A conceptual model of the groundwater contribution to streamflow during drought in the Afon Fathew catchment, Wales

Environmental Change, Adaptation and Resilience Programme
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M Ascott, B Brauns, E Crewdson, D Morgan, D Gooddy

Keyworth, Nottingham British Geological Survey 2023

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British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG

Tel 0115 936 3100

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Tel 0115 936 3143
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Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
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Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw,
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Tel 01232 666595
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Foreword

This report is the published product of a study by the British Geological Survey (BGS) into the groundwater contribution to streamflow in the Afon Fathew catchment in Wales. This research was commissioned by Dŵr Cymru Welsh Water as a part of the project “Fathew flow investigation” and was completed by BGS under sub-contract to HR Wallingford.

Acknowledgements

The authors are grateful to staff at Dŵr Cymru Welsh Water (Jo Cullen, Kate Lambert-Smith, Ian Brown) for commissioning and giving permission to publish this research. Additionally, we would also like to acknowledge the support of the HR Wallingford (Valerie Houlden, Jo Ennis, Aodhín McBride, Eleanor Hall, Chris Counsell) and Hydro-Logic Services (Simon Bond) project team, and the landowners and farmers in the Afon Fathew catchment for giving access for the fieldwork.

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Summary

In 2022 BGS was commissioned by Dŵr Cymru Welsh Water (DCWW) to undertake desk and field investigations to develop a conceptual understanding of the contribution of groundwater to streamflow during drought in the Afon Fathew, Wales. This report details the findings of these investigations. In addition to a desk study, two field visits were completed to survey water features in the catchment, take samples for groundwater residence time indicators, and undertake a passive seismic (Tromino) geophysical survey. The results of the desk study and field visits were combined with flow accretion profile data to develop a conceptual model of groundwater flow to the Afon Fathew during drought, described herein.

The Fathew is underlain by a bedrock of silty mudstones which are traditionally considered to be poor aquifers. In the Fathew catchment there is evidence from boreholes for local-scale groundwater flow in the bedrock within fractures and other discontinuities. An upper weathered layer, in combination with faulting and folding patterns, is likely to control the geometry and magnitude of bedrock groundwater flow systems and the location of springs. The residence time indicator data suggest that groundwater in the bedrock is over 40 years old. Estimated discharge from bedrock springs (< 2 l/s, 0.17 Ml/day) is very small relative to the total flow in the Fathew and tributary inflows. The Tromino has shown the superficial deposits in the catchment to be highly heterogeneous in the valley bottom. Changes in the likely permeability and areal extent of the superficial deposits going down the valley bottom correspond to changes in river flows in the Fathew based on the accretion profiles. The Fathew and its tributaries are losing over well drained alluvial gravels, and gaining over low permeability lacustrine and clay-ey alluvial deposits. The Fathew is likely to be hydraulically isolated from the Dysynni catchment. 60% of low flow inflows to the Fathew are coming directly from upland tributary inflows. where very limited superficial deposits are present. In these upland settings during dry periods it is likely that the majority of discharge is coming from baseflow from bedrock.

Baseflow support to the Fathew during drought periods can be conceptualised as a two-phase system: (1) Discharge from the superficial deposits to the river, particularly associated with the down-catchment variability in the permeability and thickness of the deposits, (2) Discharge from the weathered bedrock aquifer into the river, from both springs and tributary inflows. The contribution of these two processes is likely to vary as drought conditions develop. Moreover, flows in springs and tributaries may contribute to downstream storage within the superficial deposits, which may complicate the deconvolution of the Fathew river flow hydrograph into different flow components. This temporal sequencing requires further investigation. Further work such as groundwater and surface water monitoring during dry periods and electrical resistivity tomography may be beneficial to constrain these uncertainties.

1 Introduction

This report details the results of activities undertaken to develop an improved conceptual understanding of the baseflow contribution to the Afon Fathew during drought. This work was commissioned by Dŵr Cymru Welsh Water (DCWW) and undertaken by BGS in Summer 2022.

This report is structured as follows. Section 2 provides an overview of the geology and hydrogeology of the catchment based on a desk-based review of existing literature. Section 3 reports the results of two field surveys undertaken in Summer 2022 to better constrain the hydrogeology of the Afon Fathew catchment. The first field survey assessed the water features in the catchment and in the second survey groundwater residence time indicator sampling and passive seismic (Tromino) surveying was undertaken. Section 4 uses this information to develop a conceptual model for groundwater flow in the Fathew catchment. Recommendations for further work are presented in section 5.

2 Desk-based conceptualisation

2.1 GEOLOGY

2.1.1 Bedrock geology and structure

The bedrock geology and faulting in the Afon Fathew catchment is shown in Figure 1 and is reported by Pratt et al. (1995). A bedrock cross-section across the southwestern edge of the Afon Fathew catchment is shown in Figure 2. In addition to the work of Pratt et al. (1995), we also reviewed the field slips from the original survey of the area. The bedrock of the catchment is entirely of Ordovician age and dips c. 40-60° to the southeast. The north side of the valley, the valley bottom and the immediate south side of the valley is underlain by the Ceiswyn Formation. This consists of thinly bedded, turbiditic silty mudstones each of c. 0.01 – 0.2 m thickness and grey-black in colour, with occasional veins of quartz at outcrop. Exposures in the northeast of the catchment at Hendre forest have shown the Ceiswyn formation to be well cleaved and jointed (Martin et al., 1981). To the west of the catchment, the Ceiswyn formation also contains thin sequences of fine grained sandstones at outcrop of up to 10 m thickness near Brynglass, Dolau-Gwyn and Dol-Deheuwydd, although these are reported to not be laterally extensive. The Ceiswyn formation is reported to be up to 1500 m thick in the region.

The areas south of the valley bottom consists of younger Ordovician deposits. The Nod Glas mudstone immediately overlies the Ceiswyn formation and consists of a thin outcrop of black mudstones with very faint lamination. The Nod Glas is reported to be softer than the underlying Ceiswyn formation and consequently the former is often present on an area of flat ground or hollow on the valley side (Martin et al., 1981). Locally it has been reported to have well developed and highly deformed cleavage which may influence hydraulic conductivity and groundwater flow patterns (Glendining et al., 1981). Above this are the Broad Vein Mudstone and Narrow Vein Mudstone which are massive, tough grey silty mudstones, the latter just 13-15 m thickness and occupying a relatively flat band at outcrop. Both the Broad vein and Narrow Vein mudstone have been mined for slate at quarries, Dolgoch in the Fathew catchment and nearby Bryn Eglwys.

The high ground to the south of the catchment is mapped as the Garnedd-Wen Formation. This is predominantly a massive silty mudstone and is reported to be up to 1200 m thick in the area. The formation is generally poorly exposed. Field slips recorded during previous geological mapping suggest that some of the higher ground is overlain by a thin layer of peat (generally unmapped on 1:50,000 geological mapping), on which drainage channels have been incised by 0.5 m in areas south of Tarren Nant-y-Mynach and far west near Tarrenhendre. The formation also includes a number of sandstone sequences. On the southern hillside between Brynglas and Dolgoch there are two narrow beds of sandstone, each up to 20 m thick with high matrix porosity and separated by 20 – 50 m of sandy mudstone. A further sandstone sequence of variable lithology (pale grey, coarse to fine silty sandstone) is found in the upper catchment of the Pandy. The Tal-y-llyn fault runs the entire length of the Afon Fathew along the valley bottom, resulting in the lineament from Bala, to the south of Cadair Idris to the coast at Tywyn. In the valley bottom presence of gullies and linear knolls have been interpreted as several faults rather than a single one.

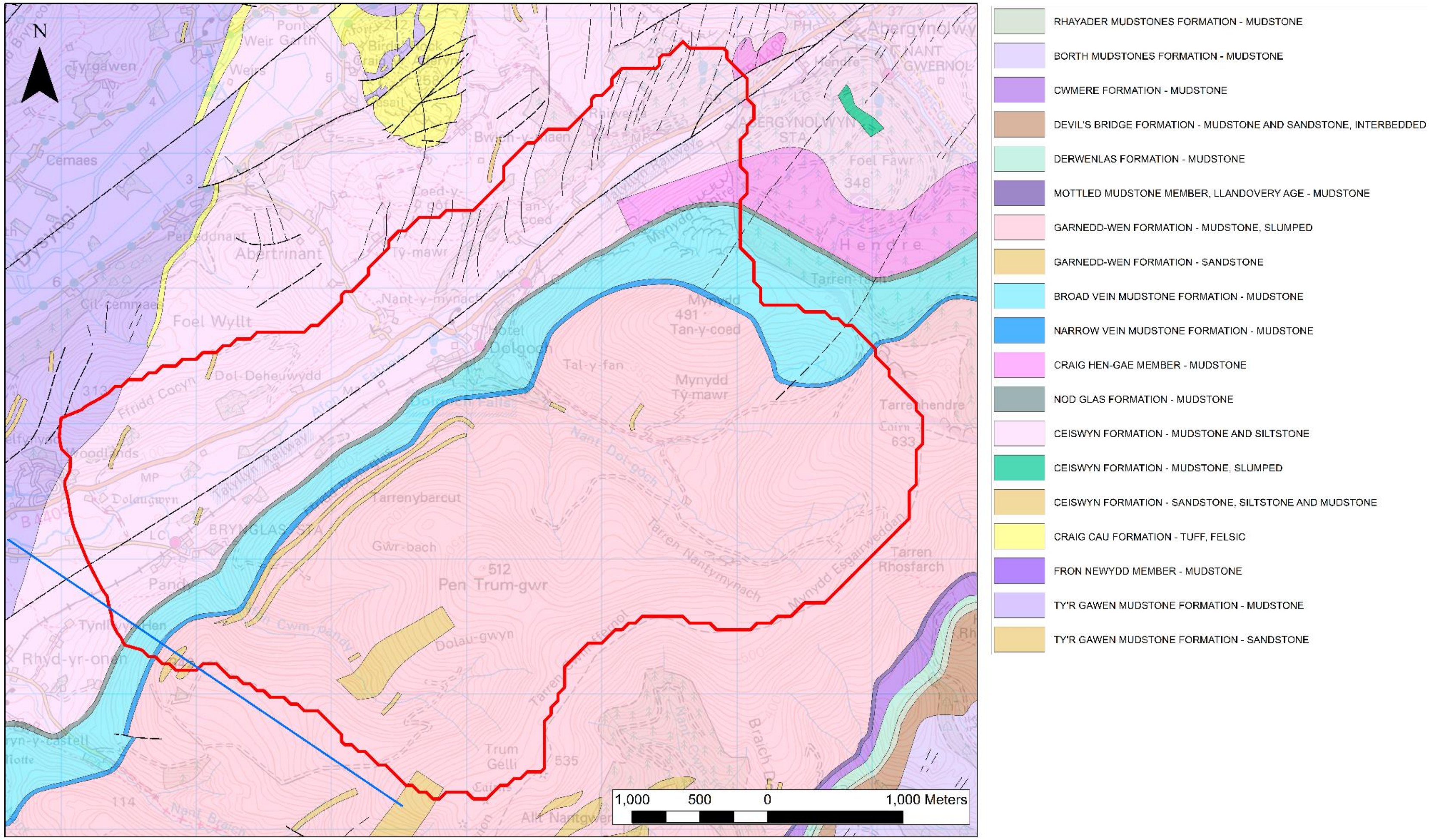


Figure 1 Bedrock geology and faults and folds in the Afon Fathew catchment (red solid line). The blue solid line indicates the line of section in Figure 2. Contains Ordnance Survey Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290. Contains BGS materials © UKRI. All rights reserved.

