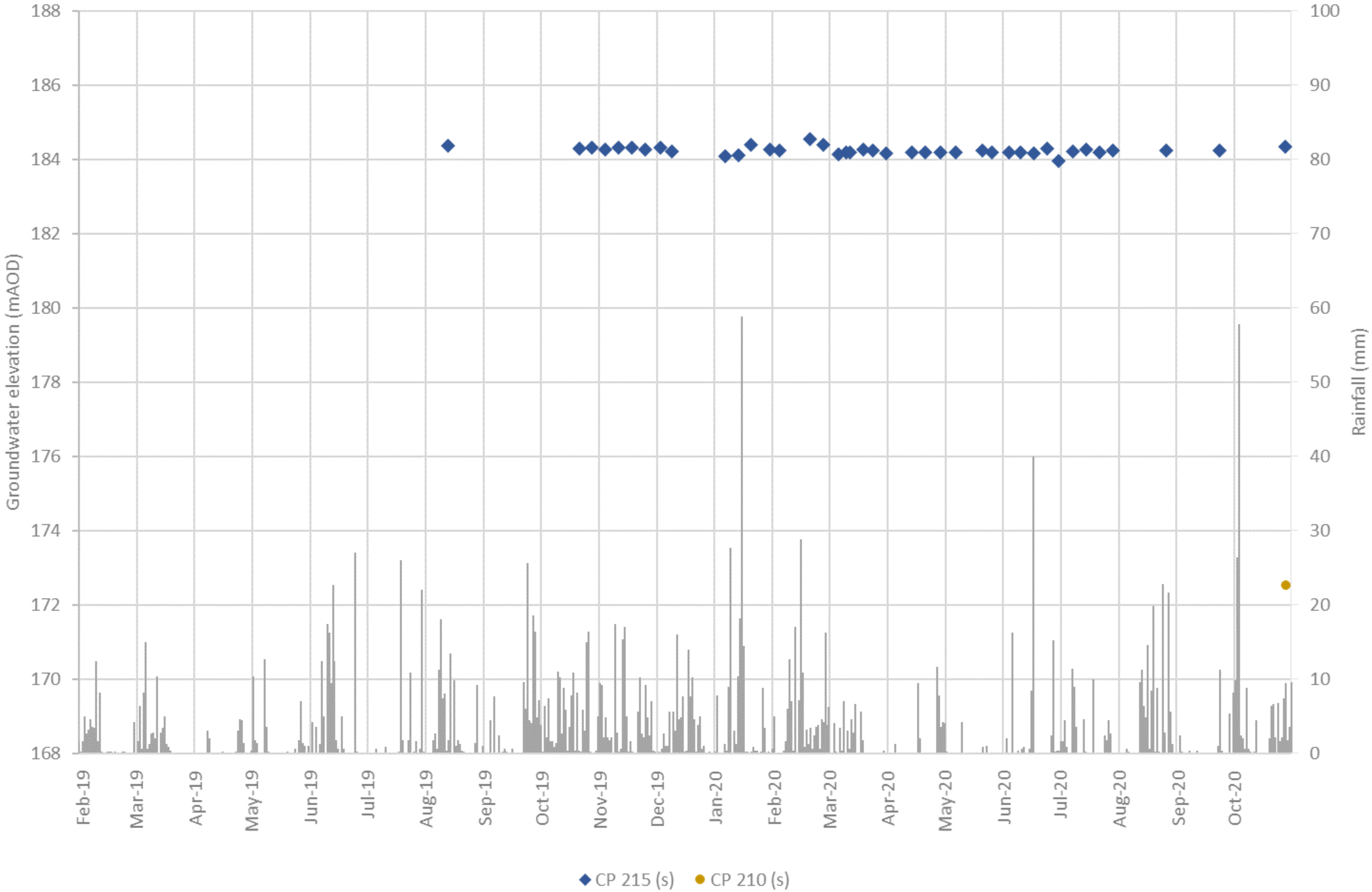

Figure B-2 Mass movement deposits groundwater monitoring – CH1+000 to CH1+400 (northern side of A417), mid Crickley Hill

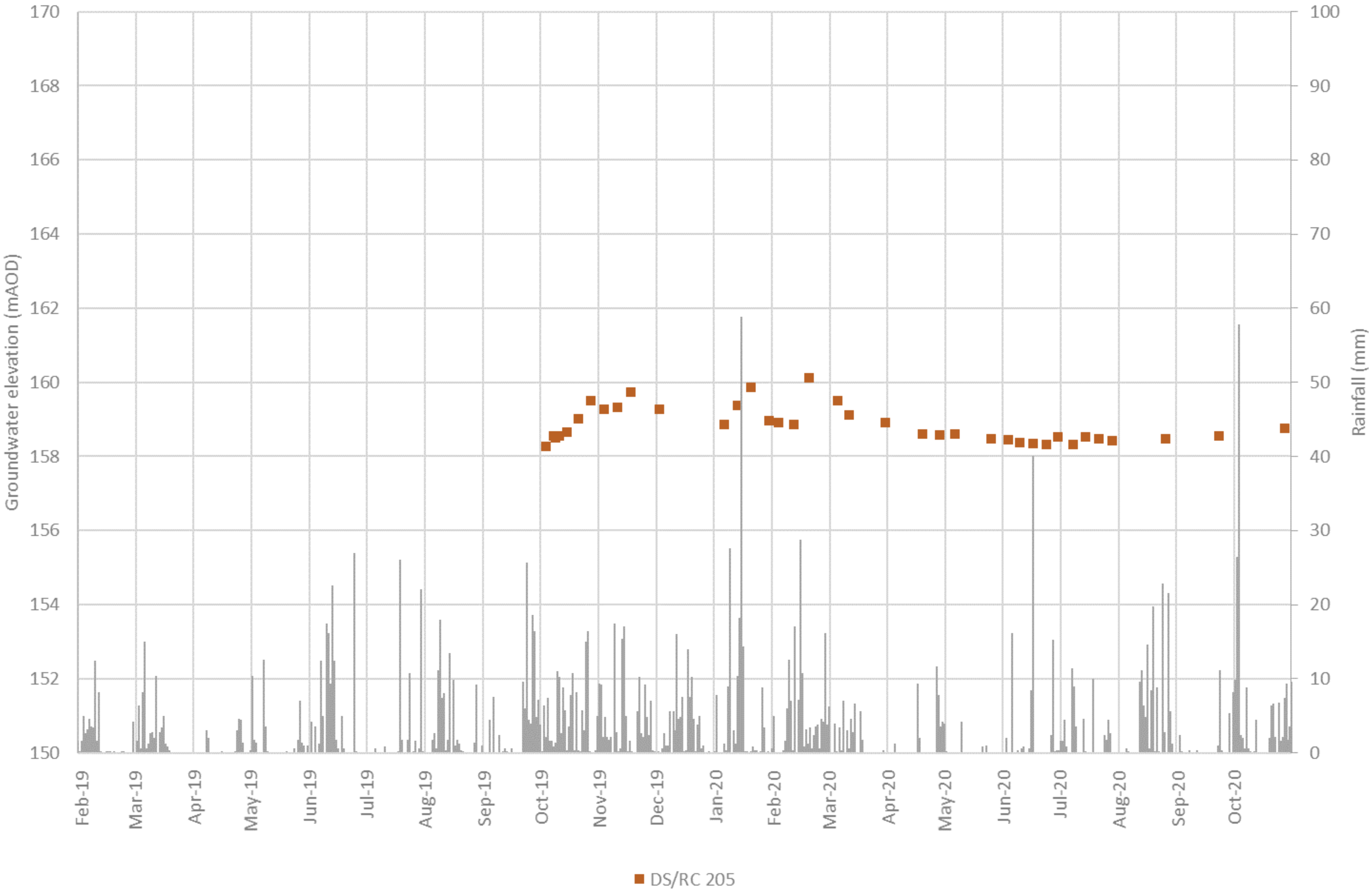

Figure B-3 Mass movement deposits groundwater monitoring – CH1+000 to CH1+400 (northern side of A417), mid Crickley Hill

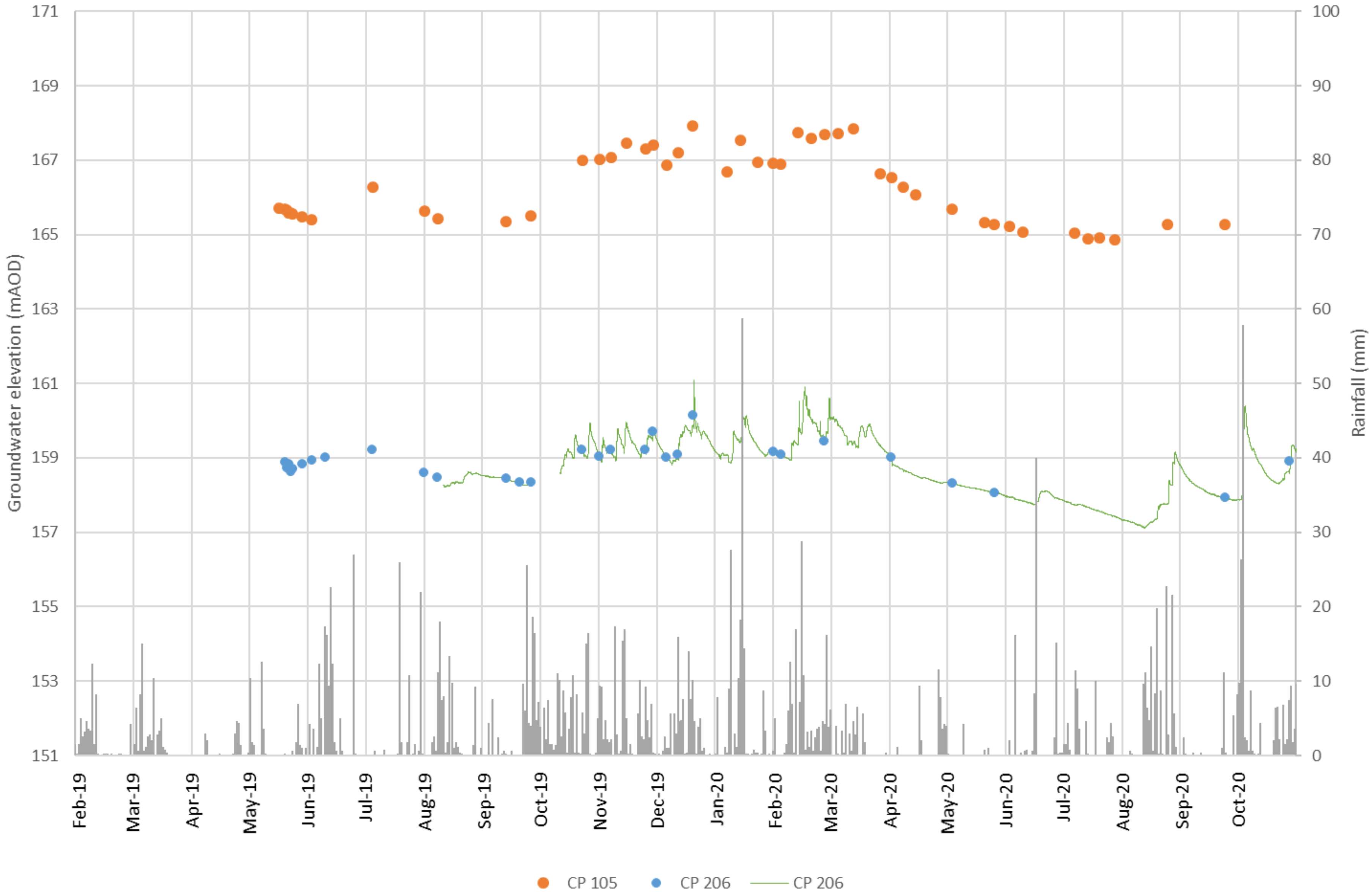

Figure B-4 Mass movement deposits groundwater monitoring – CH1+000 to CH1+400 (southern side of A417), mid Crickley Hill

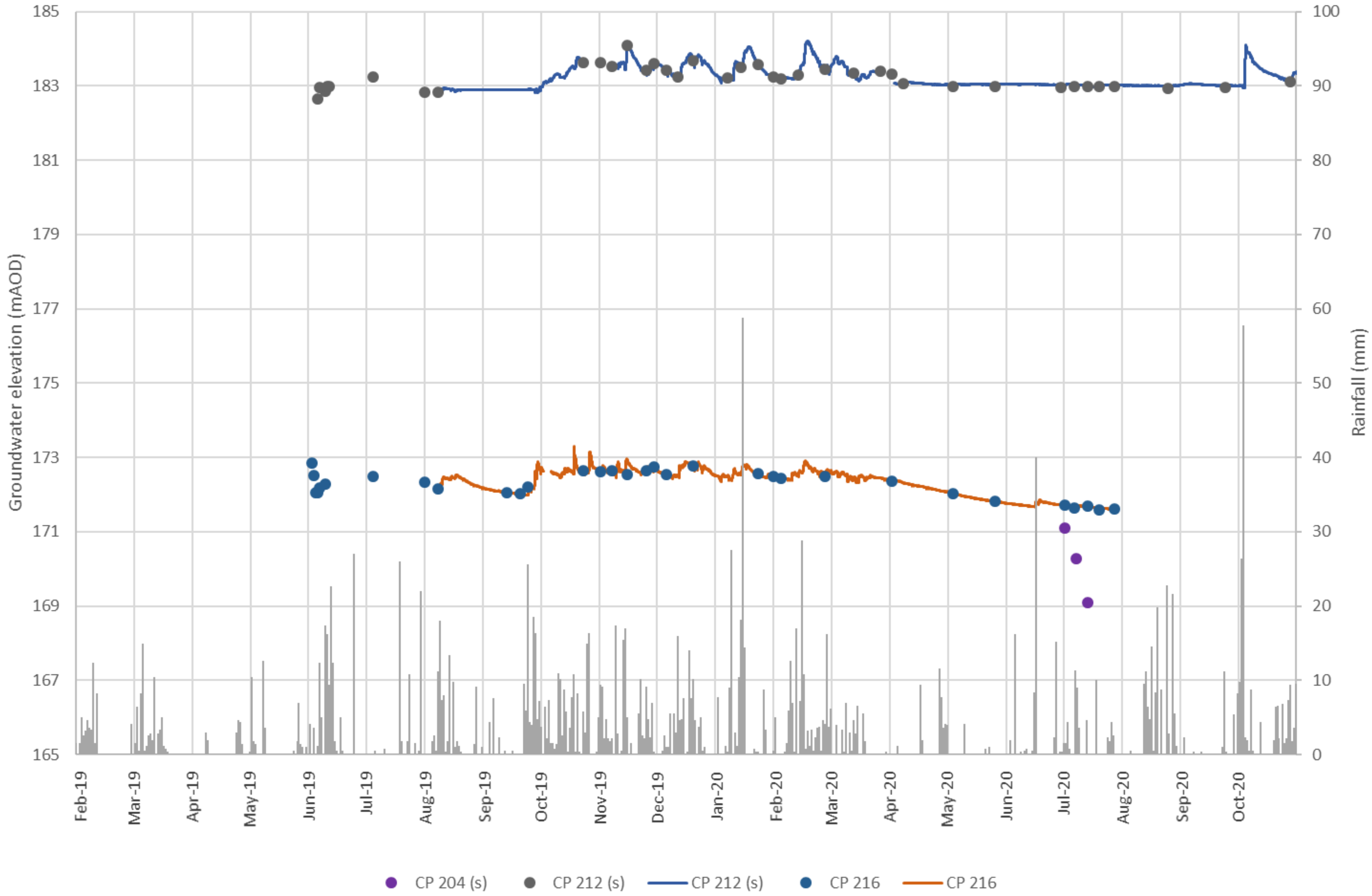

Figure B-5 Mass movement deposits groundwater monitoring – CH1+000 to CH1+400 (southern side of A417), mid Crickley Hill

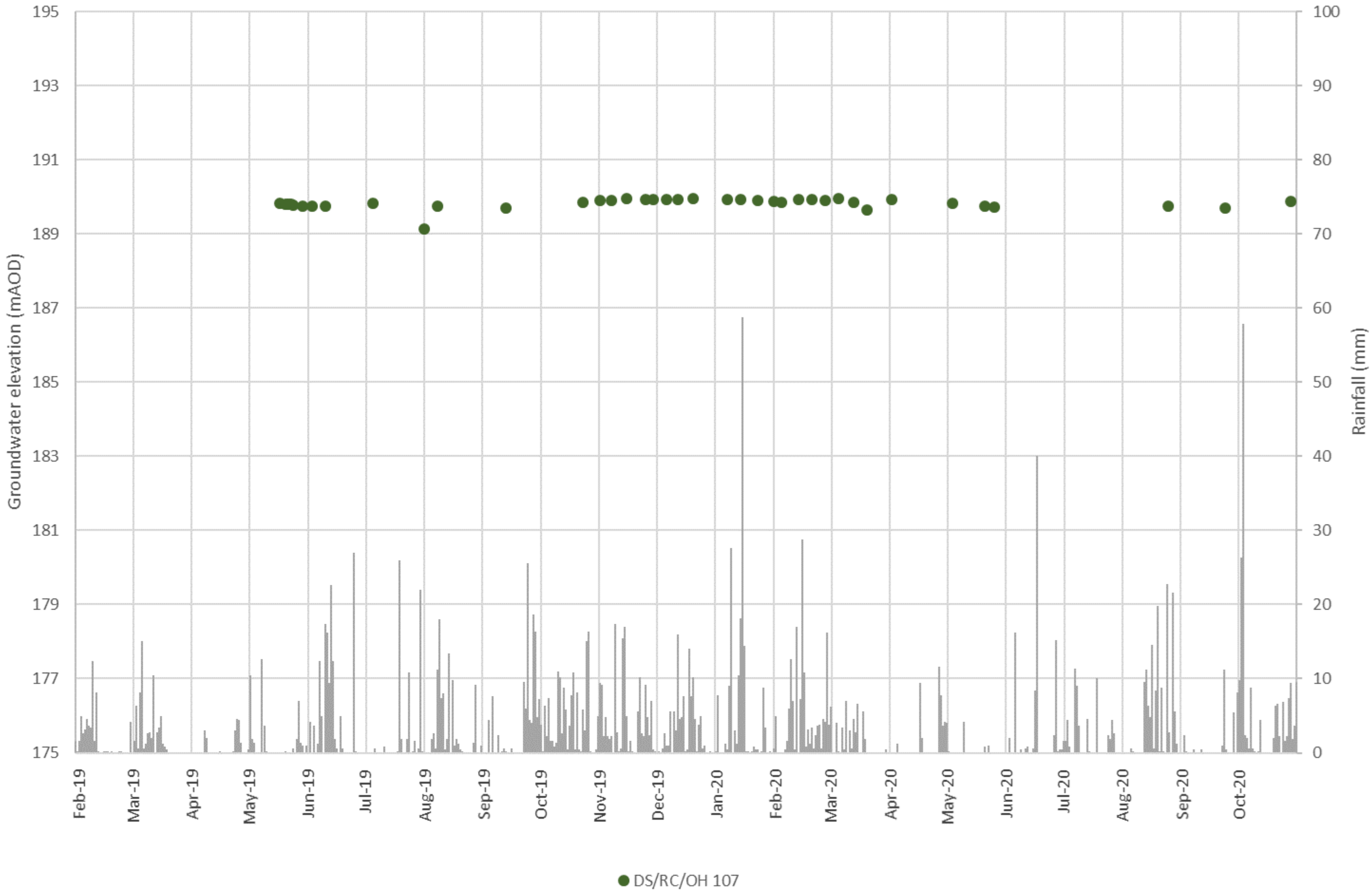

Figure B-6 Mass movement deposits groundwater monitoring – CH1+400 to CH1+700 (southern side of A417), upper Crickley Hill

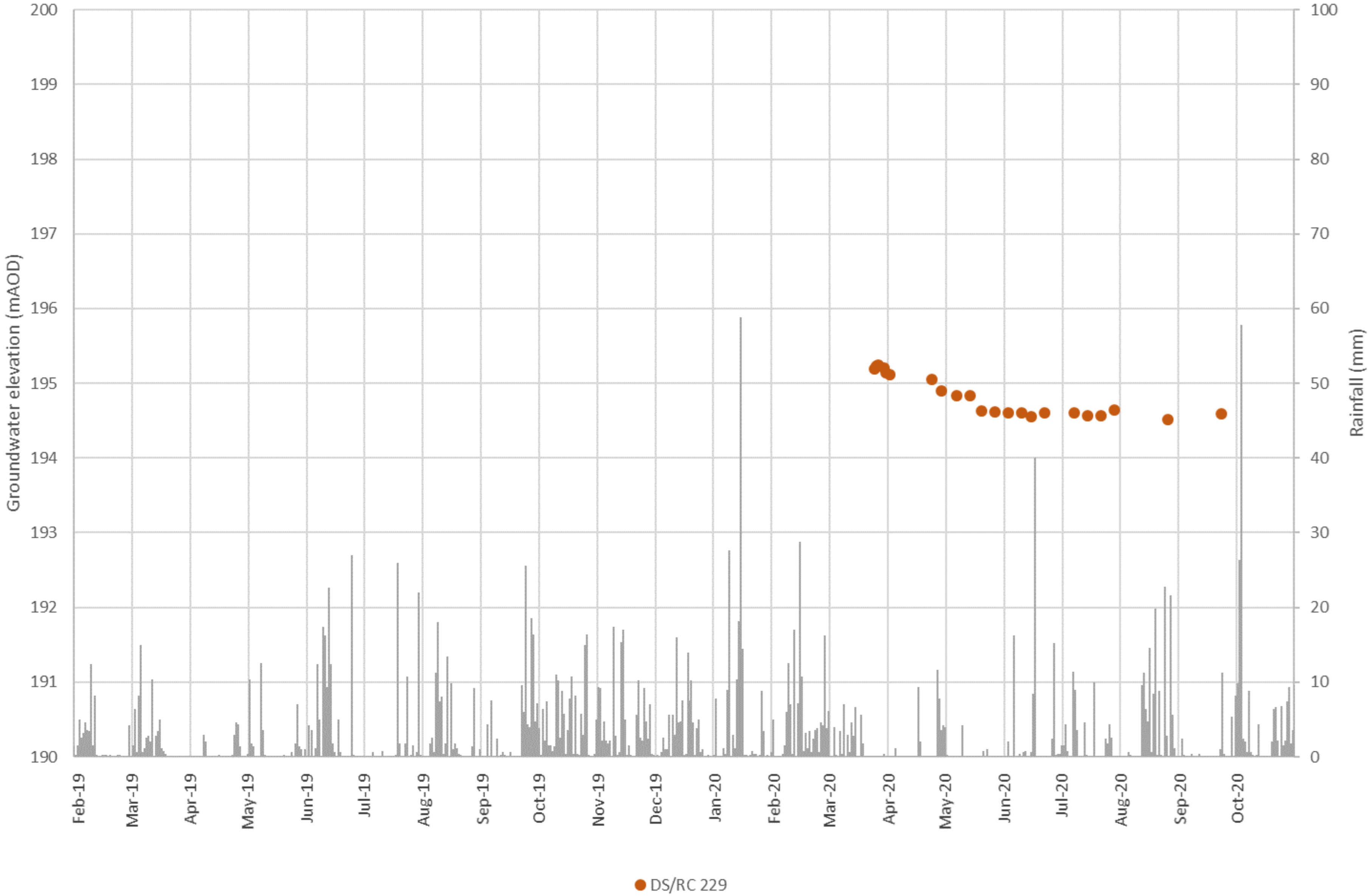

Figure B-7 Mass movement deposits groundwater monitoring - CH1+400 to CH1+700 (northern side of A417) - upper Crickley Hill

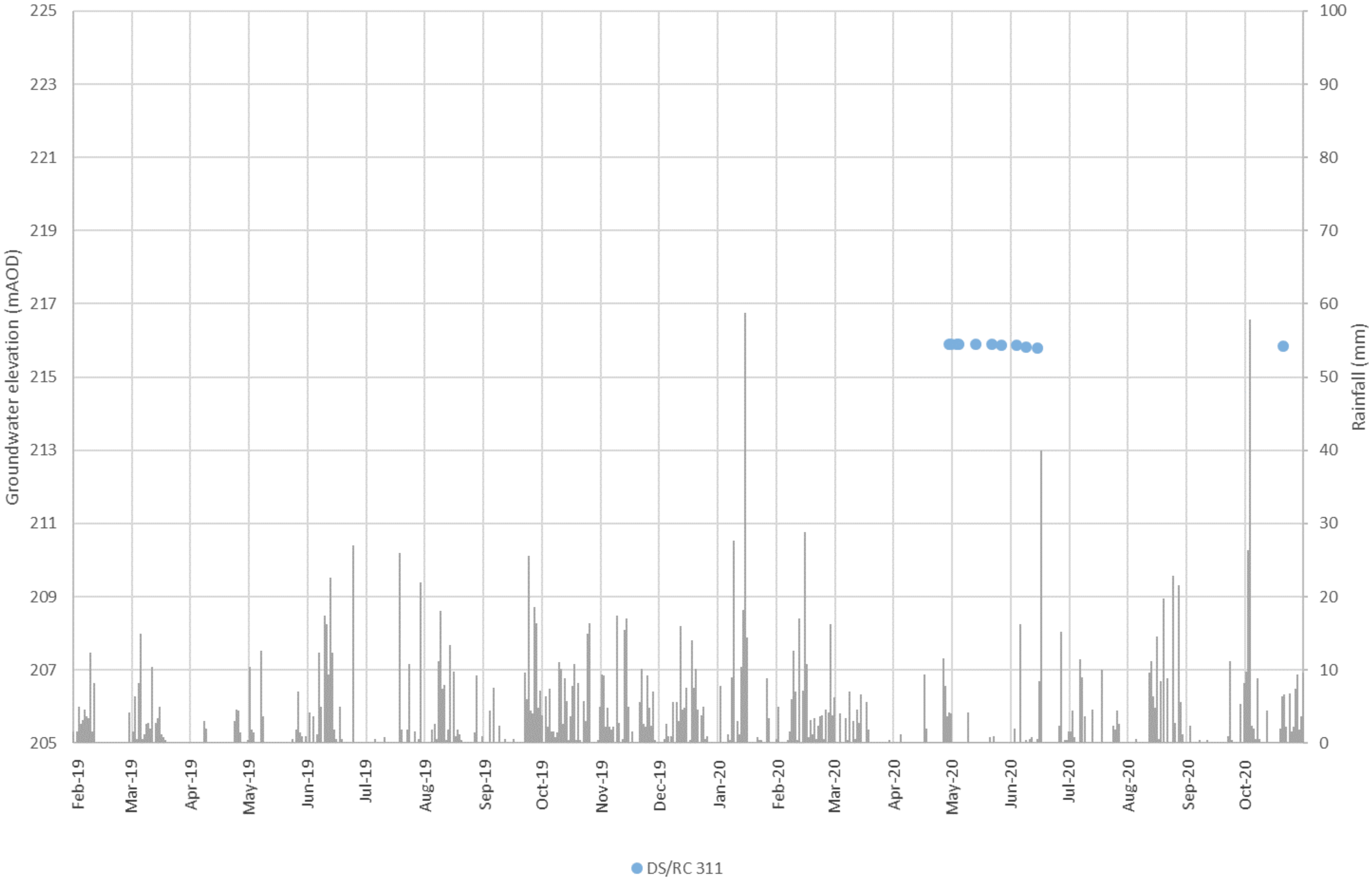

Figure B-8 Great Oolite limestone groundwater monitoring – CH3+000 to CH3+500, Shab Hill junction

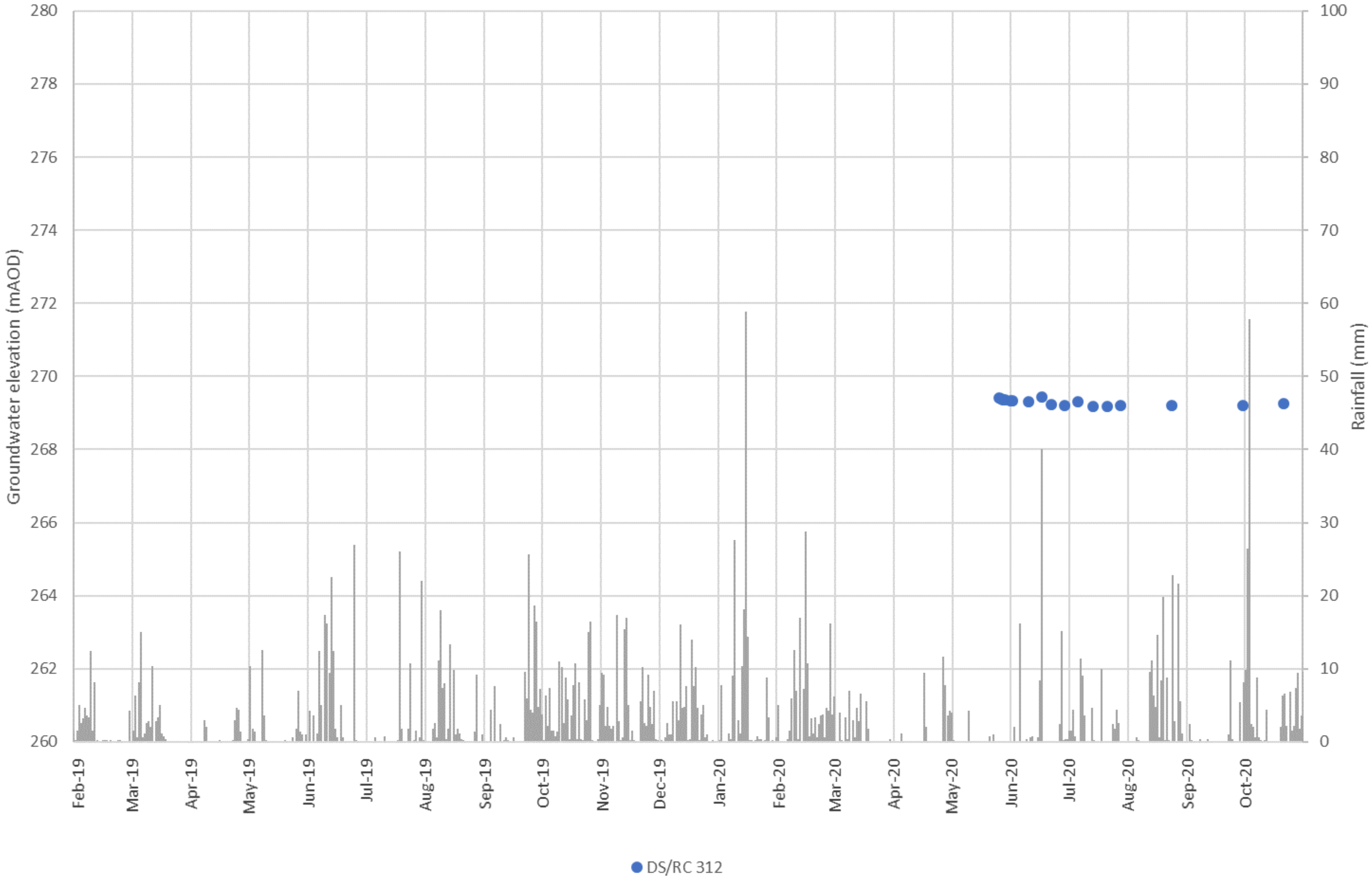

Figure B-9 Great Oolite limestone groundwater monitoring – CH3+000 to CH3+500, Shab Hill junction