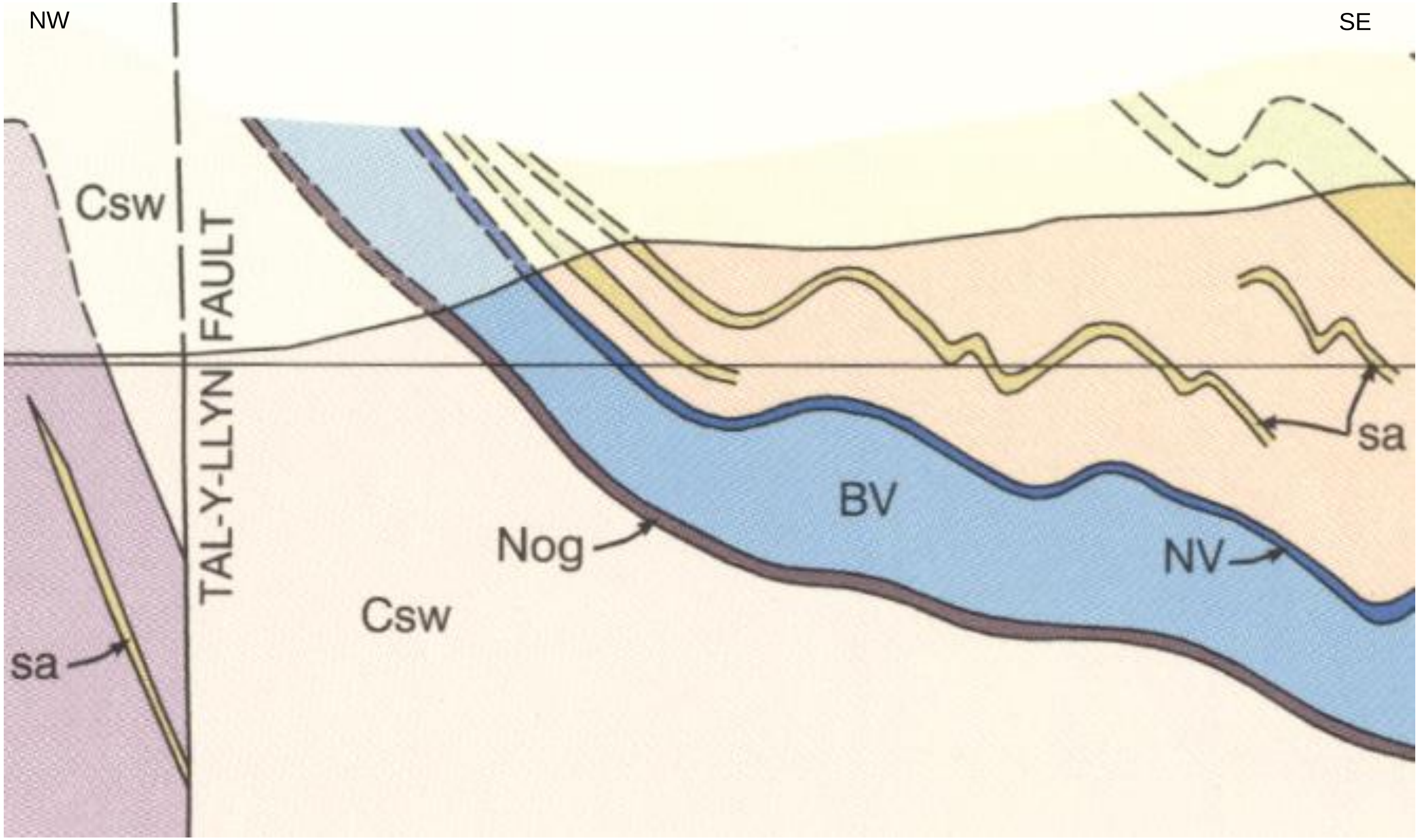


Figure 2 Bedrock cross section across the southwestern edge of the Afon Fathew catchment (showing geology interpolated above (dashed lines) and below (solid lines) modern-day topography). Geology shown in cross section: Ceiswyn Formation (Csw), Nod Glas Mudstone (Nog), sandstone beds (sa), Broad Vein Mudstone (BV), Narrow Vein Mudstone (NV). Reproduced from British Geological Survey (1995) © UKRI.

2.1.2 Superficial and mass-movement deposits

Superficial and mass-movement deposits in Afon Fathew catchment are shown in Figure 3. At the head of the valley at Abergynolwyn Station there are landslip deposits. It has often been considered that, together with recent glacial activity, these deposits resulted in the diversion of the Afon Dysynni from along the Bala lineament to a northwestern direction (Stephens, 1990). However, the glacial geomorphological history of this “river capture” has been subject to debate. The elevation of the base of the Fathew-Dysynni col (below the landslip deposits) are reported to be some 30 m above the Dysynni river (see Figure 4, Watson (1962)). Superficial deposits are present continuously from Abergynolwyn station down the length of the Fathew valley, however these are highly heterogeneous. With the exception of one borehole at Ty-Gwyn (see section 2.2.3), the thickness of the superficial deposits is unproven in the Fathew catchment. Near Abergynolwyn station in the valley bottom there is a narrow (c. 120 m) strip of flat topped alluvial fan. This widens downstream to c. 205 m at Tan-y-coed-isaf. The alluvial fan is reported to be predominantly clay, with head deposits (mudstone fragments in a silty clay matrix) on the immediate valley sides. In the valley between Tan-y-coed-isaf and Dolgoch Falls lacustrine alluvium is mapped. Exposures suggest this is predominantly silty clays with some overlying peat.

From Dolgoch to Brynglas alluvium is mapped in the immediate valley bottom, with local fan deposits. Immediately downstream of Dolgoch the land is reported to be well drained with extensive coarse alluvial gravels. Further downstream to the valley by Dol-Deheuwydd is highly heterogeneous alluvial deposits, consisting of interbedded clays and gravels where exposed. The alluvium in the valley bottom from Dol-Deheuwydd to Brynglas is reported to have a greater clay content (up to 1 m thickness in surface exposures), and peat-rich alluvial fan (exposures up to 0.8 m thickness) away from the valley bottom. There are extensive field drains in this area.

In the valley due north of Brynglas the alluvium narrows substantially to a very thin area (c. 50 m) of poorly sorted gravels overlain by c. 1 m of clay. In this area the Ceiswyn Formation is at outcrop near the valley bottom. Further downstream between Brynglas and the catchment outflow the alluvium in the valley bottom is reported to be predominantly gravels, with some clays and mudstone fragments. Alluvial fan deposits in this area are heterogeneous, with coarse gravels reported near Pandy Farm, but grey clay with exposures of up to 1 m thick near the catchment outflow. A site investigation bore at the Welsh Water Fathew intake penetrated c. 3 m of gravel and weathered silt and mudstone.

Away from the valley bottom there some isolated superficial deposits have been mapped on the hillsides. These principally consist of periglacial head deposits (mudstone fragments in a silty clay matrix located near Brynglas, peat dominated near Ffrid cocyn), some isolated alluvial fan deposits (grey clay with subrounded mudstone fragments at Abertrinant) and peat (in upland areas near Pen Trum-gwr and Tarren Nant-y-Mynach). It has previously been reported that peat growth occurs in the region along spring lines associated with faults or bedrock formational boundaries, although mapped peat deposits in the Afon Fathew catchment are not present near these features.

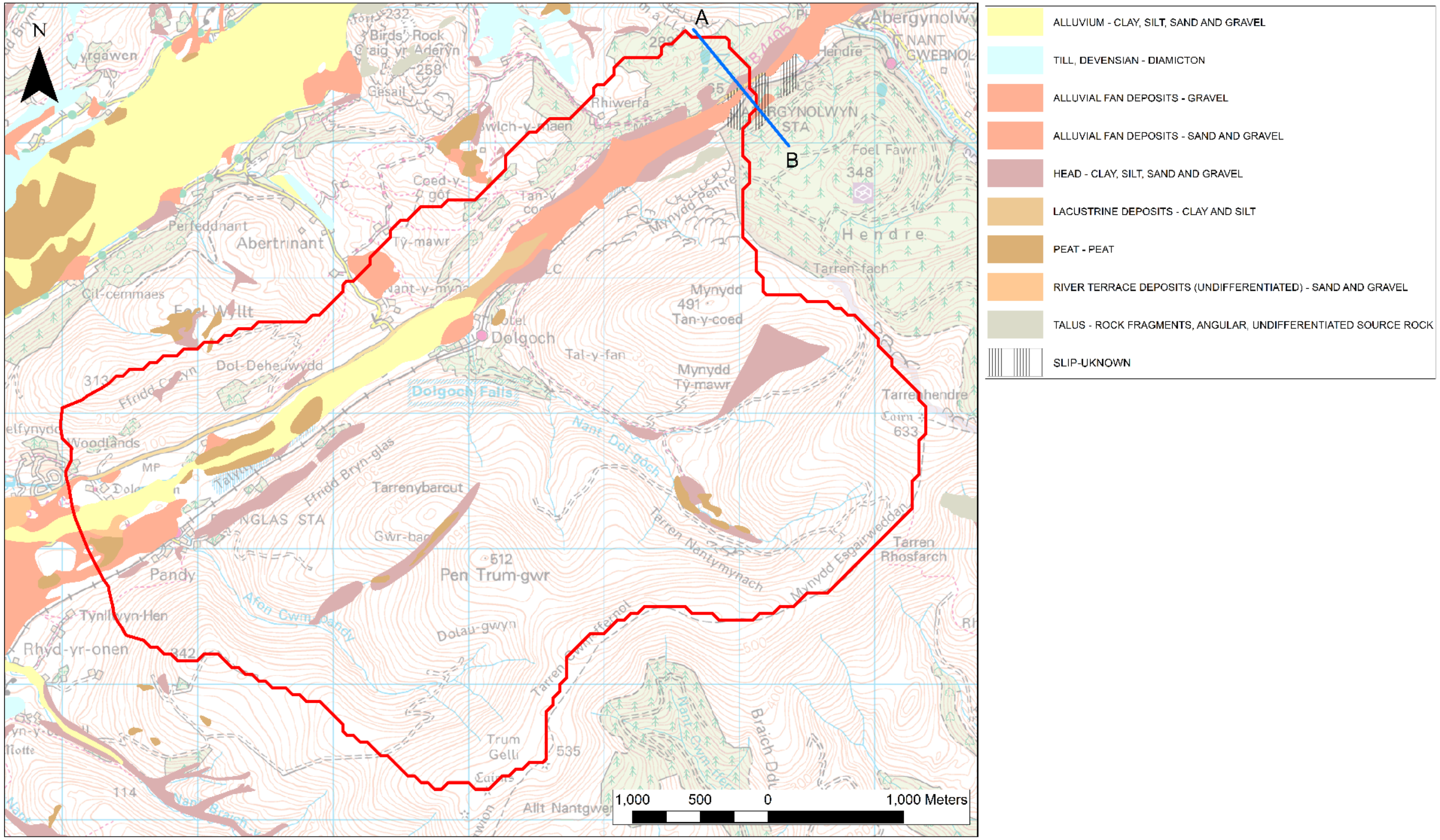


Figure 3 Superficial and mass-movement deposits in the Afon Fathew catchment (red solid line). Blue solid line indicates line of section AB in Figure 4. Contains Ordnance Survey Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290. Contains BGS materials © UKRI. All rights reserved.