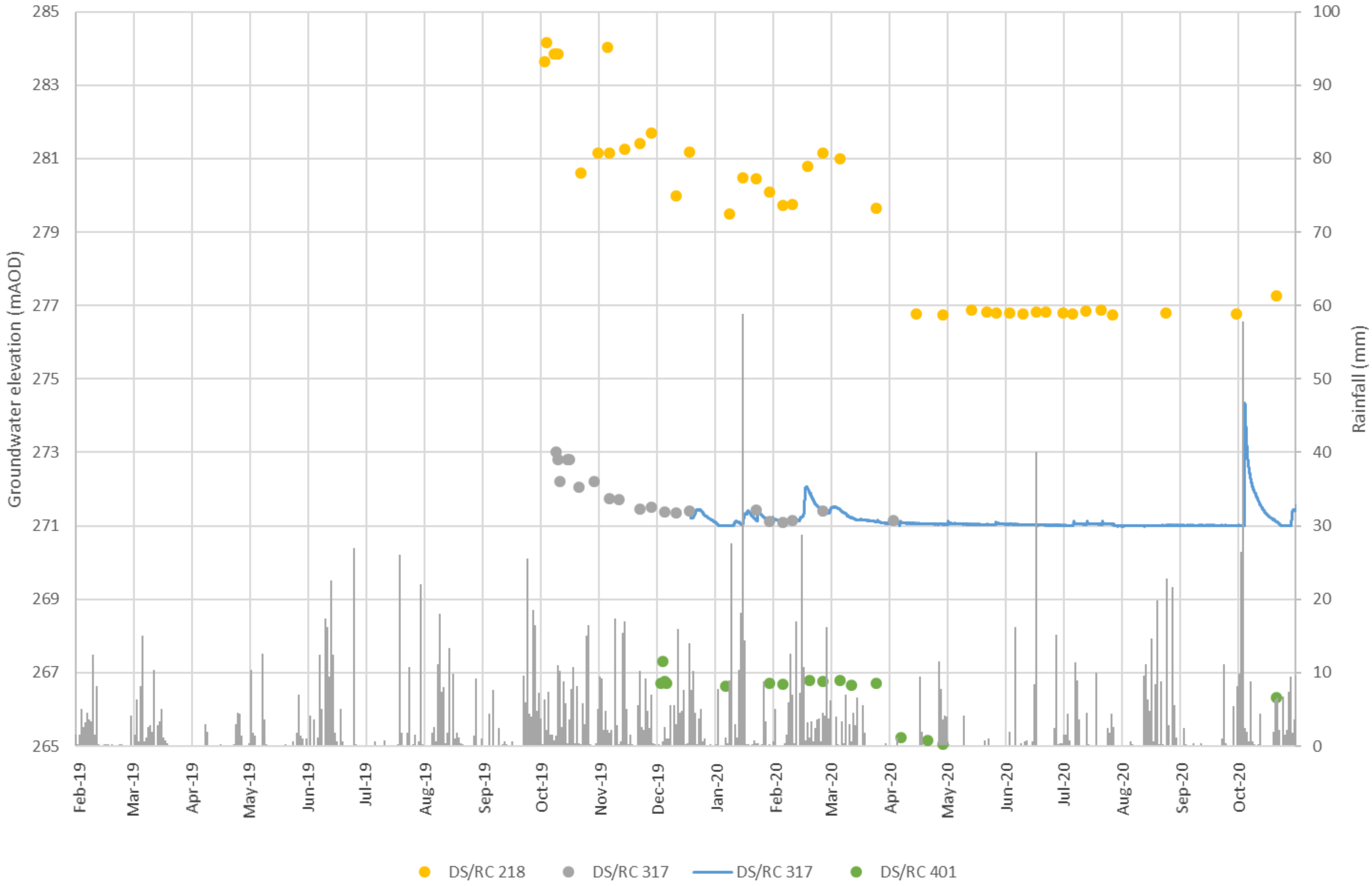

Figure B-10 Great Oolite limestone groundwater monitoring – CH3+500 to CH5+000, Shab Hill junction to Cowley junction

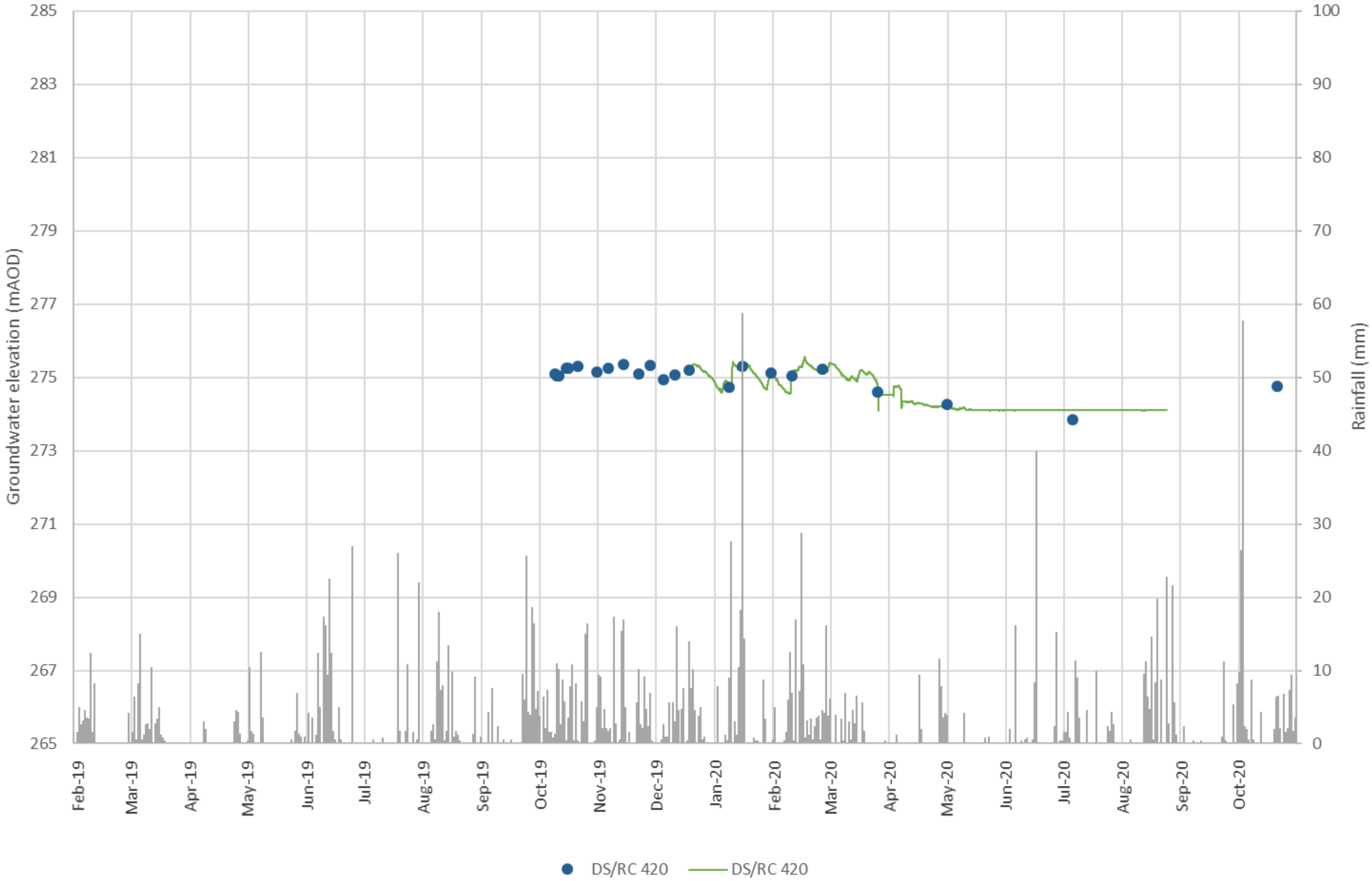

Figure B-11 Great Oolite limestone groundwater monitoring – Bushley Muzzard SSSI

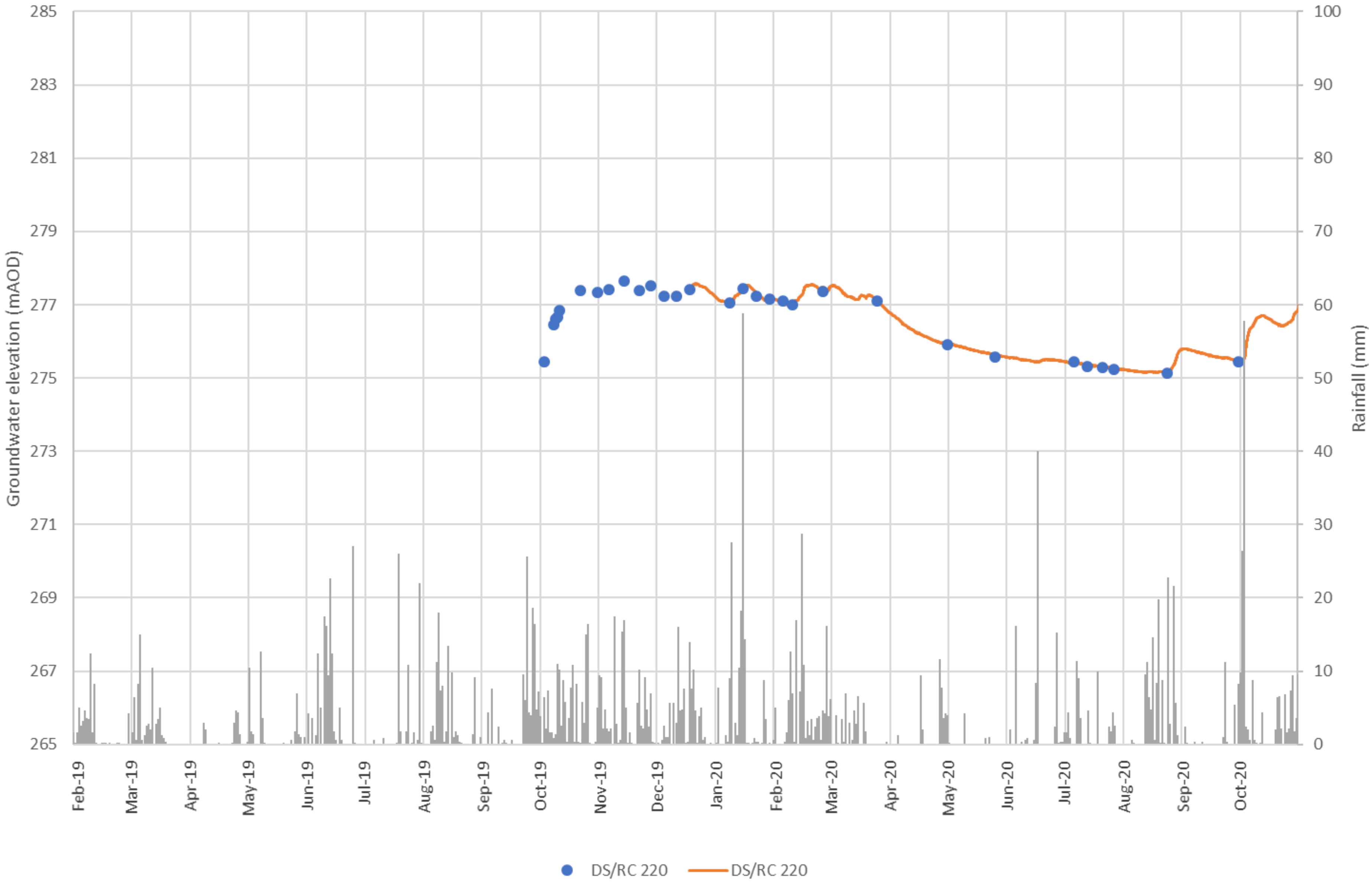

Figure B-12 Fuller's Earth Formation groundwater monitoring, CH3+500 to CH5+000, Shab Hill junction to Cowley junction

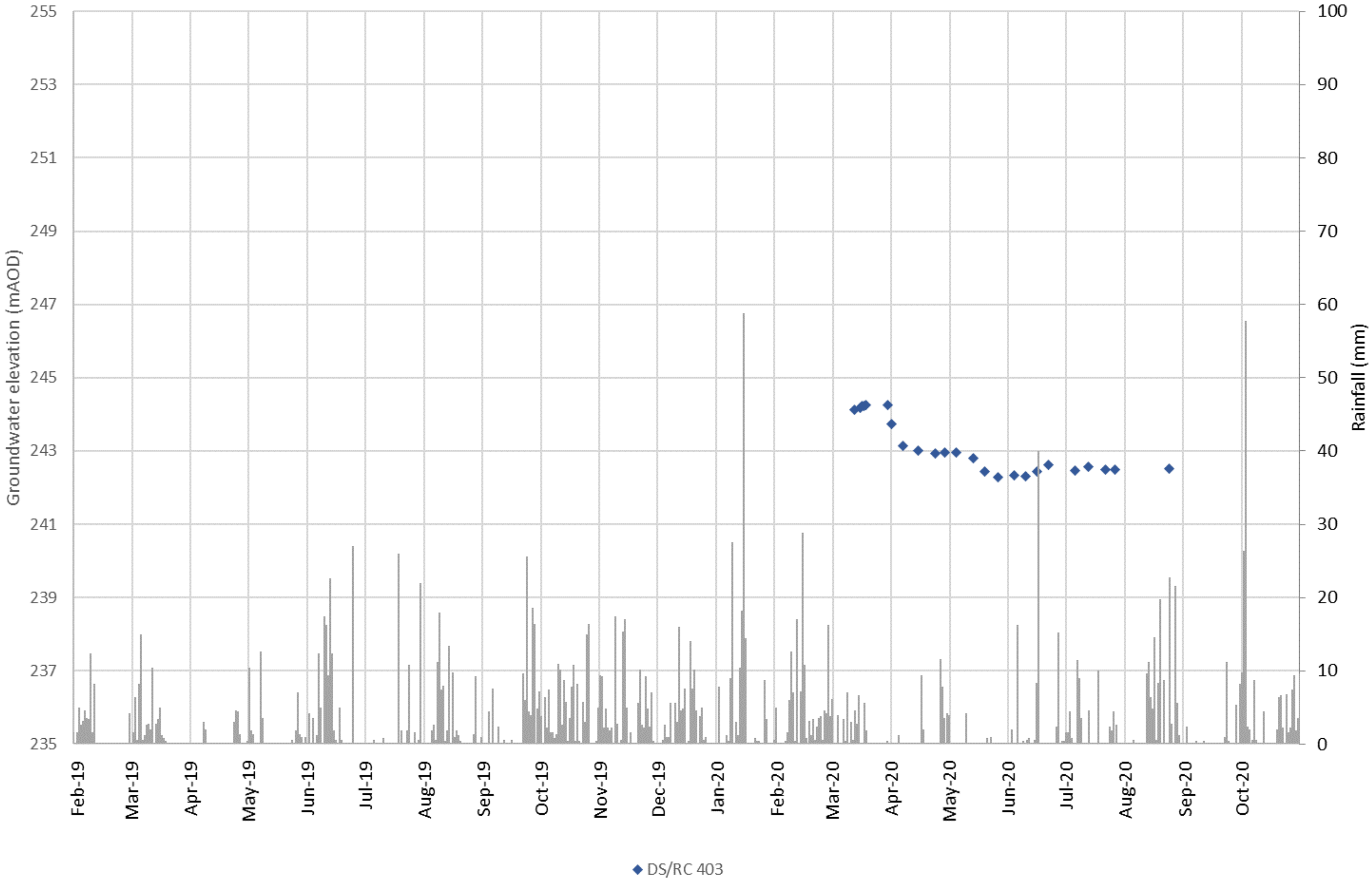

Figure B-13 Fuller's Earth Formation groundwater monitoring, CH3+500 to CH5+000, Shab Hill junction to Cowley junction

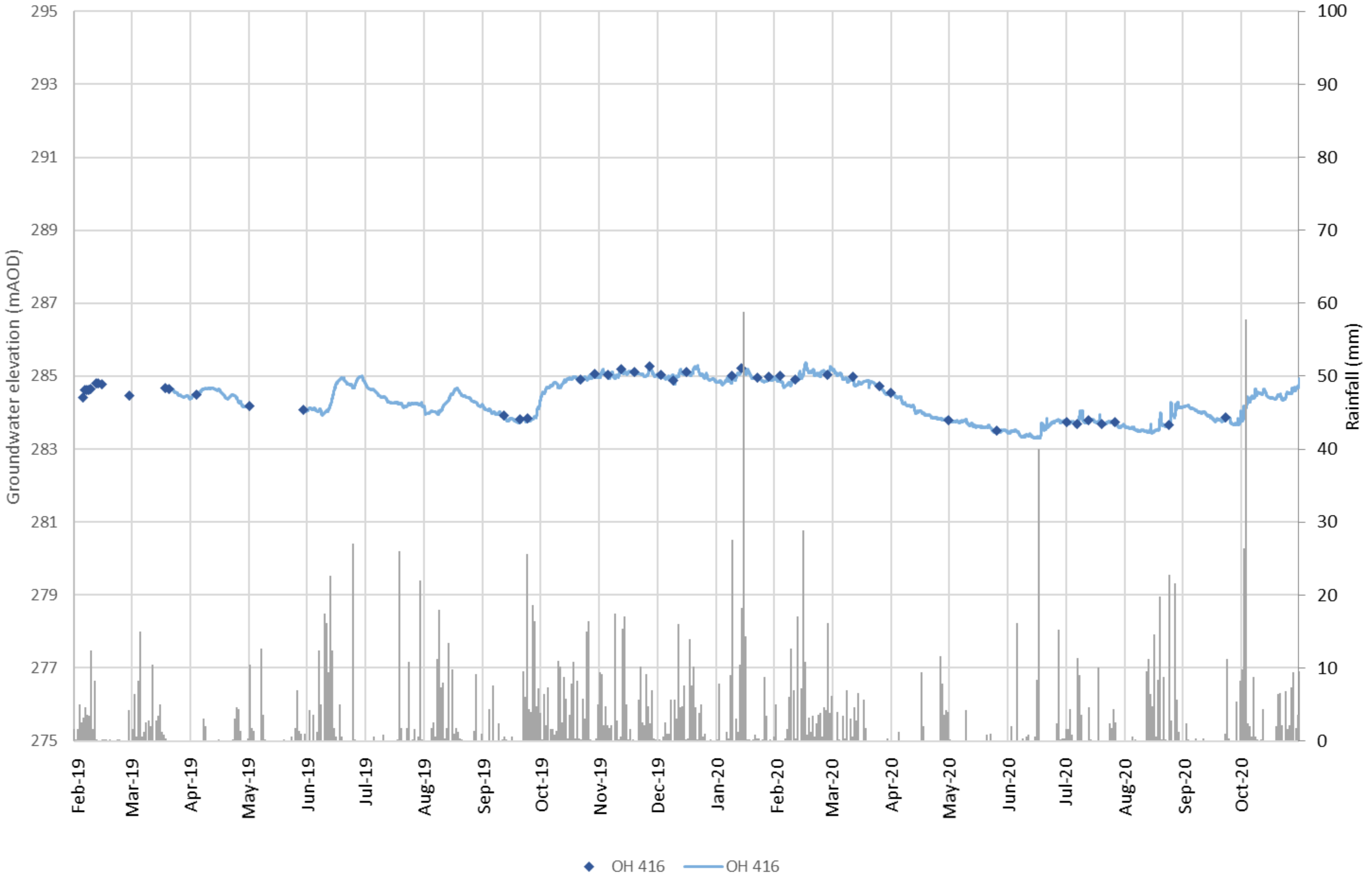

Figure B-14 Fuller's Earth Formation groundwater monitoring, Ermin Way

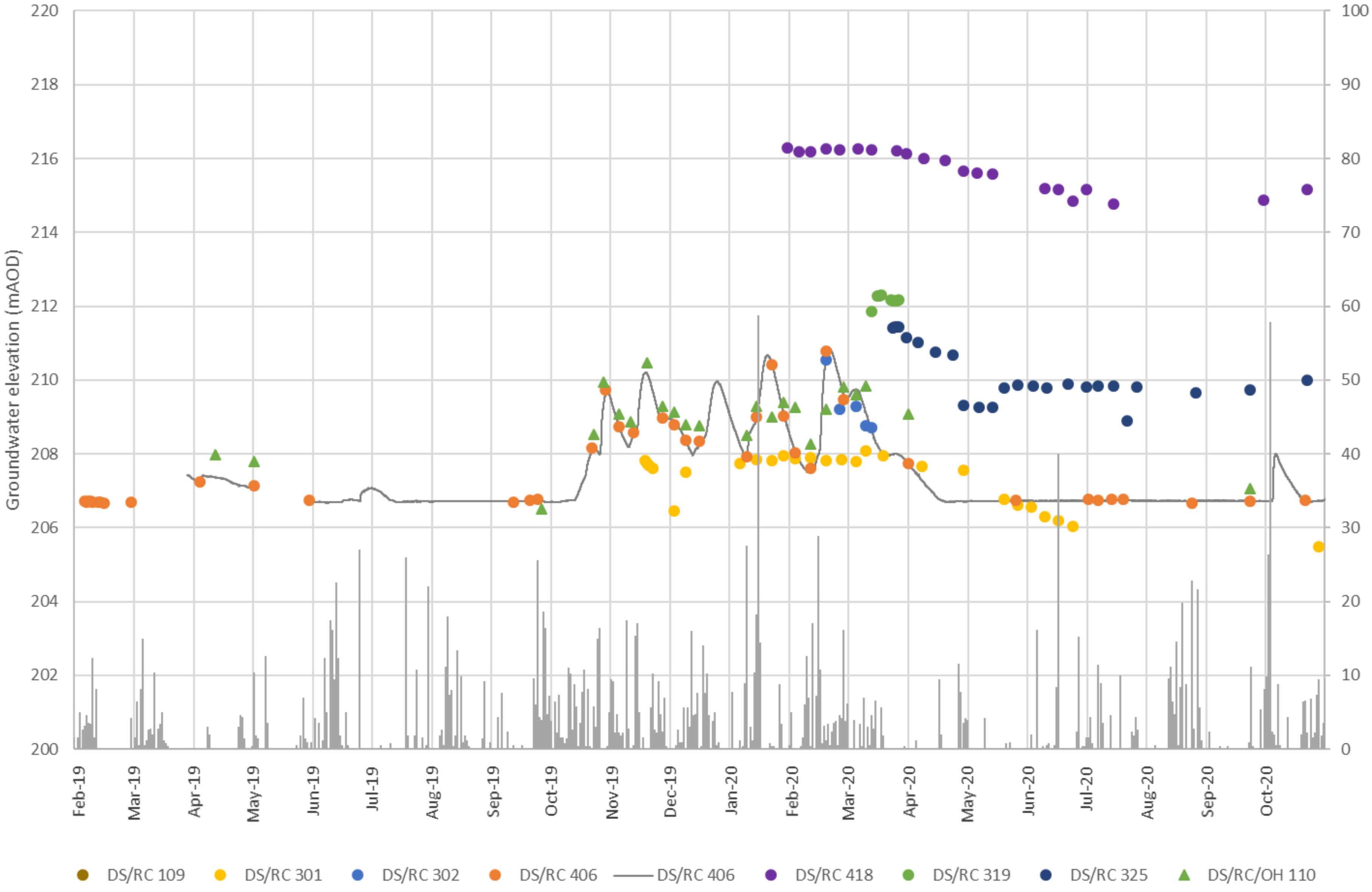

Figure B-15 Inferior Oolite Group groundwater monitoring – Ch 1+700 to Ch 2+250, Air Balloon

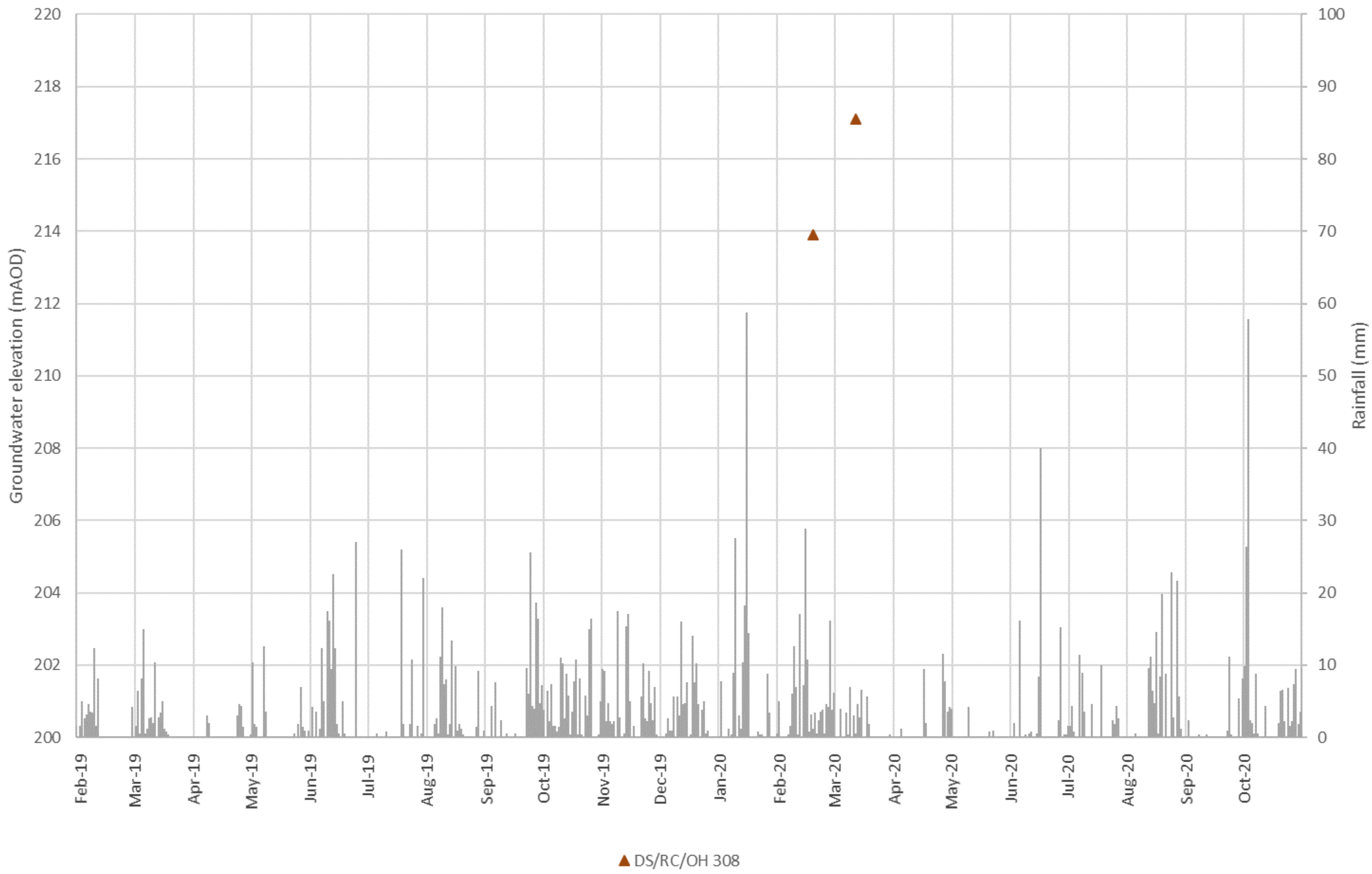

Figure B-16 Inferior Oolite Group groundwater monitoring – Ch 2+250 to Ch 2+750, Air Balloon