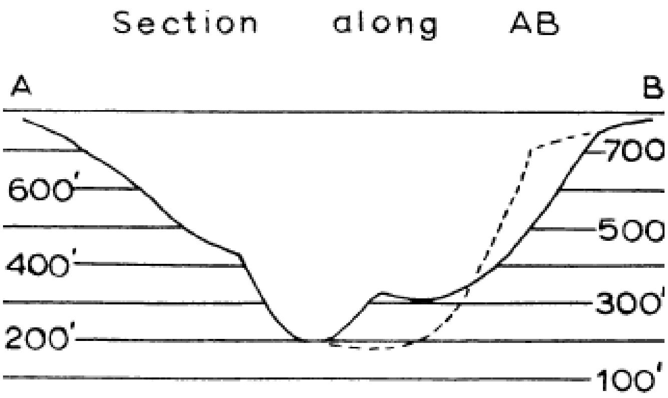


Figure 4 Topographic cross section across the Fathew-Dysynni col. Line of section indicated in Figure 3. Reproduced after Watson (1962) from Transactions and Papers (Institute of British Geographers) © 1962 The Royal Geographical Society (with the Institute of British Geographers), with permission from Wiley.

2.2 HYDROGEOLOGY

2.2.1 Hydraulic properties

It should be noted from the outset that there is a dearth of information relating to the hydraulic properties of both the bedrock and superficial deposits in the Fathew catchment. The Fathew is only mapped hydrogeologically on the national scale 1:625,000 hydrogeological map of England and Wales, there are no regional or local scale hydrogeological maps of this area. There is no information on the permeability and storage of the formations in the Fathew catchment, although there are two boreholes in BGS records with limited data present (see section 2.2.3). As a result of this, this desk-based assessment of the hydrogeology of the formations in the Fathew catchment is reliant on the literature related to groundwater flow in Ordovician rocks and superficial deposits in other catchments in Wales. Previous studies have been summarised by Robins and Davies (2016) and Jones et al. (2000), with the nearest analogous hydrogeological study being the work of Glendining et al. (1981) on the Dyfi catchment.

The bedrock formations in the Afon Fathew catchment are classified as “Low productivity aquifers” on national scale 1:625,000 hydrogeological maps, with only limited, local yields. Groundwater flow and storage occurs virtually entirely through fractures and other discontinuities, with primary porosity having a negligible role. The orientation of the fracture network typically defines the hydraulic conductivity vector and groundwater flow direction. Fracture system development is considered to be controlled by proximity to local structural features such as faults and fold axes, as well as the development of a weathered upper horizon due to periglacial frost-shattering (Jones et al., 2000). Spring locations are often associated with lineaments and faults, although presence of field drainage within peat deposits in upland areas may have altered spring discharge locations. Water tables are often shallow where there is insufficient storage to accept recharge, although groundwater in these settings may be perched and may only reflect small scale fracture flow systems. The outcrop sandstone sequences in the Fathew may have slightly greater permeability through enhanced weathering and fracture development and the potential for storage in the matrix. Glendining et al. (1981) suggest that the Bala Fault that runs the length of the river Fathew is a flow boundary, although no evidence for this is presented.

The potential for groundwater flow within the superficial deposits in the Afon Fathew is likely to be highly variable dependent on lithology and presence of gravel or clays. In areas of the valley bottom where the superficial deposits are predominantly sands and gravels, these are likely to be able to store and transmit groundwater. When at the surface, these have been shown regionally to receive direct rainfall recharge and may be in hydraulic continuity with the river as observed through presence of gaining and losing river reaches (Robins and Davies, 2016). However, presence of persistent clay and silt within the superficial deposits is likely to inhibit recharge and groundwater flow, and as such groundwater flow may be isolated in gravel sequences. A significant uncertainty in the Afon Fathew in relation to the baseflow support is the vertical structure and heterogeneity within the superficial deposits. In other similar catchments in west Wales (Robins and Davies, 2016), clay and silt layers have been shown to result in shallow perched water tables in upper strata, with semi-confined more permeable deposits below. Incision of the river bed to the lower permeable deposits results in further complexity. In the Afon Fathew, the vertical heterogeneity, thicknesses, and extent of river incision in the superficial deposits is largely unknown, which is a significant constraint on our understanding of the potential for baseflow support from these deposits.

2.2.2 Groundwater-Surface Water Interactions and baseflow contributions

In an assessment of the glacial geomorphology of the Fathew, Watson (1962) provides some insights into the nature of the superficial deposits in the valley bottom. It was reported that there is no permanent stream for c. 1500 m downstream of Abergynolwyn station, with streams from Ty'n-yr-efail, Rhiwerfa and Mynydd Pentre normally sinking into the stream bed just above the valley floor in normal conditions. This may suggest the alluvial fan deposits have some permeability in this area, despite the mapping suggesting extensive silty clays. Further, Watson (1962) suggests the superficial deposits in the reach between Abergynolwyn and Tan-y-coed-uchaf may be "loosely packed open material" or "infilling gravels". C. 400m further down the valley (taken to be near Tan-y-coed-uchaf) It was reported that there is permanent drainage, with the water table "permanently at the surface". Between Tan-y-coed-uchaf and Pandy the Fathew valley bottom is reported to be "marshy", and at Pandy itself. Watson (1962) also notes the presence of exposed bedrock in the valley bottom.

In the nearby Dyfi catchment, Glendining et al. (1981) showed that the direction of first-order streams is parallel with the orientation of mapped joints (c. 120 degrees), which are generally vertical or sub-vertical. The same appears to be true in the Fathew, with the Pandy and Dolgoch streams in the same general direction. Using daily streamflow data for 1962-1971, Glendining et al. (1981) also used a simple water balance approach to develop initial estimates of baseflow contributions to the Dyfi. A master recession curve analysis was used to divide stream flow in the Afon Dyfi into an early runoff recession, a recession associated with release of water from river gravels and alluvium, and a still slower recession associated with release of water from the bedrock. Mean annual stream baseflow was calculated as c. 22% of effective precipitation (infiltration + runoff). Of the mean annual stream baseflow, 88% of this was from infiltration from the bedrock and 12% was from the superficial deposits. This is likely to be an overestimate as it does not consider interflow or flow between the superficial deposits and the bedrock, but it does highlight the potential for groundwater contributions to baseflow in a hydrogeologically similar nearby catchment.

2.2.3 Boreholes and springs

Records are held in BGS archives for two boreholes in the Fathew catchment. The locations of these (in addition to other sites visited during the walkover survey) are shown in Figure 5.

A borehole at Rhiwerfa (BGS reference SH60NE5) was drilled to 80 m depth in 2008. The borehole logs report 1 m of superficial deposits, followed by 9 m of "grey and black mudstones", 3 m of "grey clay" and 67 m of "grey and black marl". The mudstones, clays and marls are interpreted as the Ceiswyn Formation. The rest water level was reported as 12 m below ground level, with an estimated yield during drilling of 1.5 l/s (0.123 Ml/day).

A borehole at Ty-Gwyn (BGS reference SH60NE6) was drilled to a depth of 30 m in May 2022. 2 m of superficial deposits were encountered (reported as clay, silt and sand), followed by 28 m of "extremely fractured dark grey-brown mudstone", interpreted as the Ceiswyn Formation. Water strikes occurred at 5, 10, 15, 20 and 25 m below ground level, and a low-moderate yield of 3.3 l/s (0.29 Ml/day) was reported. It is likely that the fracturing in the mudstones observed in this borehole are derived from the development of the weathered zone.

Several springs are mapped in the catchment (see results of catchment water features survey in section 3), but no historical spring flows or yield data are available. In the nearby Dinas Mawddwy area, springs from the Ceiswyn Formation are reported to be due to the presence of calcareous bands in the uppermost strata of this formation. Regionally, springs are reported to be at the interface of the superficial deposits and the bedrock (Glendining et al., 1981; Robins and Davies, 2016).

3 Results of field activities

3.1 WATER FEATURES SURVEY

3.1.1 Overview of activities and general observations

A water features survey was conducted during the BGS field campaign, identifying the main inflows into the Afon Fathew, locating potential sources of springs, and surveying part of the Dysynni catchment. Where applicable, field parameters (temperature, dissolved oxygen (DO), specific electrical conductivity (SEC), oxidation-reduction potential (ORP)) were measured, and flows were estimated via flow measurement into a bucket. In addition, two boreholes not captured by the BGS database were identified and sampled for residence time indicators. An overview of the survey points with measured parameters is given in Figure 5.

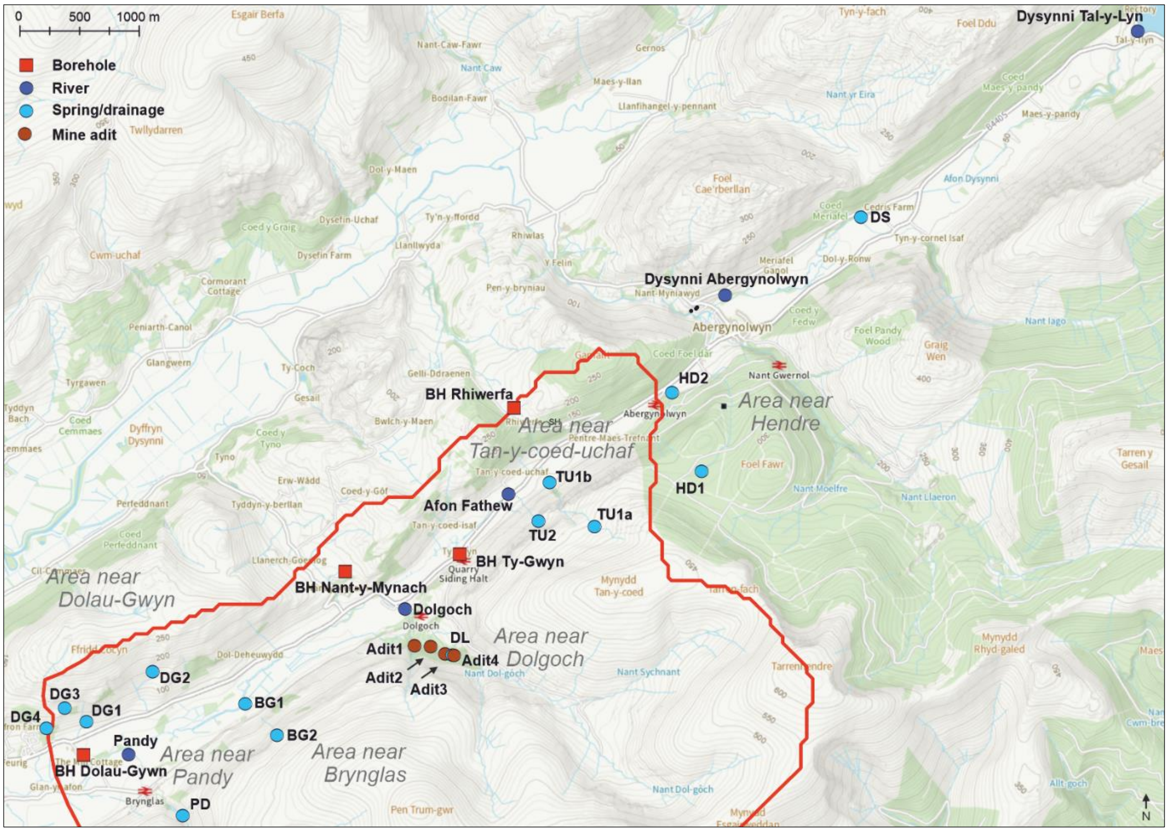


Figure 5 Overview of survey points where measurements were taken (BG = Brynglas, DG = Dolau-Gwyn, DL = Dolgoch, HD = Hendre, PD = Pandy, TU = Tan-y-coed-uchaf). Contains Ordnance Survey data © Crown copyright and database right 2022.

During the field survey, some general observations and colloquial information on the catchment was gained through personal communication with farmers, landowners and tenants. This indicated the following:

- There may be a rain shadow effect, with less rainfall in the western/ downstream portion of the Afon Fathew catchment compared to upstream and the upper reaches of the Afon Dysynni upstream of Abergynolwyn. Farmers observed that when weather systems travel from the coast eastwards over the catchment, precipitation starts at, or approaching, Abergynolwyn station.
- Springs are used by several of the landowners and tenants for water supply; some provide a sufficient yield all year round, some do not (either due to reduced flows or drying out completely for part of the year). The majority of perennial springs are captured on the northern flank of the valley, though several springs around Brynglas and the Pandy were also noted to have continuous flow, at least enough to sustain a single domestic dwelling and farming activities.
- Spring flows may be lower in 2022 than usual. Several of the farmers commented on the very low stream flows in 2022, mentioning also that some springs had dried up during the dry season that would not usually. Farmers noted that contrary to their expectations, higher spring discharge/drainage did not follow some of the heavier rainfall events in May/June 2022 (no specific date given).
- There may be an increase in borehole drilling in the Afon Fathew valley in 2022 compared to previous years, landowners spoke of neighbours who had enquired or were planning to drill boreholes this year.
- One landowner commented during a conversation on 28 June 2022 that they had never seen the Pandy as low as this year (2022) despite farming the land for several decades.
- Two hydropower schemes were found in the area (on the Pandy and at Dolgoch falls, see Appendix II for more details). However, at the time of the first field visit (end of June 2022), the field team was informed that the Hydro Power scheme on the Pandy was not running in the weeks before and at the time of visit on 28 June 2022. According to the landowner, the scheme was restarted in mid-July, and it was running at the time of the second field visit (early August). One tenant/landowner mentioned that they saw a correlation between the installation of the Pandy Hydro Power Scheme and reduced flow on some of the springs in the area . Consequently locals were seeking to install boreholes for domestic use. Run-of-river hydropower schemes are generally not consumptive, although no evidence for this was available at the time of writing for the two schemes in the Fathew catchment. Assuming that

the schemes are not consumptive, impacts on spring discharges are likely to be negligible.

3.1.2 Observations and field parameters in the Fathew, Dolgoch, Pandy and Dysynni rivers

During both visits, the observation by Watson (1962) that there seems to be permanent drainage near Tan-y-coed-uchaf can be confirmed (Figure 6 A). However, this permanent drainage is very low and while it is visible on the surface just south of the Tan-y-coed-uchaf-farm, it disappears a few hundred metres further downstream (just north of Ty-Gwyn Farm, see Figure 6, B), before it resurfaces near Ty-Gwyn Farm at the transition from the alluvial fan to the lacustrine deposits (Figure 6, D/E).

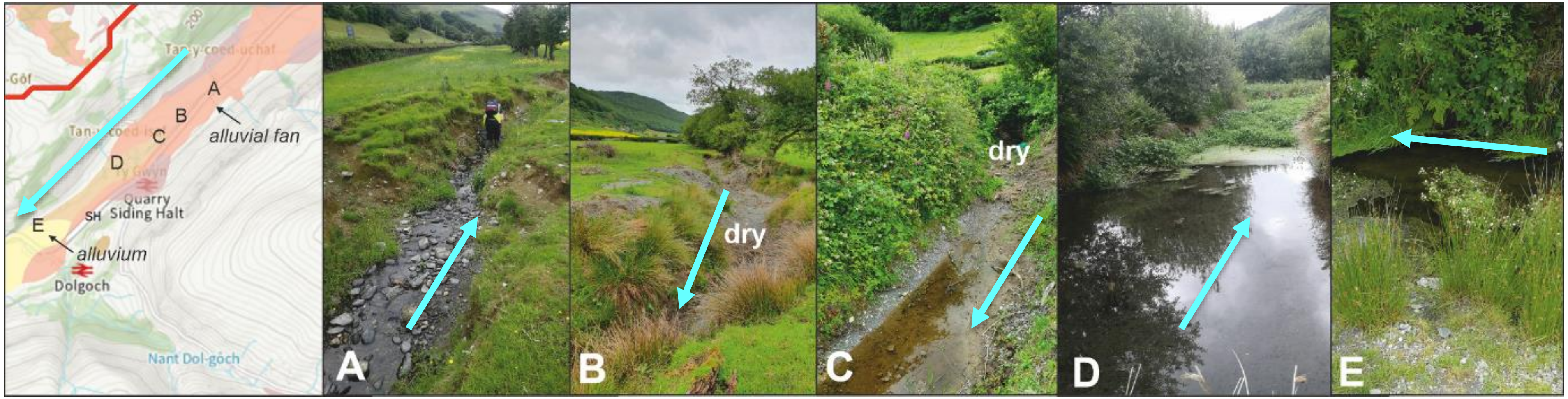


Figure 6 Map superficial deposits (left) and photos showing flow of the Pandy near Tan-y-coed-uchaf described by Watson (1962) as permanent drainage (A), disappearance into the alluvial fan deposits further downstream (B) resurfacing at the boundary between alluvial fan – lacustrine deposits (C), ponding in the lacustrine deposits (D), and flow in the lacustrine deposits (E). Arrows indicate flow direction (arrows point from upstream to downstream including where no flow observed). Contains Ordnance Survey data © Crown copyright and database right 2022.

Aside from the two major inflows (Dolgoch and Pandy), flow from the hillsides that continued into towards the Afon Fathew could only be observed in two locations (from the southern hillside at Tan-y-coed-uchaf and from the northern hillside at Nant-y-Mynach, further documented in the subsection on springs and drainage below).

Field parameters were obtained during the first field campaign from two locations on the Afon Dysynni), from the Afon Fathew and its major two tributaries (Dolgoch and Pandy) Locations are presented as blue circles in Figure 5, and measurements listed below in Table 1.

Table 1 Measured field parameters and grid references of locations along the Afon Fathew/Pandy/Dolgoch/Dysynni (SEC= specific electrical conductance, DO= dissolved oxygen, ORP = oxidation-reduction potential, T=temperature).

Name	Date	Elevation (m aOD)	pH	SEC (µS/cm)	DO (mg/l)	ORP (mV)	T (C)
Dysynni-Tal-y-Lyn SH71050944	29/06/22	83	8.2	57	10.7	420	17.1
Dysynni-Abergynolwyn SH67560719	30/06/22	33	6.7	58	9.9	481	17.0
Afon Fathew SH65840558	29/06/22	42	7.4	137	11.6	218	15.2
Dolgoch SH64980462	29/06/22	38	6.7	50	10.4	365	13.5
Pandy SH62690344	29/06/22	24	6.7	61	10.5	418	14.0

Overall, the field parameters were similar across the Afon Fathew, Dolgoch, Pandy, and the Afon Dysynni at Abergynolwyn. All locations had circumneutral pH except at Tal-y-Llyn on the Afon Dysynni. The measured specific electrical conductance (SEC) of 137 µS/cm, measured on the Afon Fathew upstream of Dolgoch, is much higher than the waters on the Dolgoch and Pandy (50 to 61 µS/cm). This indicates more highly mineralised waters, and could be due to a greater proportion of older, slower moving, groundwater along this reach of the Afon Fathew which corroborates observations at the location (near Tan-y-coed-uchaf) of fewer inflows and stagnant/ dry reaches (shown in Figure 6).

3.1.3 Drainage and springs

A number of suspected spring locations identified during the desk study were visited in the field and investigated. Aside from establishing an overview of springs draining into the Afon Fathew, another aim of this walkover survey was to establish suitable locations for collecting samples for residence time indicators (groundwater age tracing). During the survey, field parameters were collected at a number of points (listed in Table 2, see light blue points in Figure 5 for locations), and surface discharges were estimated. The discharge was measured by filling a container of known volume and measuring the time taken to fill (either 10L in a bucket, or lower volumes in a beaker where flows were visibly small). Unfortunately, all visited locations offered only limited opportunity for residence time indicator sampling. Most sites did not comprise of discrete outflows from the bedrock, and where this was the case, it was difficult to collect a water sample without prior exposure to the atmosphere (it is critical to exclude atmospheric air from the sample for accurate dating using CFCs and SF_6 residence time indicators). Therefore, no springs (or surface drainage) were sampled for residence time indicators. Groundwater age or recharge year could not be ascertained for these water features.

Table 2 Information on measured drains/springs (Q=discharge, SEC= specific electrical conductance, DO= dissolved oxygen, ORP = oxidation-reduction potential, T=temperature), names indicative of area (see caption). Observation areas are ordered from northeast (upstream) to southwest.

Name and NGR	Date	Elevation (m aOD)	Estim. Q (l/min)	pH	SEC (µS/cm)	DO (mg/l)	ORP (mV)	T (°C)
Draining into the Dysynni catchment								
DS SH68760789	30/06/22	41	n.d.	5.0	53	10.0	541	n.d.
HD1 SH67540585	30/06/22	254	n.d.	5.0	72	5.0	555	n.d.
HD2 SH67200644	30/06/22	70	60	7	92	11.0	413	12.2
Drainage towards the Afon Fathew								
TU1a SH66550533	27/06/22	305	n.d.	5.0	50	n.d.	n.d.	n.d.
TU1b SH66180569	29/06/22	59	30	5.0	87	10.0	555	n.d.
TU2 SH66090537	27/06/22	168	(3?)	5.0	69	n.d.	n.d.	n.d.
BG1 (drain) SH63660386	30/06/22	25	n.d.	5.8	109	11.2	489	13.7
BG2 SH63890364	04/08/22	148	(>3?)	7.0	113	11.0	224	10.3
DG1 SH62340371	28/06/22	68	3.2	7.5	121	10.5	439	13.2
DG2 SH62890413	28/06/22	149	18	5.9	108	9.3	472	n.d.
DG3	28/06/22	133	3.9	7.3	109	9.8	423	13.5

SH62160382								
DG4 SH62010366	28/06/22	74	7.5	7.0	107	10.1	510	14.2
Drainage towards the Dolgoch / Pandy								
DL (seepage) SH65380426	01/07/22	87	n.d.	7.0	78.0	9.0	506	11.9
PD SH63140293	28/06/22	81	84	7.0	113.0	11.0	504	11.0

HD = Hendre, TU = Tan-y-coed-uchaf, DL = Dolgoch, BG = Brynglas, DG = Dolau-Gwyn, PD = Pandy

3.1.4 Upstream area from Tan-y-coed-uchaf to Dolgoch

As mentioned in section 2.2.2, the area around Tan-y-coed-uchaf is the first area at which drainage is observed (as discussed by Watson (1962)), and it can therefore be considered as the source area of the Afon Fathew. Three inflows are mapped near Tan-y-coed-uchaf and could be confirmed during the survey (Figure 7):

- Inflow TU0, a small spring, (see Figure 5) emerges from a bedrock outcrop on the northern side of the valley (no field parameters or discharge measured here, but flow observed whilst conducting the Tromino survey – surveyed approximately 5 m upslope and 15 m downslope of the outflow).
- Two locations on the southern side of the valley (inflow TU1a/b and TU2 in Table 2), with TU1 being the major inflow. Due to land access restrictions, the mapped source area of TU1 could not be visited, but flow was observed downstream at the railway bridge, and the location was included as measuring point AF01 in the accretion profile (see Section 3.4).

Surface flow observed at TU1 (gauging point AF01 in Figure 15), drains from the hillside, then seeps into the superficial deposits between the railway bridge and the upstream of Tan-y-coed-uchaf and then re-emerges just south of the farm at accretion profile gauging point AF02 (Figure 8).

Figure 7 Surface flows in the Afon Dolgoch upstream catchment around Tan-y-coed-uchaf. Arrow indicates flow direction (points downstream).

Figure 8 Seepage and re-emerging to and from gravels of the flow originating from TU1 between gauging AF01 and AF02 (up- and downstream of Tan-y-coed-uchaf farm).