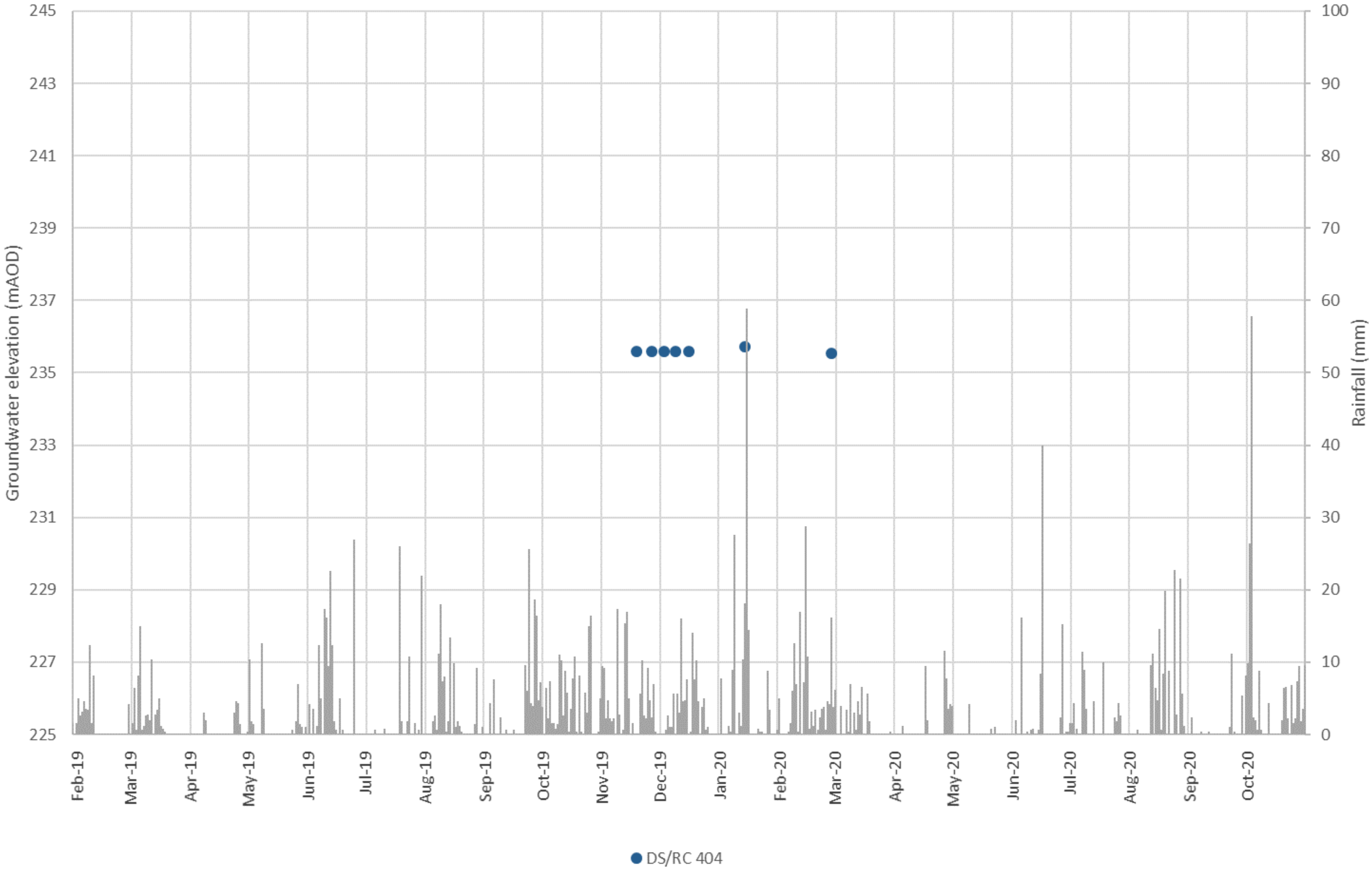

Figure B-17 Inferior Oolite Group groundwater monitoring – Barrow Wake

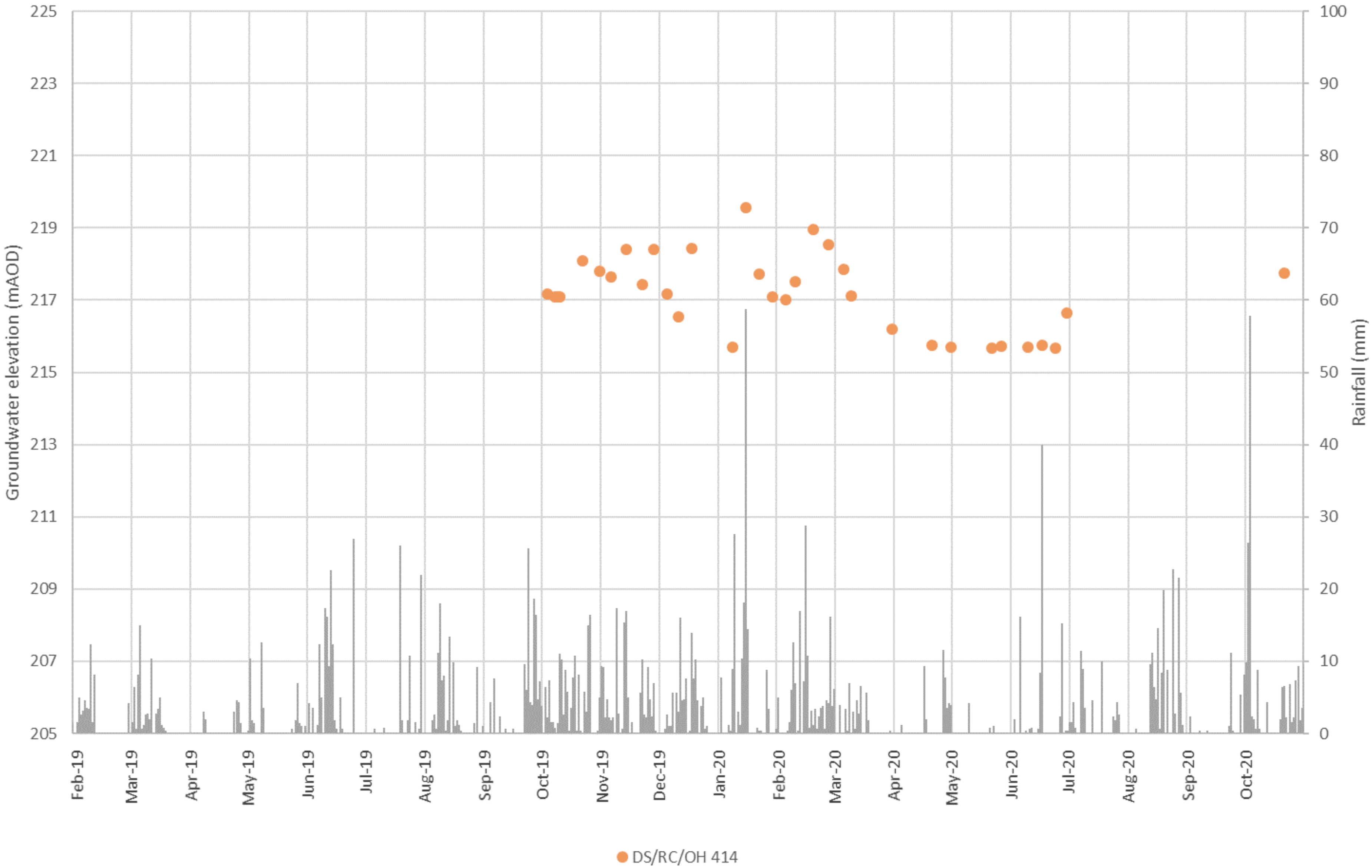

Figure B-18 Inferior Oolite Group groundwater monitoring – Barrow Wake

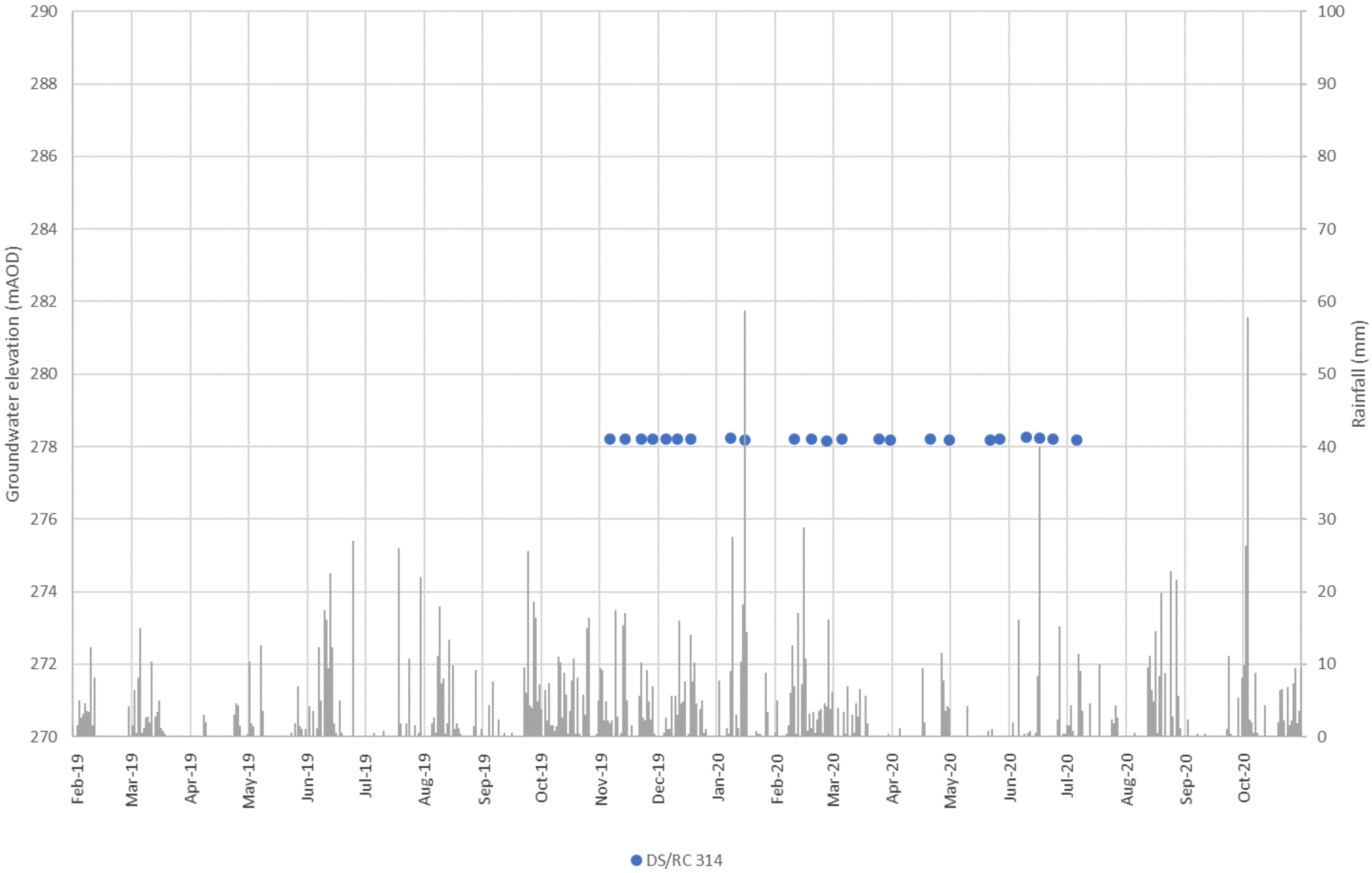

Figure B-19 Inferior Oolite Group groundwater monitoring – B4070 realignment

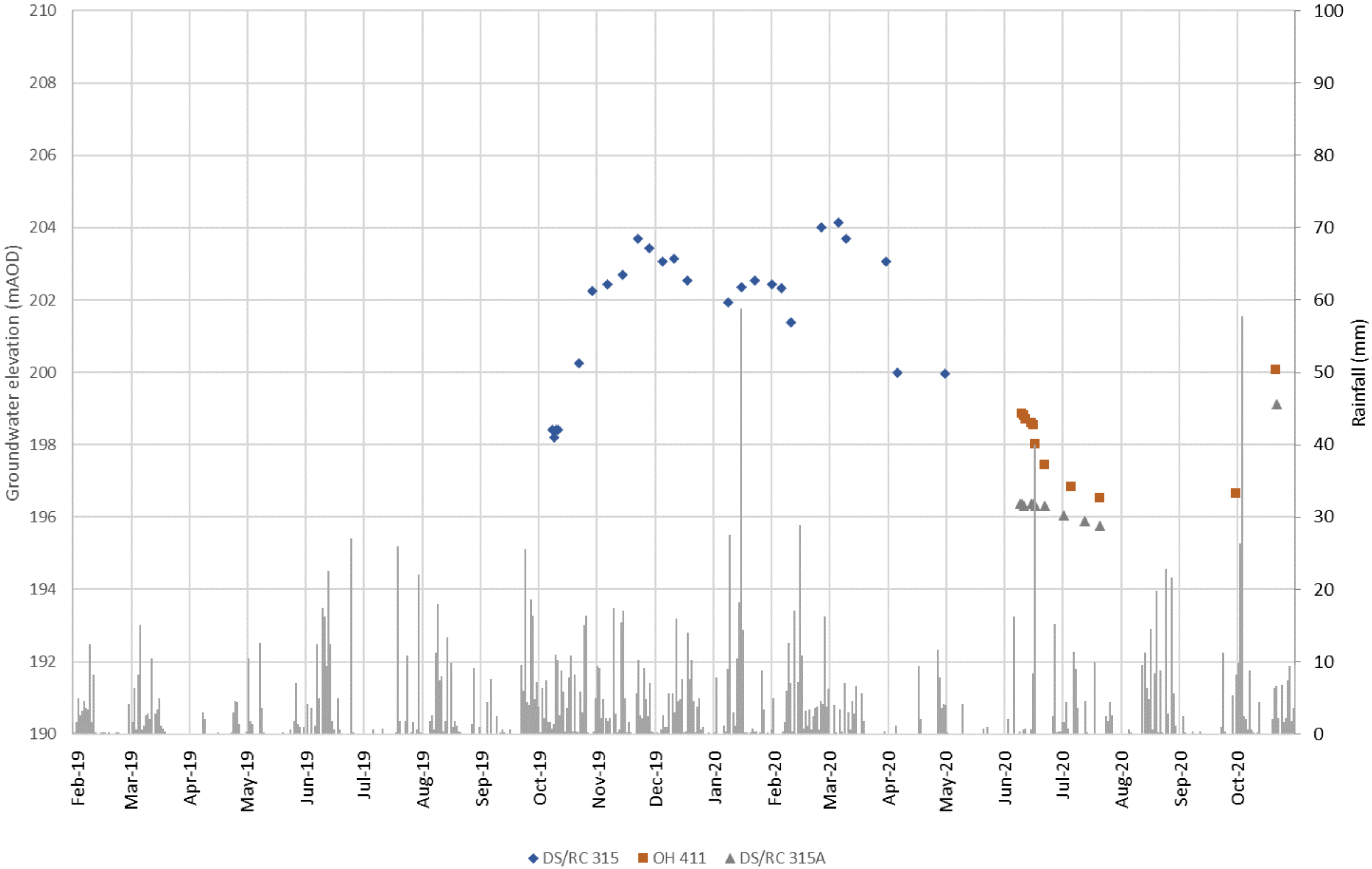

Figure B-20 Inferior Oolite Group groundwater monitoring – Shab Hill junction

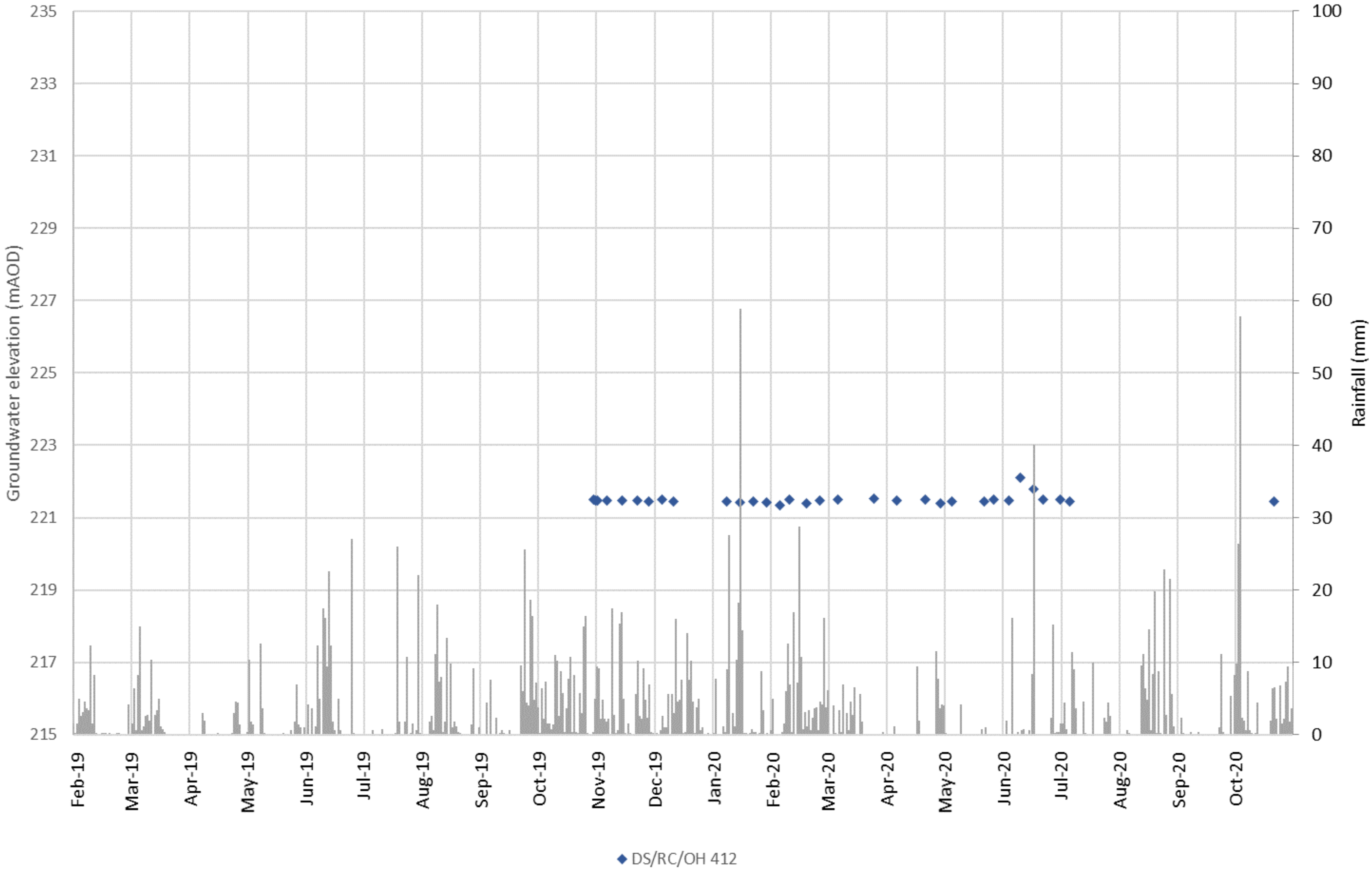

Figure B-21 Inferior Oolite Group groundwater monitoring – Shab Hill junction

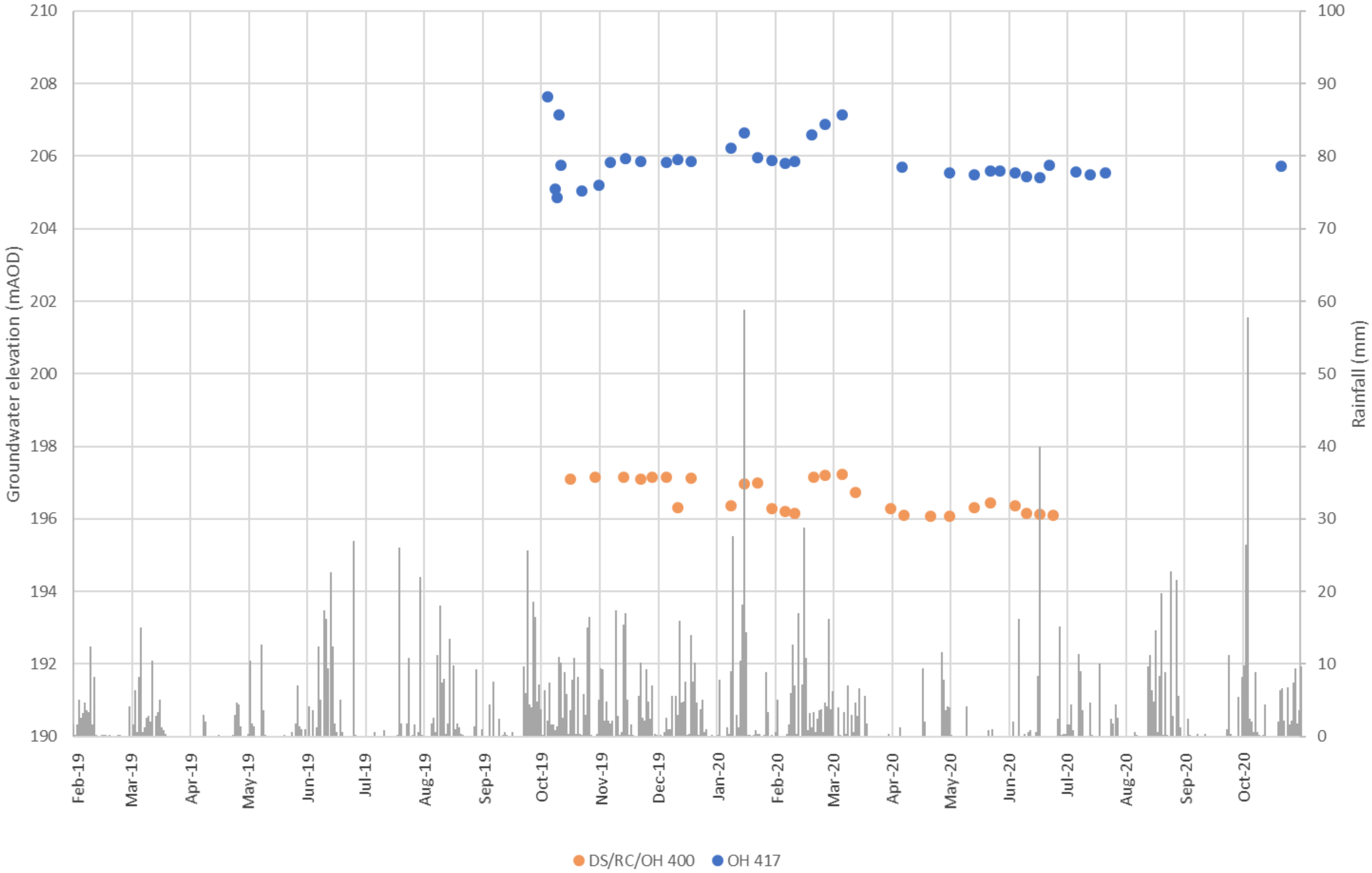

Figure B-22 Inferior Oolite Group groundwater monitoring – Shab Hill junction to Cowley junction