Flow re-emerges in the lacustrine deposits near Ty-Gwyn farm (Figure 6). In this area, another inflow from the northern valley side is mapped on the Ordnance Survey (OS) map. This inflow was not accessible during the walkover survey. A moderately full surface water channel was observed in this area adjacent to Ty-Gwyn. Downstream of where the flow re-emerges, though abundant, the water appeared to be mainly stagnant with little flow and could be described as ‘pond-like’ (see Figure 6, D).

It should be noted that out of the four mapped inflows, only the one north of Tan-y-coed-uchaf is identified as a spring on the OS map and no spring locations in the Afon Fathew catchment are mapped in the BGS database. Due to rainfall in the days preceding the field visit, it was difficult to ascertain whether the observed flows at TU1 and TU2 originated from discrete springs, or surface drainage. The low pH (pH 5; similar to rainfall) and relatively low mineralisation (SEC of < 90 µS/cm) may signify the latter (refer to Table 2).

3.1.5 Mid-stream area around Nant-y-Mynach and Brynglas

Several artificial drainage channels are located within the alluvium downstream of the Fathew-Dolgoch confluence (e.g., at BG1 shown in Figure 5 and gauging point AF7 in Section 3.4, Figure 15). In addition to the drainage system in the valley bottom, two additional groups of surface water features were identified along the hillsides:

- Inflow NM0, on the northern hillside near Dol Deheuwydd Farm, a few hundred metres west of Nant-y-Mynach. The inflow is culverted from the hillside below the road (B4405) adjacent to gauging point AF6 (Section 3.4, Figure 15), the culvert outflow could not be traced, it is assumed to join the drainage system in the valley bottom, communication with the relevant landowner may confirm or disprove this. The flow was inaccessible due to fencing/hedging so field parameters and discharge volume could not been measured. The flow was observed to be relatively minor and it is unknown whether it derived from surface water drainage of recent rainfall, or from a spring.
- Two springs (BG1 and BG2) were reported on the southern hillside by the landowner. The springs are used as water supply for Brynglas farm, but no discharge data is available. The main spring is captured by pipes set into the bedrock and water flow is diverted into a tank on the hillside (BG2, Figure 9). Field parameters were measured in the tank. At the time of visit, the inflow into the tank was very low (if any), and the overflow from the tank was inactive.

Figure 9 Source area for BG2 at an outcrop area along the southern hillside and its location in relation to the accretion profile gauging point AF07 and the drain at BG01.

3.1.6 Downstream area around Dolau-Gwyn and Pandy

A number of surface water features and potential springs were located on the northern side of the Afon Fathew valley just north and north-east of Dolau-Gwyn farm (DG1-4). One of the springs had been the primary water source for several dwellings on the farm before it became insufficient in recent years. Today, the Dolau-Gwyn borehole is used as the supply for the main house, though the mill cottages still use spring water for domestic purposes and a small abstraction from the Afon Fathew for the garden. The inflow into the hillside entrapment tank of the primary spring was minimal during the visit in June 2022. The discharge rate could not be quantitatively measured due to access to the tank but was estimated y as 0.5-1 l/min.

On the southern side of the valley (around Pandy Farm), no major inflows towards the Afon Fathew could be identified, though there are numerous inflows to the Afon Pandy from the southern hillsides. Local farmers refer to these as springs and described the majority as flowing year-round, the most reliable are used for private water supply. Since 2015 a hydroelectric power station operates on the Afon Pandy upstream of Pandy Farm, downstream of the springs.

Figure 10 Obtaining physico-chemical parameters at DG1 and nearby (within 20 m) outcrop of weathered bedrock.

Figure 11 Discharge measurement (left) and field parameter measurements (right) at DG2. The point of measurement was a few meters downstream of the suspected source, which is mapped as spring on the OS map and seems to originate from bedrock. The source was inaccessible due to dense vegetation. There was another surface flow observed south of DG2, also located within very dense vegetation and so the exact source could not be determined.

Figure 12 DG3, a flow of 3.9 l/min was measured and field parameters obtained (refer to Table 2).

Figure 13 DG4, discharge and field parameters measured from outlet. The pipe is set into the hillside (uphill of a holiday park). No source could be traced further uphill, though a narrow patch of bulrush grows on the hillside for several metres above the pipe indicative of moist ground conditions.

3.1.7 Mine adits

Four former slate mine adits are present on the northern banks of the Nant Dolgoch, the remnants of a quarry which was active from 1877 to 1884. Located at Dolgoch falls, approximately halfway between Bryncrug and Abergynolwyn, the near-horizontal adits yield some water which flows into the stream. Discharge measurements and field parameters were obtained at all four adits on 1st July 2022. The adits can be accessed from the main footpath that leads along the northern bank of the stream.

Other sources of surface inflow from drains as mapped on the OS map were confirmed during the survey. Visual observations on the day suggest that flow from the adits provide a minor contribution to the total Nant Dolgoch discharge.

Figure 14: Entrance to adit 1 and lower Dolgoch Falls.

Figure 15: Entrance to adit 3 (left), drainage from hillside between adit 2 and 3 (centre) and entrance to adit 4 (right).

Adit 1 has a reported length of approximately 30 m, it leads from the footpath along the Dolgoch Falls into a chamber with an open roof (fenced off). Adit 2 has an approximate length of 96 m and is reported in the literature as the wettest of the adits, and we report adit 4 as having the greatest discharge (see Table 3). Adit 3 is the shortest of the four adits with a length of 16 m, while adit 4 is the longest and most complex. Adit 4 has an initial length of 67 m before forking into a left branch (extending another 24 m from the junction) and a right branch that continues for another 88 m into the rock and from which a narrow drive of approximately 4.9 m length branches off to the left (Eade, 2009).

Table 3 Estimated discharge and field parameters of mine adits and (for comparison) nearby hillside drainage.

Location	Estimated discharge (l/min)	pH	SEC (µS/cm)	DO (mg/l)	ORP (mV)	T (C)
Adit 1	0.8	6.9	154	9.7	389	13.2
Adit 2	1.2	7.3	166	9.5	376	11.5
Adit 3	6.9	6.7	98	9.1	498	11.4
Adit 4	13.1	7.4	151	10.6	426	10.5
Drain*	n.d.	7.3	78	9.1	506	11.9

* drainage from the hillside between Adit 3 & 4; measured for comparison

Two additional abandoned quarries, the Cwm-Pandy quarry about 2.6 km southwest of Dolgoch, and the Bryn-Eglwys quarry about 4 km west of Dolgoch are present in the catchment but were not visited during the water features survey in June 2022.

3.2 SUMMARY OF POTENTIAL SPRING DISCHARGES INTO THE AFON FATHEW VALLEY

Table 4 summarises the estimated and measured discharges of the springs visited during the field survey. The flow contribution of these springs to the overall catchment water balance appears to be very small. Moreover, some of these springs are captured for private supplies. If water use for private supply is consumptive, then the springs may not contribute to the water balance. The magnitude of these spring discharges is discussed further in Section 4 in comparison to discharges in the Afon Fathew, Pandy and Dolgoch.

Table 4 Summary of discharge contributions (both measured and estimated values) to Afon Fathew from springs visited during the field surveys.

Area	Side of catchment	Estimated flow (l/s)	Estimated flow (Ml/day)	Date of observation and comments
Tan-y-coed-uchaf	N	0.05	0.00432	01/07/2022 Not measured, only estimated.
Nant-y-Mynach	N	0.05	0.00432	03/08/2022 Inflow near BH Nant-y-Mynach estimated – attempted to trace source but no distinct outflow from bedrock observed, bedrock depressions and dense vegetation observed; fold belt present in bedrock which could provide fracture flow pathways; nearby springs at Ty-Mawr and Llanerch-Goediog drain to north.
Dolau-Gwyn	N	0.5	0.0432	28/06/2022 Bucket discharge measurements.
Tan-y-coed-uchaf	S	0.55	0.04752	27+29/06/2022 Combination of bucket discharge measurements and estimates (bucket measurement 0.5 l/s).
Brynglas	S	0.05	0.00432	Estimation for consumption in 2022 Estimated average contribution based on a high estimated consumption of 4 m^3/day.
Pandy	S	0.05	0.00432	28/06/2022 Not measured and minimal flows observed; only estimated.
Total		1.25	0.108	

3.3 BOREHOLES AND GROUNDWATER RESIDENCE TIME INDICATORS

3.3.1 Summary of field activities

In addition to the two boreholes identified during the desk study (at Ty-Gwyn and Rhiwerfa, see Appendix I for borehole logs and Figure 5 for locations), two additional boreholes were confirmed during the field visit in June 2022: one borehole at the downstream end of the

Afon Fathew catchment at Dolau-Gwyn (near the inflow of the Pandy), and one borehole at Nant-y-Mynach (slightly downstream of the inflow of the Dolgoch).

Both the boreholes at Dolau-Gwyn and Ty Gwyn were drilled relatively recently in response to insufficient flow from springs that were previously used as main supplies. The Rhiwerfa and Nant-y-Mynach boreholes are located on the hillside on the northern flank of the catchment, the boreholes at Ty-Gwyn and Dolau-Gywn are in the valley bottom relatively close to the Afon Fathew (c. 100-120m). Landowners reported that there were no boreholes on the southern side of the catchment at the time of the surveys (personal communication, June-August 2022).

No written records were available from the landowners for the Nant-y-Mynach or Dolau Gywn boreholes, the depths and lithology remain uncertain though anecdotal evidence was gathered during the surveys and local drilling companies may be able to provide further information.

The Dolau-Gwyn borehole was said to have poor water quality at an initial drilled depth of about 24m, consequently the borehole was completed to a depth of c. 37m where the water quality was better, although it still requires treatment to remove iron and manganese (personal communication, neighbouring farmer). The filtration system on site at Dolau-Gwyn confirms the requirement for water treatment.

Rest water levels were obtained from the Dolau-Gwyn and Nant-y-Mynach boreholes only; headwork configuration prevented access to the water level at Ty-Gwyn. No access permission could be obtained to visit the Rhiwerfa borehole. .

3.3.2 Results and interpretation

Field parameters and residence time indicators (CFCs and SF_6) were obtained from the boreholes at Nant-y-Mynach, Ty-Gwyn, and Dolau-Gwyn; a summary of the results is shown in Table 5. The pH of the groundwaters are neutral to slightly acidic (similar to the river waters). The two boreholes in the valley bottom have pH of c. 6.5 based on repeat measurements in June and August 2022. The borehole on the hillside is neutral at pH 7.

The groundwaters also display variation in conductivity (SEC) and dissolved oxygen content (DO). Dolau-Gwyn and Nant-y-Mynach groundwaters have relatively high SEC values (235 to 281 µS/cm) and low oxygenation (DO; 0.01-0.02 mg/l), compared to Ty-Gwyn groundwaters where SEC ranged from 83-85 µS/cm and DO 9.58-11.00 mg/l. It is unlikely that the drilling operations would still be impacting the parameters at Dolau-Gwyn as it was installed some time ago and is the supply to a large family residence. The borehole at Ty-Gwyn had been used for several weeks prior to our sampling and the drilling record reports yields of 200 l/min so oxygenation associated with the drilling should have been negligible at the time of sampling.

Groundwater residence times for each of the three boreholes are presented in Table 5, these results represent the mean recharge year. The three CFCs and SF_6 tracers used all corroborate for each borehole, this suggests that a piston flow model would best describe the data. Piston flow would consist of groundwater recharge occurring at a discrete location, and no addition of recharge along the flow path to the borehole. This is also consistent with a flow mechanism of groundwater flow within localised bedrock fracture systems.

The results show that in the valley bottom, there is a longer groundwater residence time (mean recharge year = 1967) at Dolau-Gwyn than at Ty-Gwyn (mean recharge year = 1980). This difference is consistent with the lower oxygen content and greater mineralisation in groundwater at Dolau-Gwyn (higher SEC and lower DO values). This suggests that the borehole at Dolau-Gwyn is intercepting a larger regional groundwater flow system in the bedrock than at Ty-Gwyn. The relative location of these two boreholes would support this. Ty-Gwyn is situated in a narrow, upstream part of the valley in comparison to the location of Dolau-Gwyn downstream in a broad valley setting. This may suggest that groundwater flow to Ty-Gwyn is derived from a shorter flow path than Dolau-Gwyn, with the latter potentially affected by any down-catchment component to regional groundwater flow (e.g. along fractures associated with the Bala lineament). However, without detailed information on the borehole depth and screened interval this interpretation is somewhat speculative.

On the valley side, at the Nant-y-Mynach borehole, longer groundwater residence times are observed (mean recharge year = 1958), again with relatively low DO and higher SEC. In this case, these results are likely to reflect the relatively deep flow system intersected by this deeper borehole in comparison to Ty-Gwyn and Dolau-Gwyn.

In summary, these residence times show that groundwater in the weathered bedrock was recharged at least 40 years ago. Assuming baseflow contributions to the surface water bodies (either to the Afon Fathew or the tributaries) have similar recharge ages to the sampled boreholes, baseflow would be relatively resilient to interannual drought events in comparison to a system of groundwater comprised of entirely modern recharge.

Table 5 BH information (BH= borehole, RWL= rest water level, Q=discharge, SEC= specific electrical conductance, DO= dissolved oxygen, ORP = oxidation-reduction potential, T=temperature). CFCs and SF_6 values are recharge ages (years) assuming a piston flow model.

BH name and NGR	**Date**	**Elevation (m aOD)**	**BH depth (m)**	**RWL (m bgl)**	**Est. Q (l/min)***	**pH**	**SEC (µS/cm)**	**DO (mg/l)**	**ORP (mV)**	**T (C)**	**CFC-12**	**CFC-11**	**CFC-113**	**SF_6**
Rhiwerfa SH65890630	No access	179	80	n.d.	6.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d	n.d	n.d	n.d
Ty-Gwyn SH65440510	29/06/22 03/08/22	38	30	n.d.	13.1	6.5 6.3	83 85	11.00 9.58	364 553	10.4 10.4	1977	1978	1985	1985
Nant-y-Mynach SH64390481	03/08/22	81	c. 91**	16.8	1.2	7.06	281	0.02	-27	12.1	1952	1955	1966	<1970
Dolau-Gywn SH62320344	28/06/22 03/08/22	30	c. 24***	1.85 2.08	0.8	6.6 6.3	235 242	n.d. 0.01	n.d. 234	n.d. 12.7	1965	1962	1973	<1970

* discharge estimation based on pumping test data on borehole logs and/or personal communications with landowner

** based on personal communication with the landowner

*** based on personal communication with a neighbouring farmer

3.4 ACCRETION PROFILES

3.4.1 Identification of spot flow sites and gauging

BGS undertook an initial desktop assessment of potential spot flow gauging sites on Afon Fathew and Dysynni. The purpose of gauging on the Afon Fathew was to determine where increases in flows occur, and whether these can be attributed to inflows from tributaries or from diffuse flow inputs from groundwater in the superficial deposits and from small springs and streams. The purpose of gauging on the Afon Dysynni was to identify if any flow losses were occurring from the river to the underlying superficial deposits, which could potentially contribute to any groundwater flow from the Dysynni to the Fathew within the superficial deposits.

Sites were initially selected based on an even spacing within the main channel of the rivers and additional sites immediately up or downstream of the two tributaries to Afon Fathew (Afon Pandy and Nant Dolgoch). These were presented to the project team and DCWW on 24th May 2022. It was agreed that the proposed sites would be investigated during the first field visit.

BGS and Hydro-Logic staff visited the proposed sites on 29th and 30th June 2022 and arranged access for spot flow gauging for the sites shown in Figure 16 and Figure 17. This consisted of 10 sites on the Afon Fathew, the two tributaries and four sites on the Afon Dysynni.

Hydro-Logic undertook two rounds of spot flow gauging on 20th/21st July and 15th/16th August 2022. For each gauging location, flow, temperature, conductivity and pH were recorded.

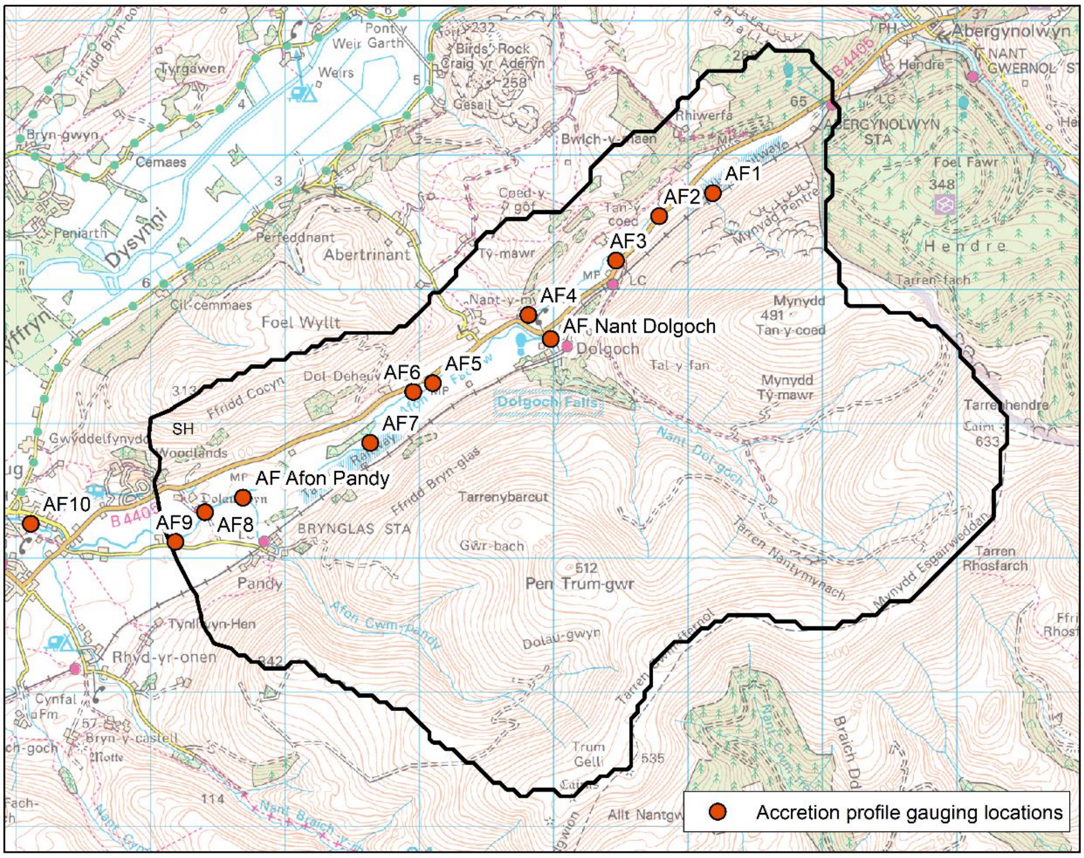


Figure 16 Location of accretion profile gauging locations on Afon Fathew and tributaries. Contains Ordnance Survey Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290.

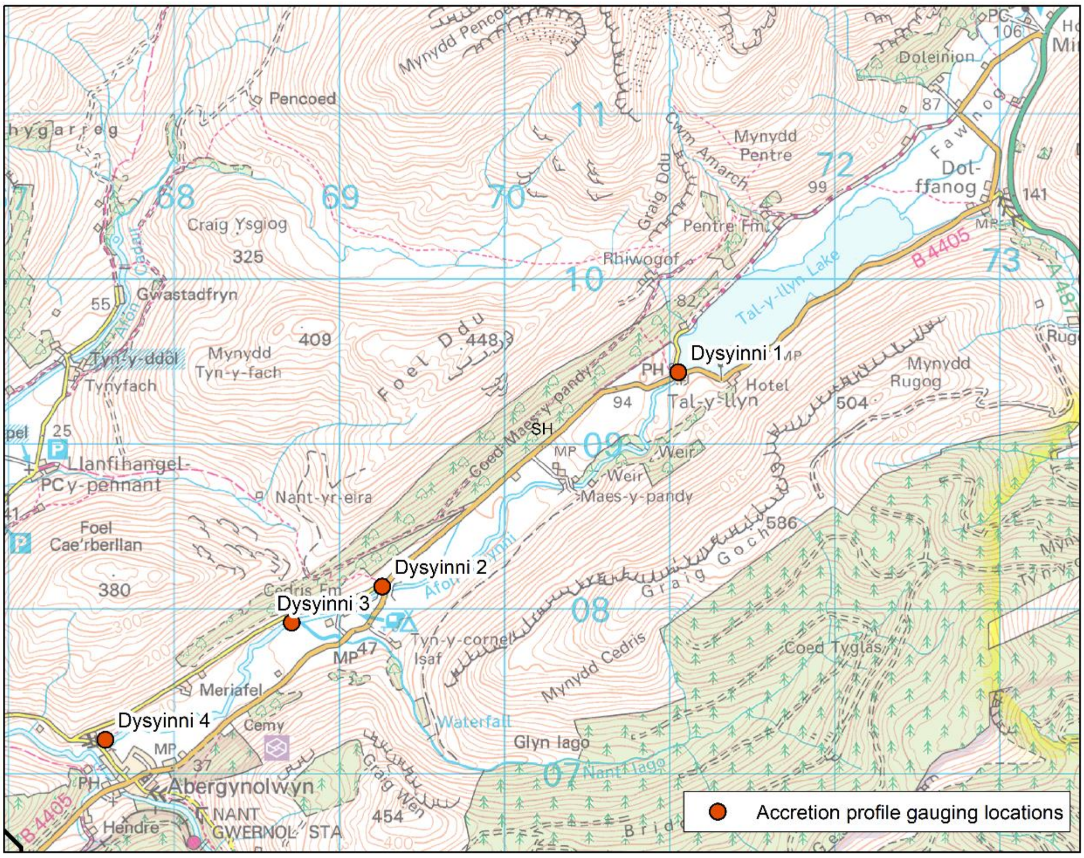


Figure 17 Location of accretion profile gauging locations on Afon Dysynni. Contains Ordnance Survey Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290.

3.4.2 RESULTS AND INTERPRETATION

3.4.2.1 Afon Fathew

Figure 18 shows the accretion profiles recorded for Afon Fathew. The profile on 20th July recorded lower flows at all sites than the profile on 15th August. In this report, interpretation is therefore focussed on the data for 20th July, with additional supplementary information from the 15th August as corroborating evidence.

On 20th July, the first three sites recorded very low flow (all < 0.3 l/s (0.026 Ml/day) and not measurable at AF3). The first significant flow accretion occurs between AF3 and AF4 (immediately upstream of AF Nant Dolgoch), where a flow of 21.1 l/s (1.82 Ml/day) is recorded. The same pattern of flow accretion in these upper reaches is evident in the data recorded on 15th August. These recorded flows in the upper sections of the Afon Fathew corroborate the findings of the water features survey reported in section 3.1, in addition to previous work by Watson (1962) and geological mapping of the area. Watson (1962) reports the river valley from Abergynolwyn station to Tan-y-coed-uchaf to be "loosely packed open material" (i.e. of relatively high permeability with limited surface water features). Below Tan-y-coed-uchaf, silty alluvium and peat (i.e. low permeability) is mapped and this is where Watson (1962) reports permanent drainage.