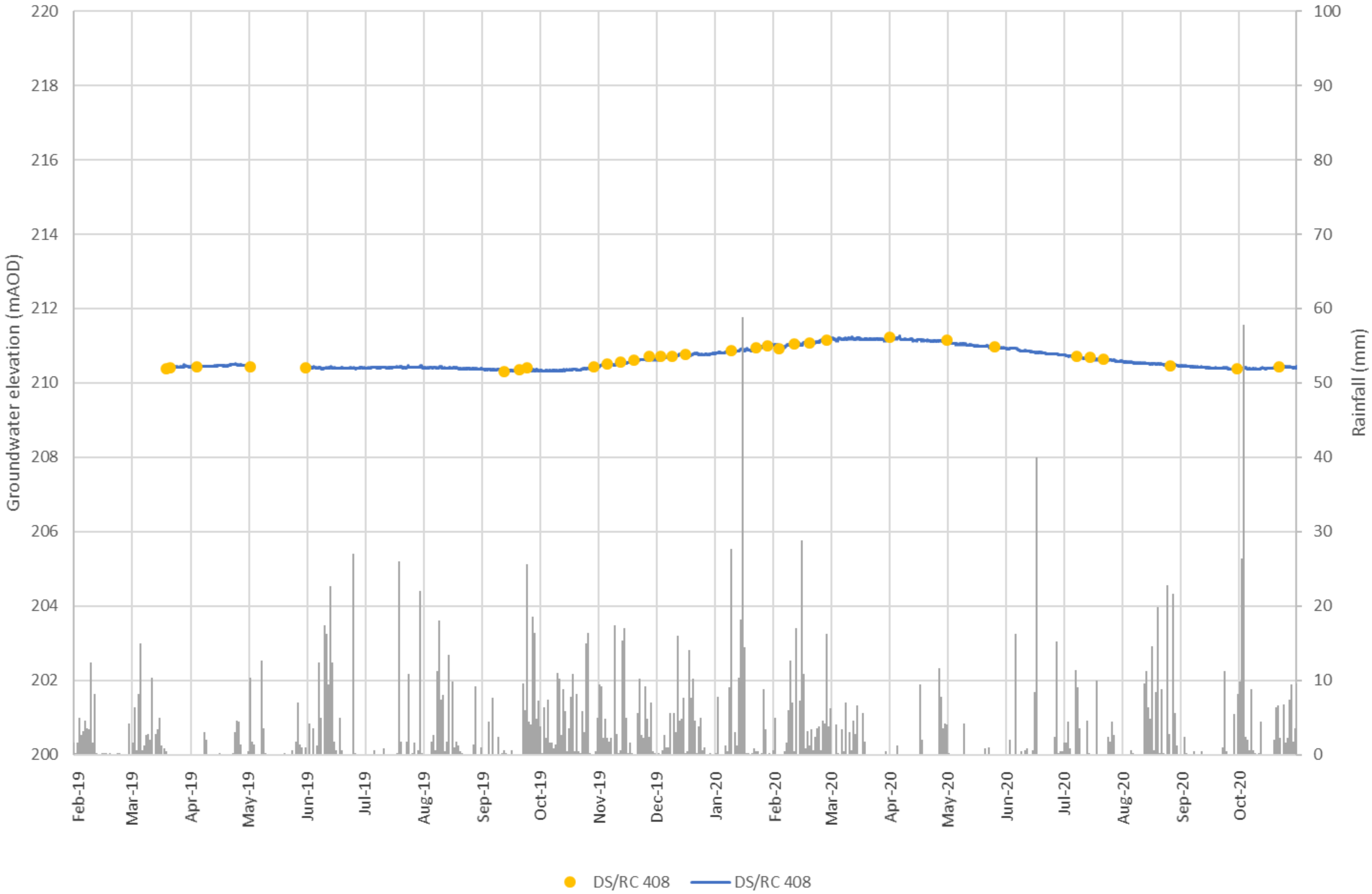

Figure B-23 Lias Group, Bridport Sand Formation groundwater monitoring – Air Balloon

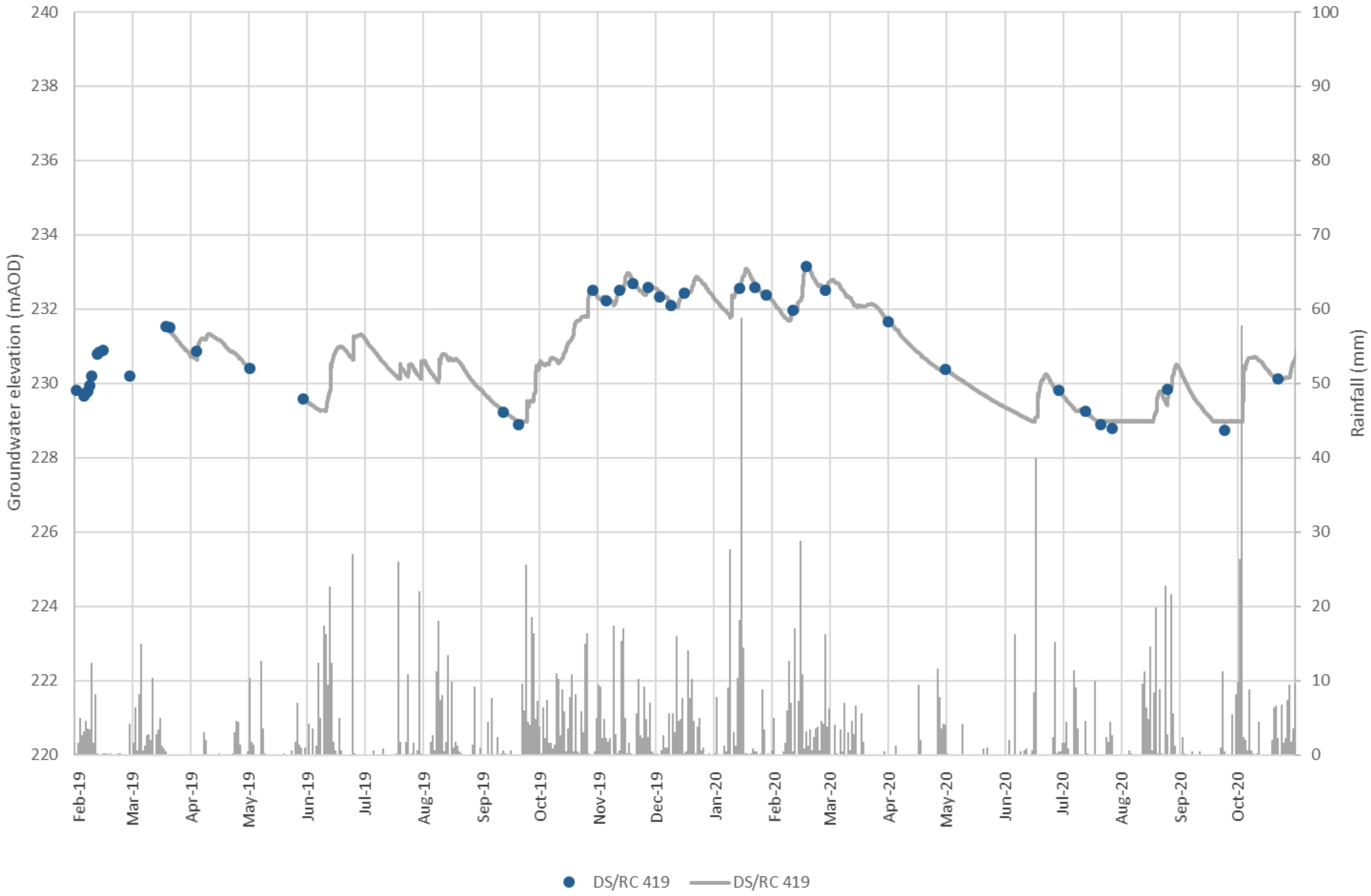

Figure B-24 Lias Group, Bridport Sand Formation groundwater monitoring – Barrow Wake

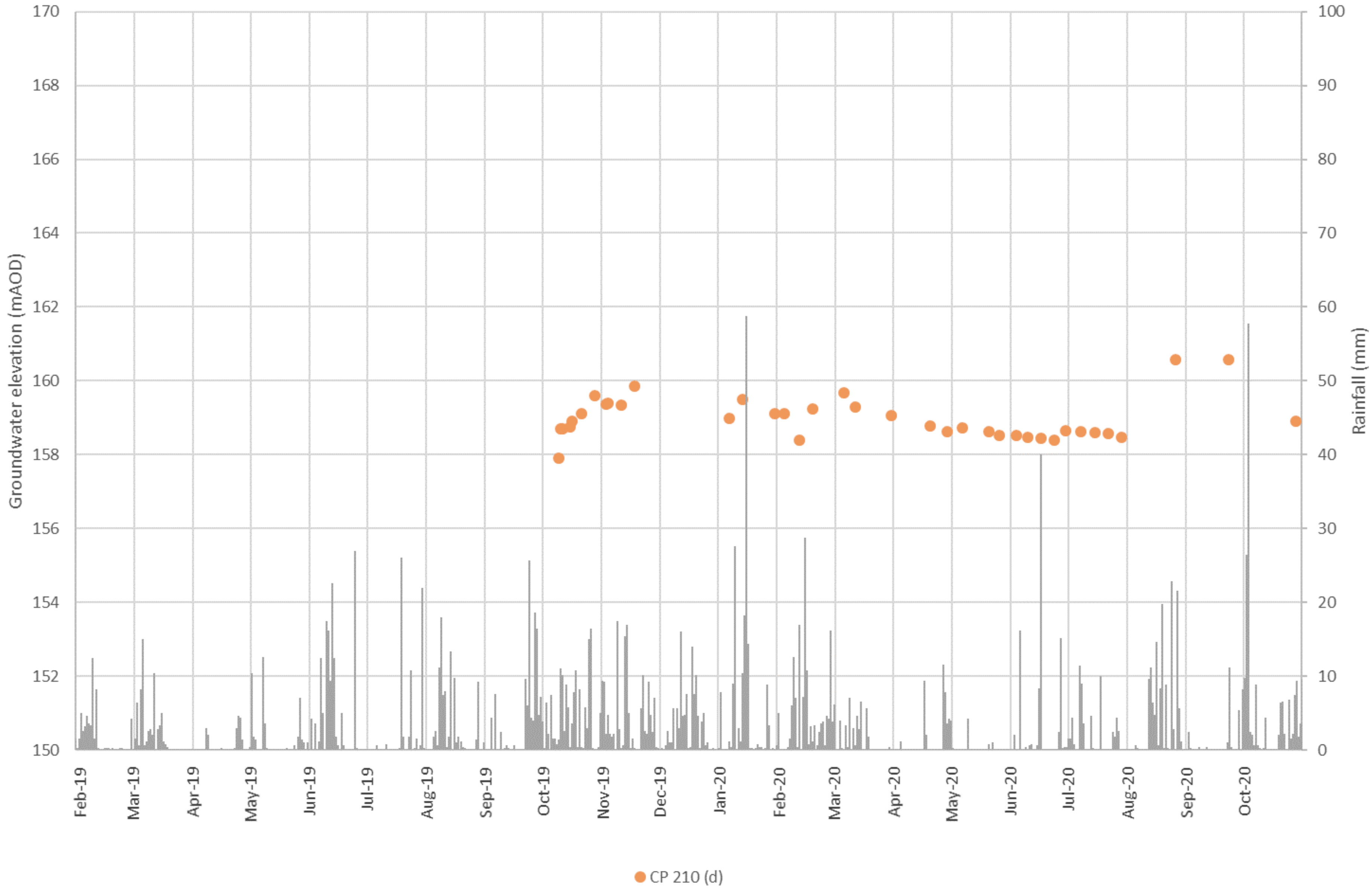

Figure B-25 Lias Group groundwater monitoring – CH1+000 to CH1+400 (northern side of A417) – mid Crickley Hill

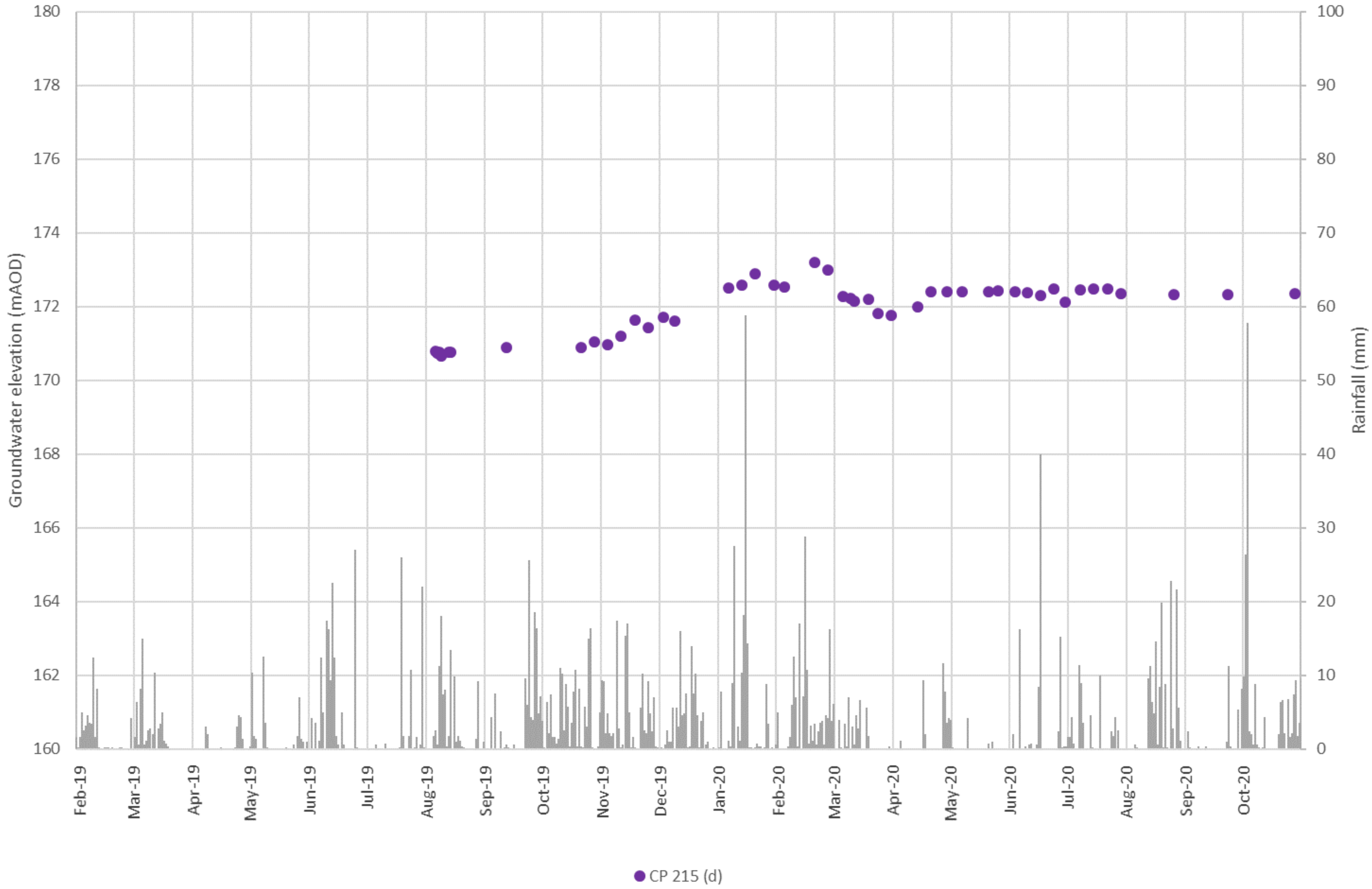

Figure B-26 Lias Group groundwater monitoring – CH1+000 to CH1+400 (northern side of A417) – mid Crickley Hill