An increase in flow is recorded between AF4 (21.1 l/s, 1.82 Ml/day) and AF5 (57.7 l/s, 4.99 Ml/day) in the 20th July data. The tributary inflow AF Nant Dolgoch between AF4 and AF5 was 55 l/s. Based on the change in flows between the AF4 and AF5 and the measured inflows at AF Nant Dolgoch, 18.9 l/s (1.63 Ml/day) is being "lost" from the Fathew in this reach. The same pattern of flows is recorded on 15th August, with c. 47 l/s (4.06 Ml/day) "lost" from Fathew in this reach. The geological mapping reports the superficial deposits to be well drained and extensive coarse gravels in this area. This suggests that some of this flow loss may be contributing to storage within the superficial deposits in this area, and groundwater discharge down-catchment. The contribution of the inflows from the Dolgoch to the Fathew between AF4 and AF5 is also evident in the conductivity measurements undertaken during the gauging. For both gauging rounds, SEC decreases from c. 85 µs/cm at AF4 to 50 µs/cm at AF5, and remains at c. 50-60 µs/cm down the Fathew to AF9. This corroborates the results of the initial walkover survey where similar SEC measurements were reported (see section 3.1.2).

Between AF5, 6 and 7 a limited change in flows is observed in both gauging rounds. In the 20th July gauging, further downstream, there is a large increase in flows from AF7 (62.4 l/s, 5.39 Ml/day) to AF8 (99.2 l/s, 8.57 Ml/day). 47% of this increase can be attributed to observed inflows from the Afon Pandy (17.3 l/s, 1.49 Ml/day). In the 15th August data 40% of the increase between AF7 and AF8 can be attribute to inflows from the Afon Pandy. The remainder is likely to be due to diffuse flow contributions from small springs and streams flows and groundwater discharge from the bedrock and superficial deposits. In comparison to the upstream reach AF4-AF5, in this area the superficial deposits have a smaller mapped area (Figure 3) and are reported to be less permeable with extensive marshy drainage. It is therefore likely that any groundwater within the superficial deposits in the more permeable reach between AF4 and AF5 is discharging to surface water in the reach AF7 – AF8.

Between AF8 and AF9 a limited change in flows is observed in both gauging rounds. A large reduction in flows is observed between AF9 and AF10 in both gauging rounds associated with the DCWW intake on the Fathew.

Overall, the Dolgoch and the Pandy make substantial contributions to flows in the Fathew. In the 20th July gauging, the Dolgoch and the Pandy contributed 49 and 15% of flows respectively in the Fathew in comparison to flows at AF9. In the 15th August gauging, when flows were slightly higher, the Dolgoch and the Pandy contributed 60 and 17% of flows in the Fathew in comparison to flows at AF9. However, as highlighted by the difference in flows in the Fathew up and downstream of the Dolgoch inflow (AF4 and AF5), it appears that flows from the Dolgoch contribute to storage in the superficial deposits in this reach.

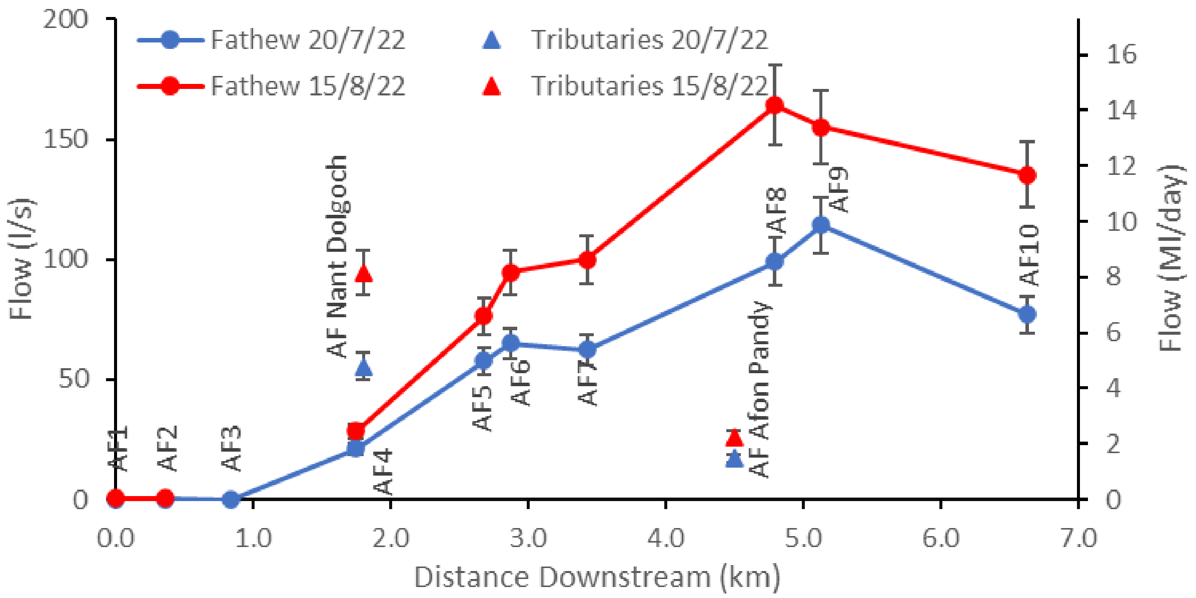


Figure 18 Accretion profile for Afon Fathew

3.4.2.2 Afon Dysynni

Figure 19 shows the accretion profiles for Afon Dysynni. Increases in flows are observed from AF1 to AF2 to AF3 for both gauging rounds. From AF3 to AF4, small decreases and increases in flow are observed in the gauging rounds on 21st July and 16th August respectively. These changes are likely to be within the uncertainty of the measurement (see error bars).

The lack of decreases in flow in the Dysynni suggests that there is not likely to be significant losses from the Dysynni to the superficial deposits in this reach. The presence of continuous flow accretion, in combination with the base of the Fathew- Dysynni col forming a topographic divide between the catchments below the landslip deposits, would suggest that groundwater flow within the superficial deposits from the Dysynni to the Fathew is unlikely to be occurring. Drilling of shallow boreholes in the superficial deposits would provide further evidence to prove or disprove this.

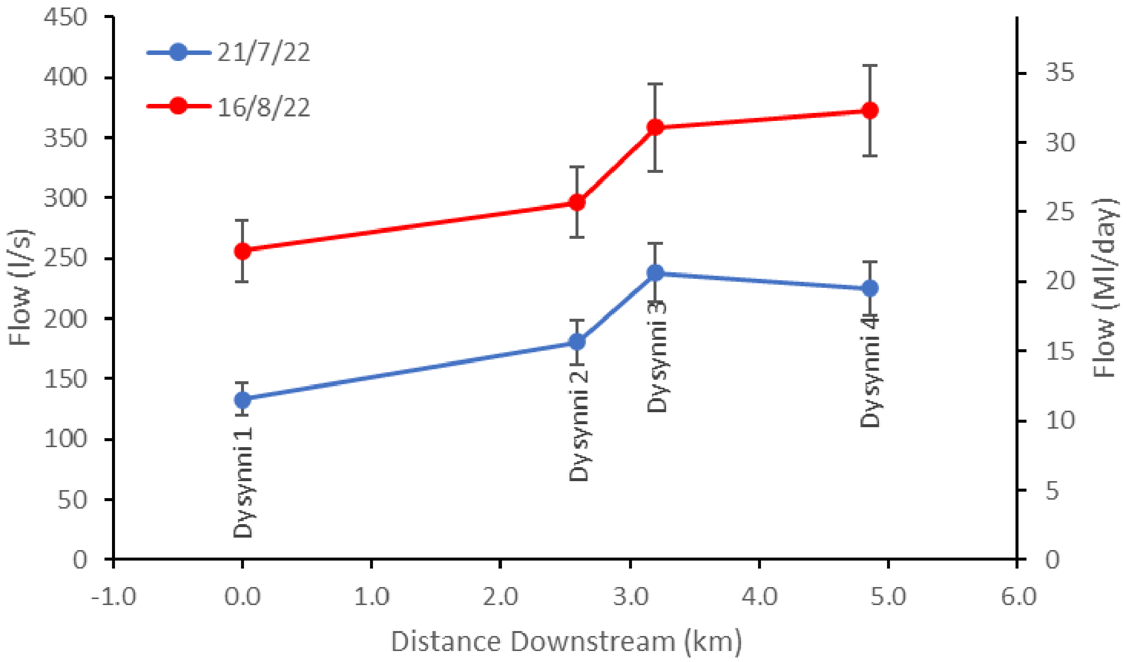


Figure 19 Accretion profile for Afon Dysynni

3.5 TROMINO

A Tromino survey is a passive seismic survey, which is particularly useful in detecting and visualising the layering of superficial deposits and underlying bedrock. The Tromino sensor is a mobile seismometer, which measures passive seismic noise in the ground that is generated by natural (e.g. wind) and anthropogenic sources (e.g. cars). Interfaces between subsurface layers, e.g. a weathered layer overlying stronger rock, can amplify the horizontal vibration component of seismic noise compared the vertical component and thus signal the change in material. This technique is referred to as Horizontal Vertical Spectral Ratio (HVSR). For more information about the Tromino sensor, the reader is referred to https://moho.world/en/tromino/geology/ and https://www.bgs.ac.uk/geology-projects/geophysical-tomography/technologies/tromino/.

Tromino measurements were taken in both field campaigns in the Afon Fathew catchment (Figure 20) and are presented in the order from upstream to downstream and all profiles are plotted from northwest to southeast. In the colour contour plots below (Figure 21 to Figure 28), the higher values of H/V ratios - in yellow, orange and red colours - represent zones of high acoustic impedance contrast (i.e. a transition from weaker to stronger strata). The zone of high H/V values at shallow depths (i.e. the top 5 m) has been interpreted as being due to the base of topsoil or relatively stiff layers in alluvial sediments, such as gravel layers. The deeper zones of H/V values have been interpreted as the interface between superficial sediments and bedrock.

It should be noted from the outset with the absence of borehole data to verify the Tromino survey, there is considerable uncertainty in the depths estimated. Thicknesses reported herein should be considered to be relative only and to an uncertainty of c. 5 m.