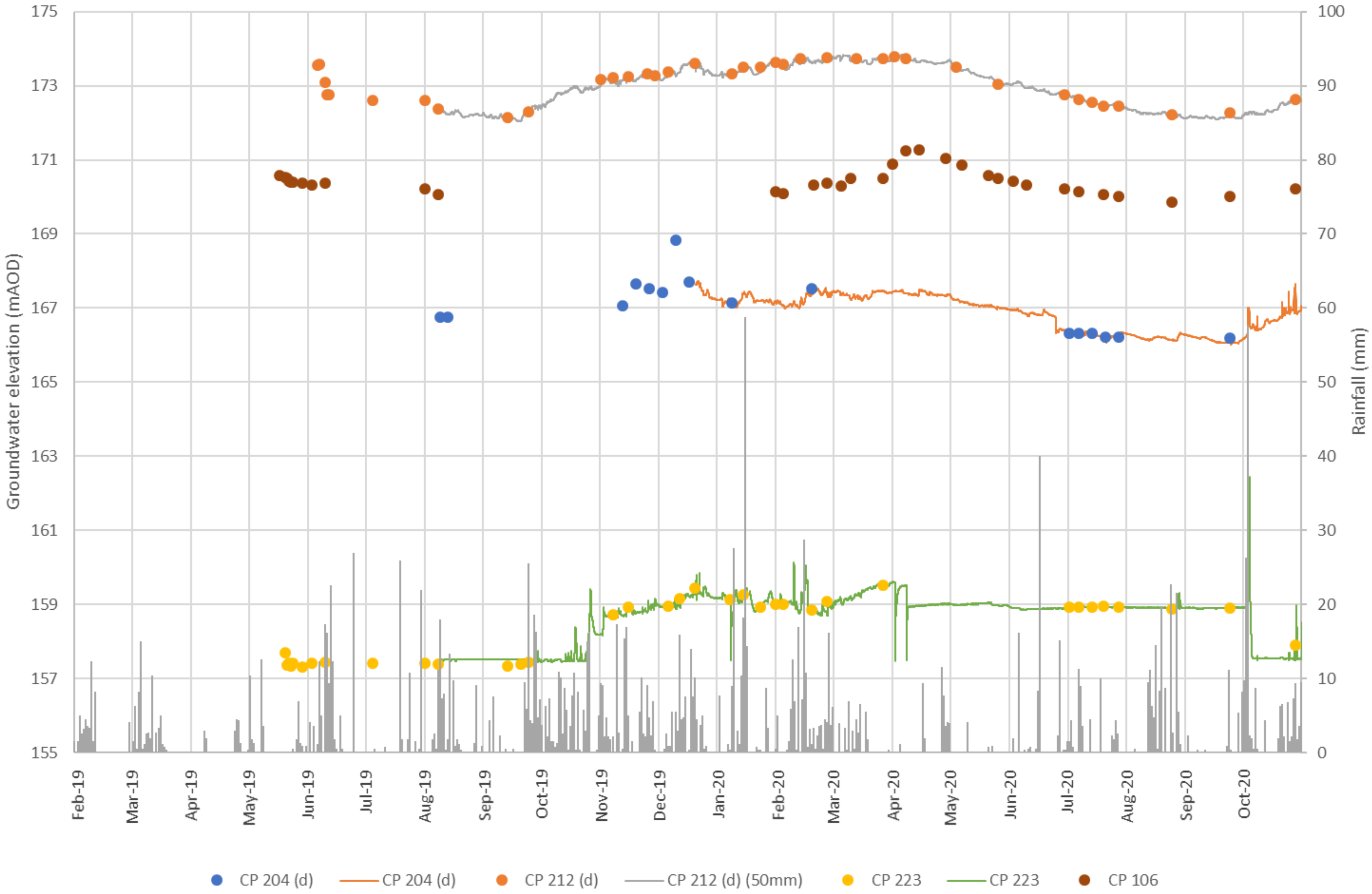

Figure B-27 Lias Group groundwater monitoring – CH1+000 to CH1+400 (southern side of A417) – mid Crickley Hill

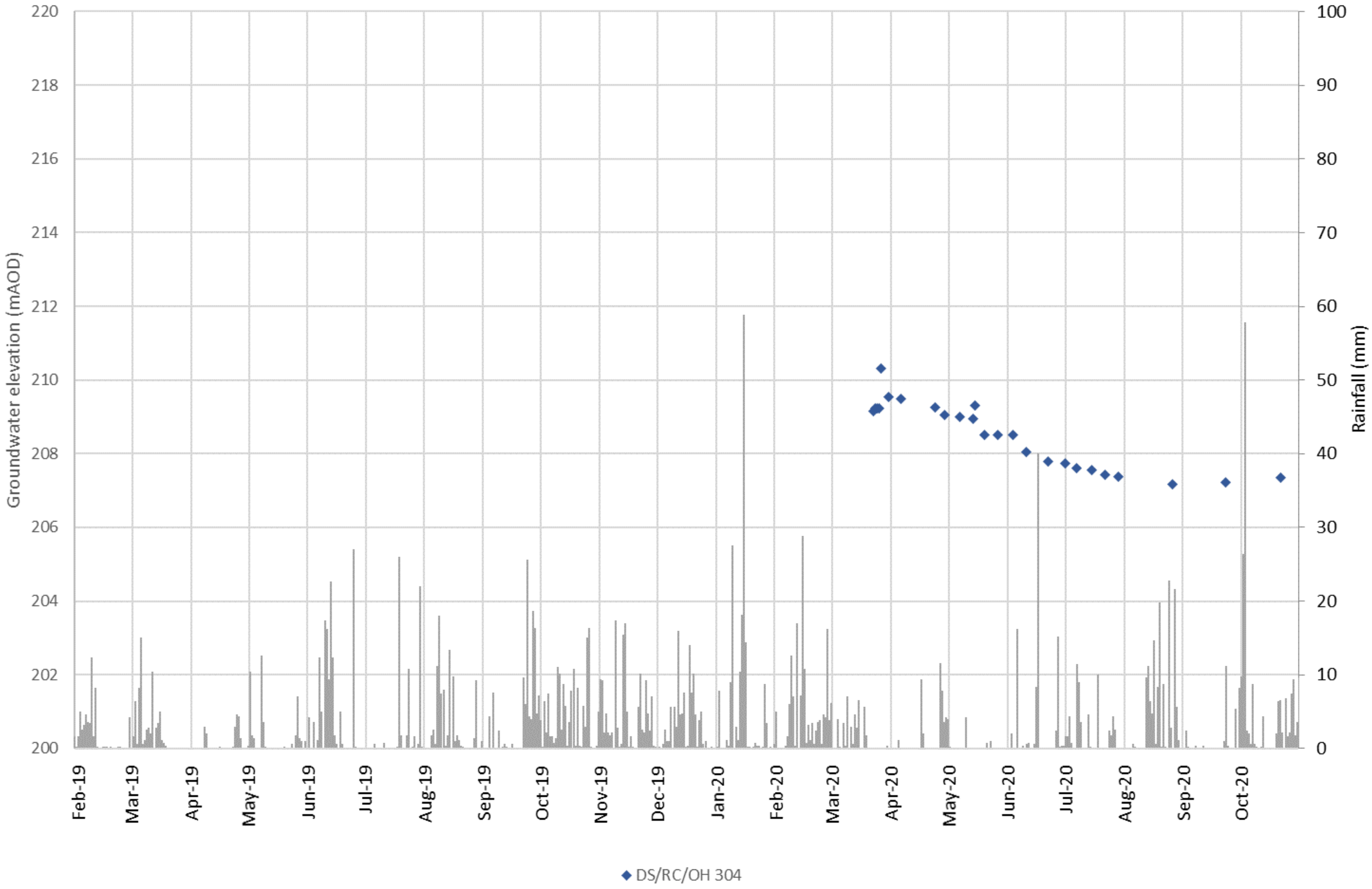

Figure B-28 Lias Group groundwater monitoring – Air Balloon

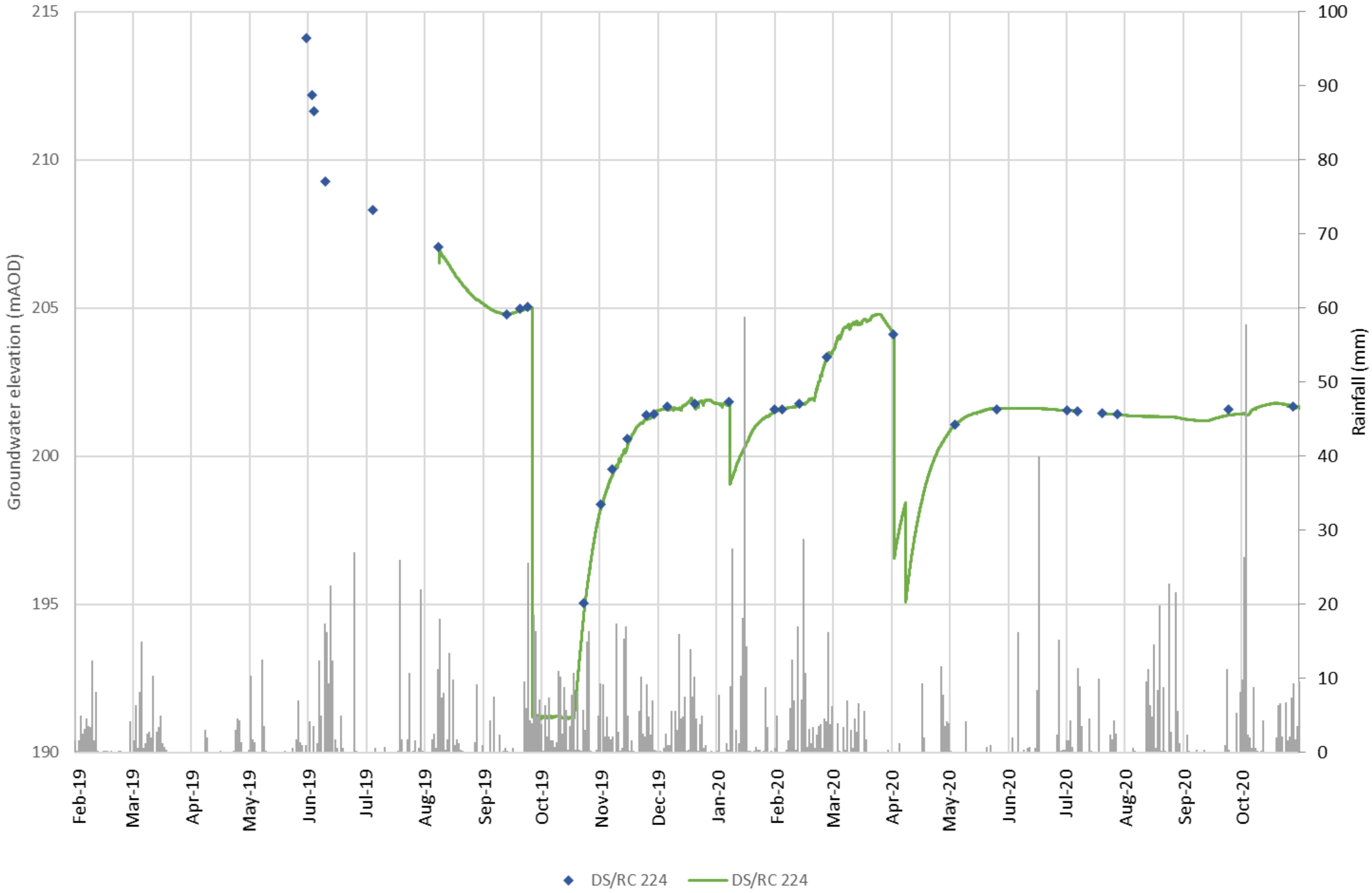

Figure B-29 Lias Group groundwater monitoring – CH1+000 to CH1+400 (southern side of A417) – Upper Crickley Hill

Appendix C Water quality results

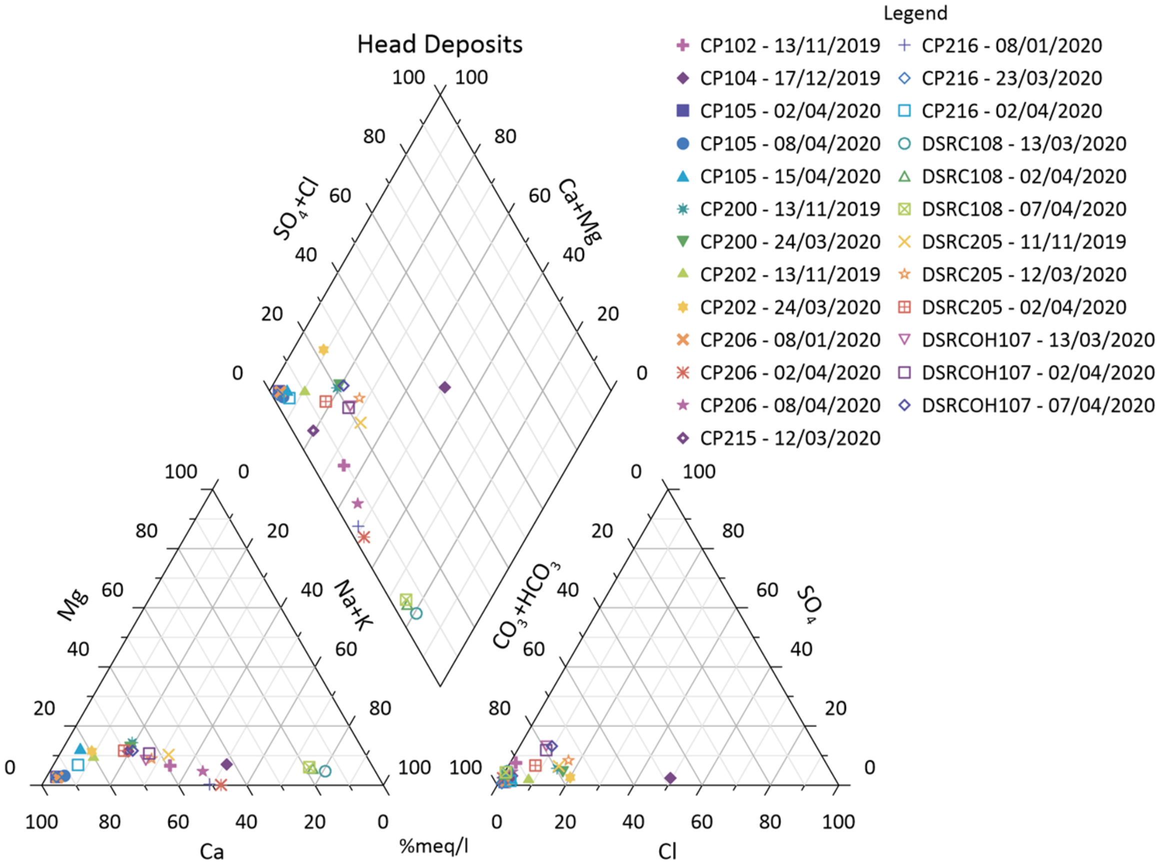

Figure C-1 Mass movement deposits groundwater quality

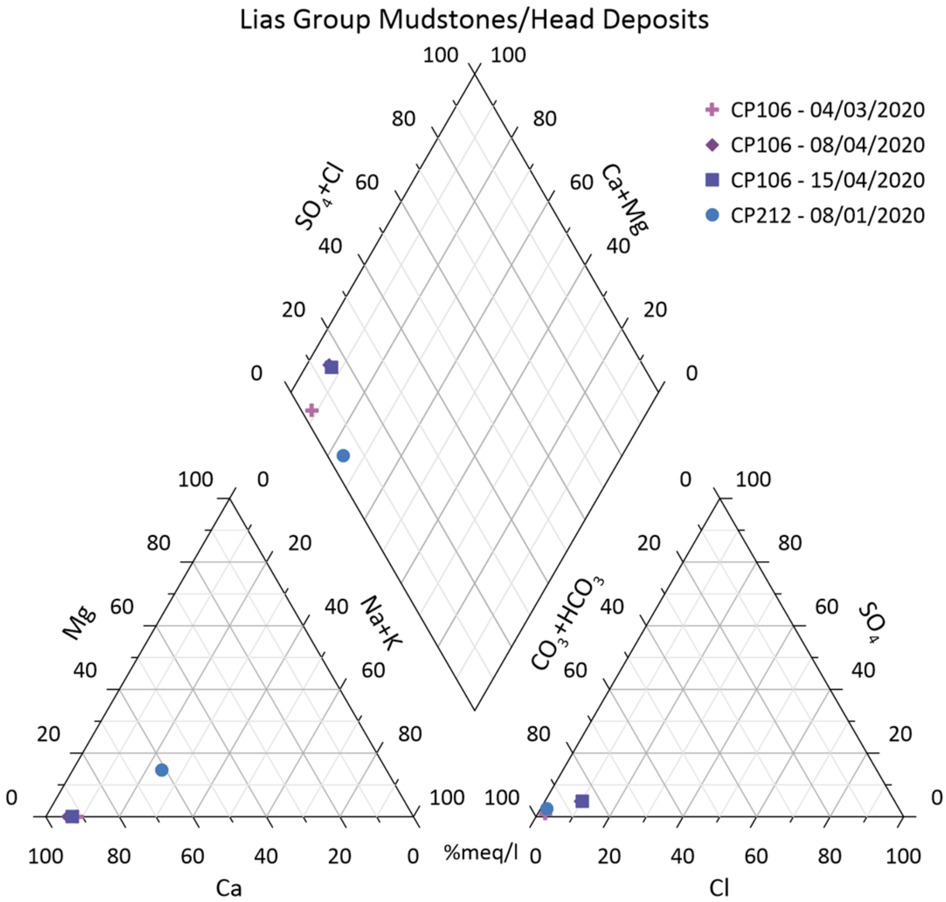

Figure C-2 Mass movement deposits/Lias Group mudstone groundwater quality

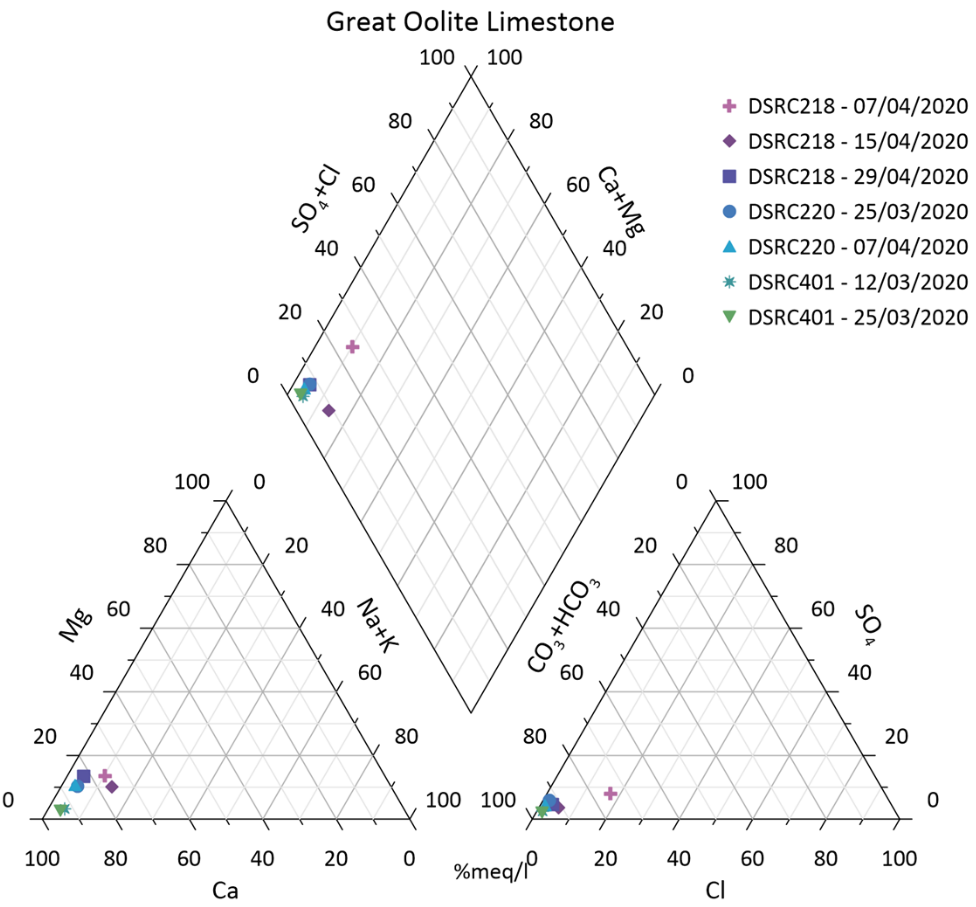

Figure C-3 Great Oolite limestone groundwater quality

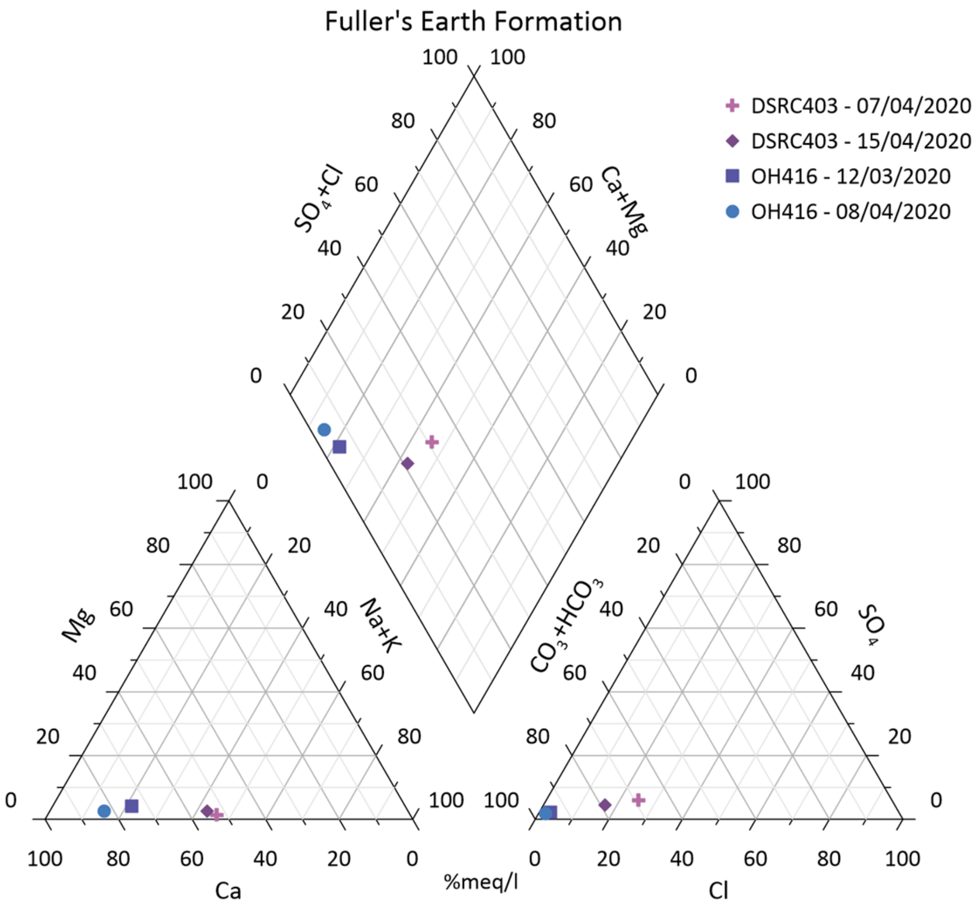

Figure C-4 Fuller's Earth Formation groundwater quality

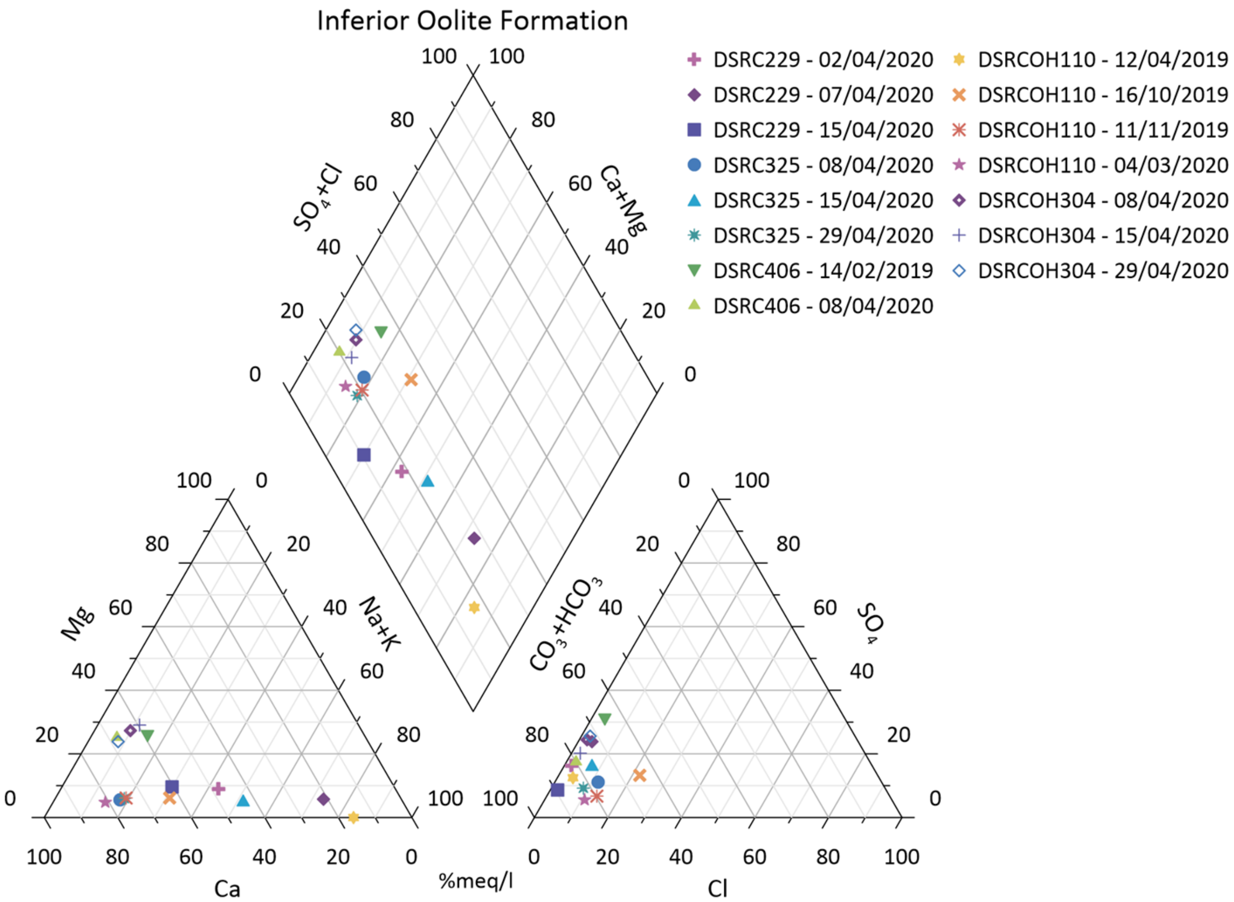

Figure C-5 Inferior Oolite Group groundwater quality

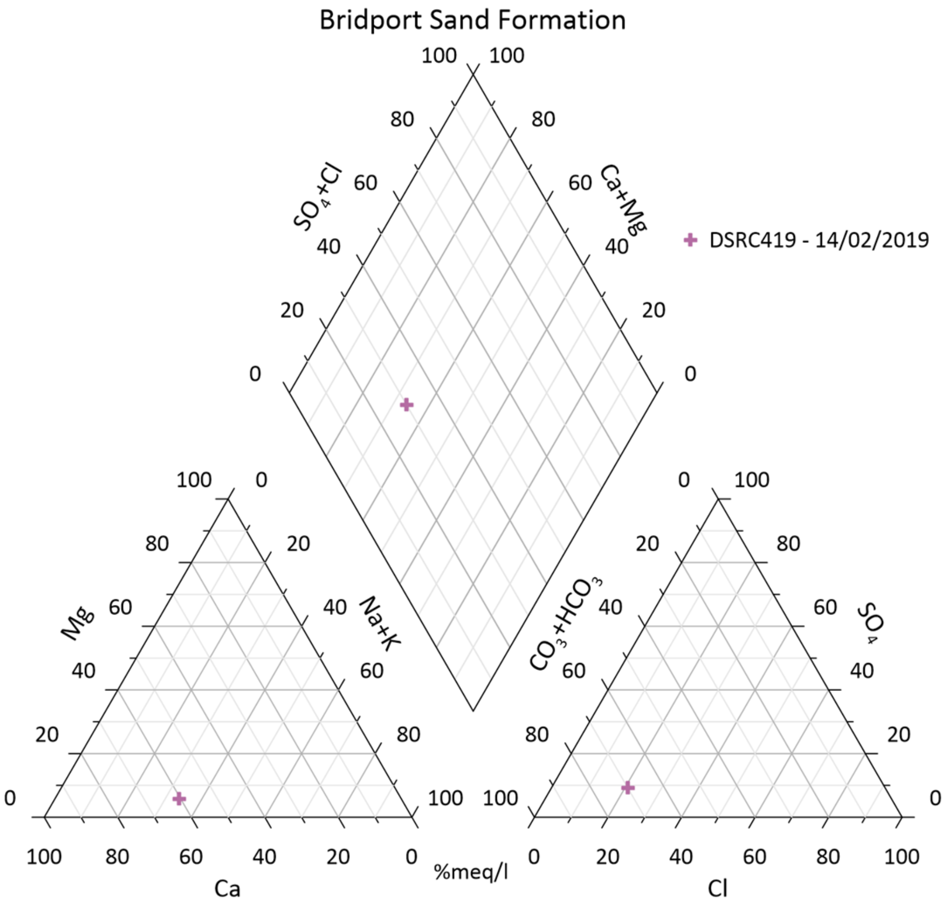

Figure C-6 Bridport Sand Formation groundwater quality

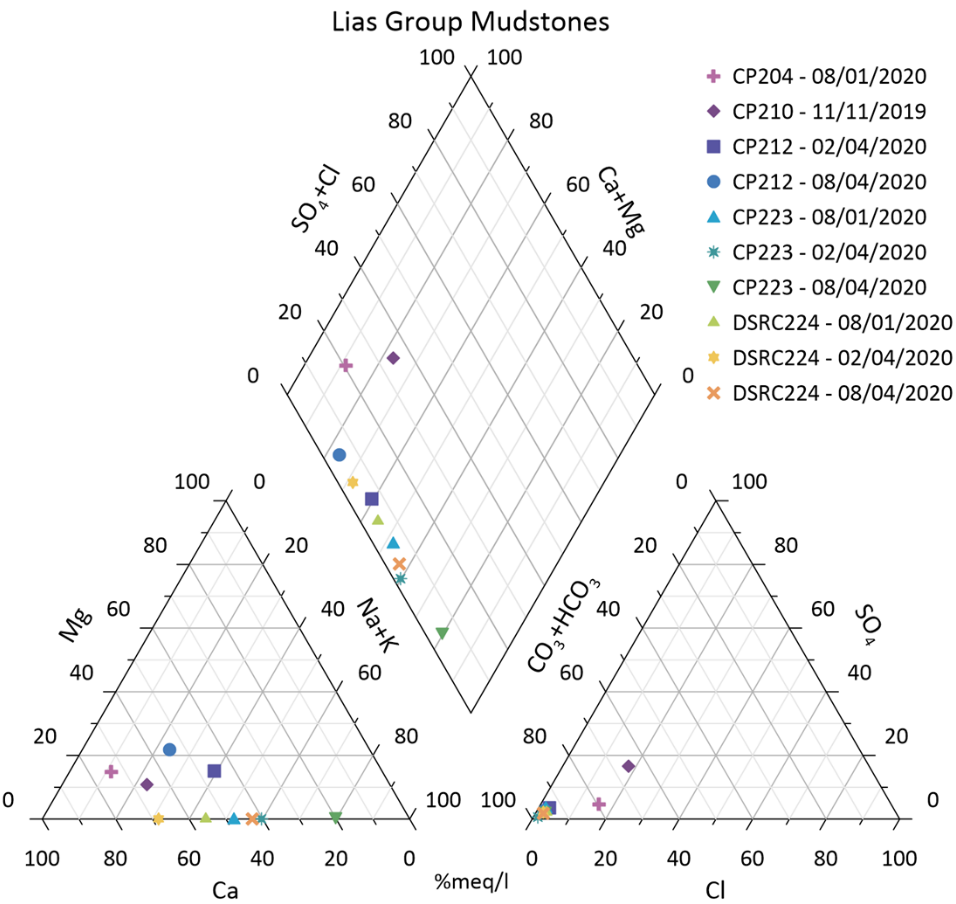

Figure C-7 Lias Group mudstones groundwater quality

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