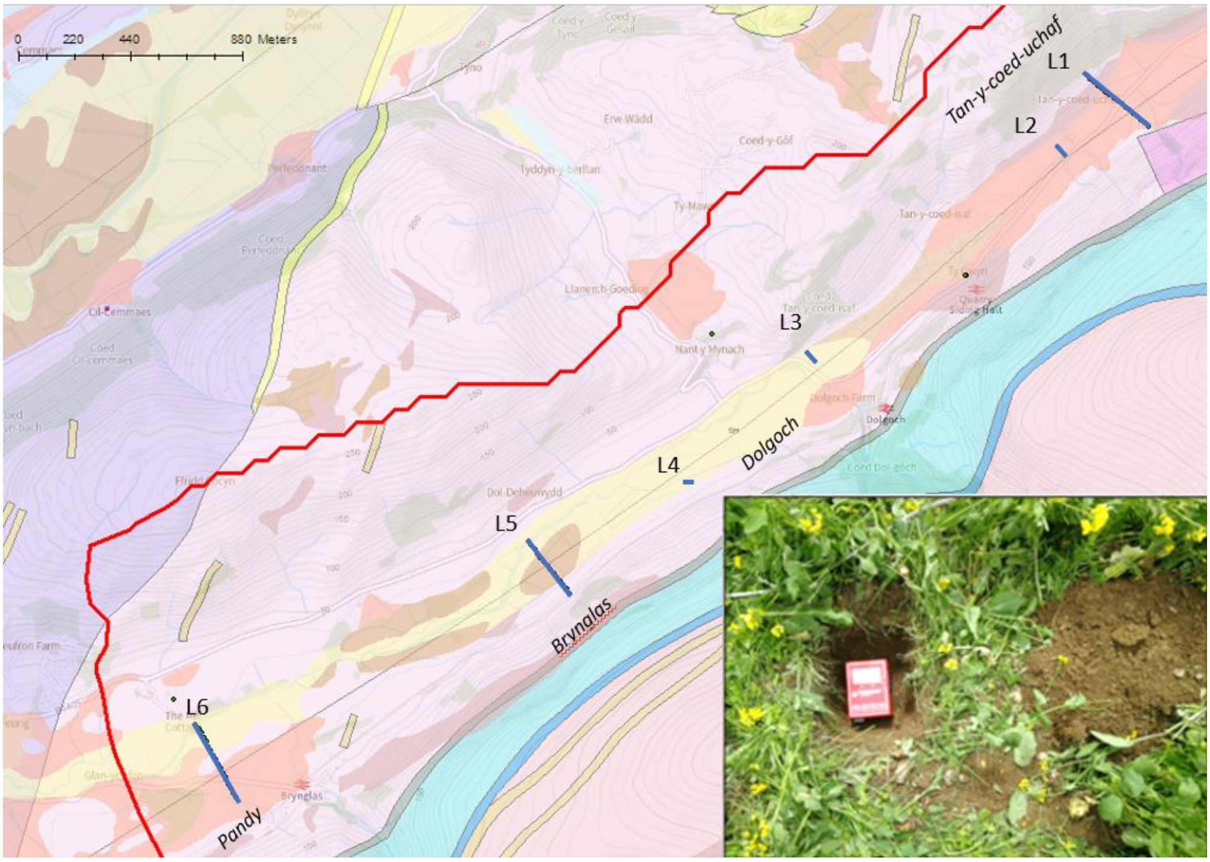


Figure 20 Tromino lines measured in the Fathew catchment and photo of Tromino measurement (bottom right). Contains Ordnance Survey Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290. Contains BGS materials © UKRI. All rights reserved.

3.5.1 Tan-y-coed-uchaf

L1 – Bedrock, head and alluvial fan (gravel)

This profile (Figure 21) shows bedrock near the surface at the beginning of the line (Chainage 0 m), which is picked out by the contrasting blue and purple colours in Figure 21. High H/V values, indicating the transition to strong bedrock can be traced out to reveal a buried valley feature down to below 0 m OD close to Chainage 100 m. This appears to shallow towards the end of the profile.

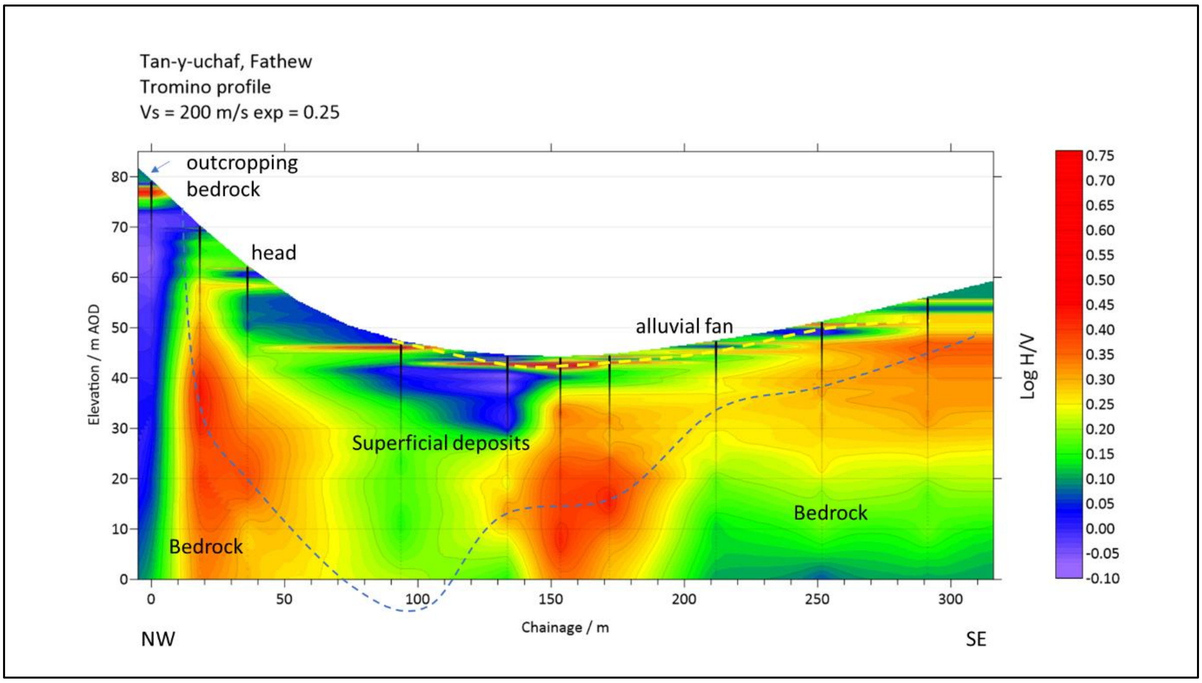


Figure 21 Tromino profile L1 at Tan-y-coed-uchaf

L2 – Alluvial fan (gravel)

A set of 7 Tromino measurements (giving a 70 m profile) was taken during the last day of the water features survey on 01 July 2022 in the upper part of the Fathew catchment near Tan-y-coed-uchaf across a section of the Alluvial Fan Deposits - Gravel. Changes in H/V ratio indicate layers at c. 1 m and 23 m bgl, interpreted as the base of soil and top of the bedrock, respectively – see Figure 23.

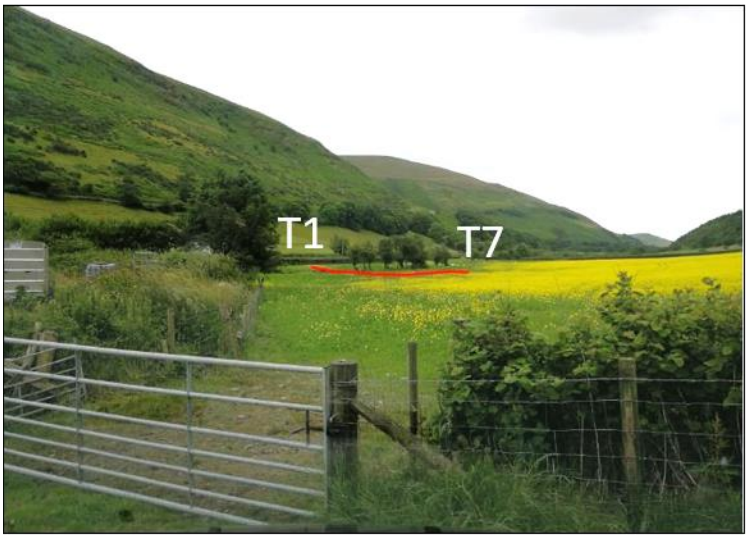
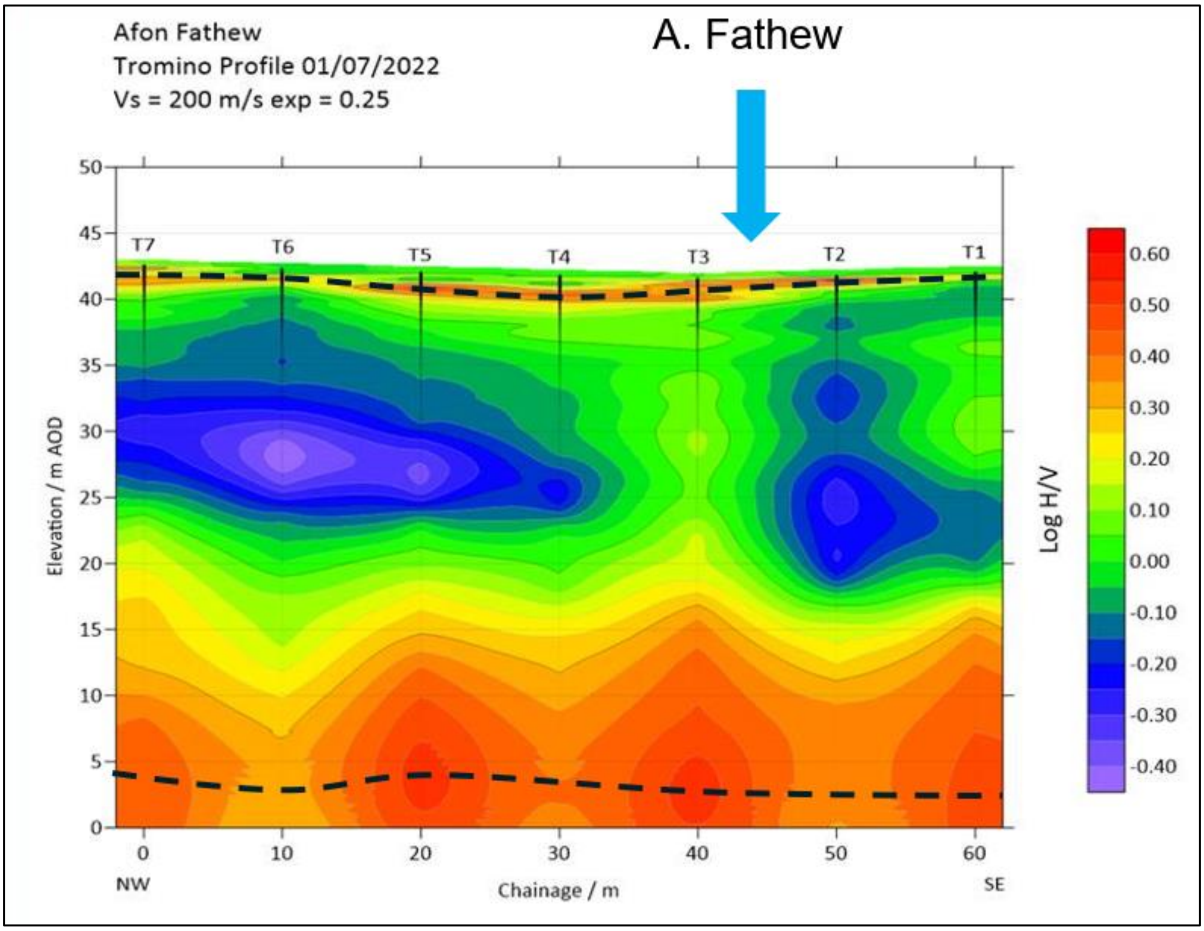


Figure 22 Layout of the Tromino profile L2 (60 m long, spacing 10 m) at Tan-y-uchaf



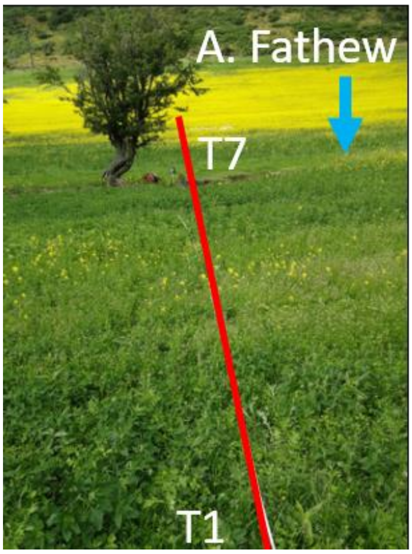


Figure 23 Results of the Tromino line expressed as contour map of H/V (top) and showing a profile of the sampling point at T2.

3.5.2 Upstream and downstream of the Dolgoch confluence

L3 – Upstream of Dolgoch confluence – alluvium

Based on two Tromino measurements, this profile shows high H/V indicates a transition to stronger material (interpreted as bedrock) at a depth of approximately 6 m (30 m AOD). See Figure 24.

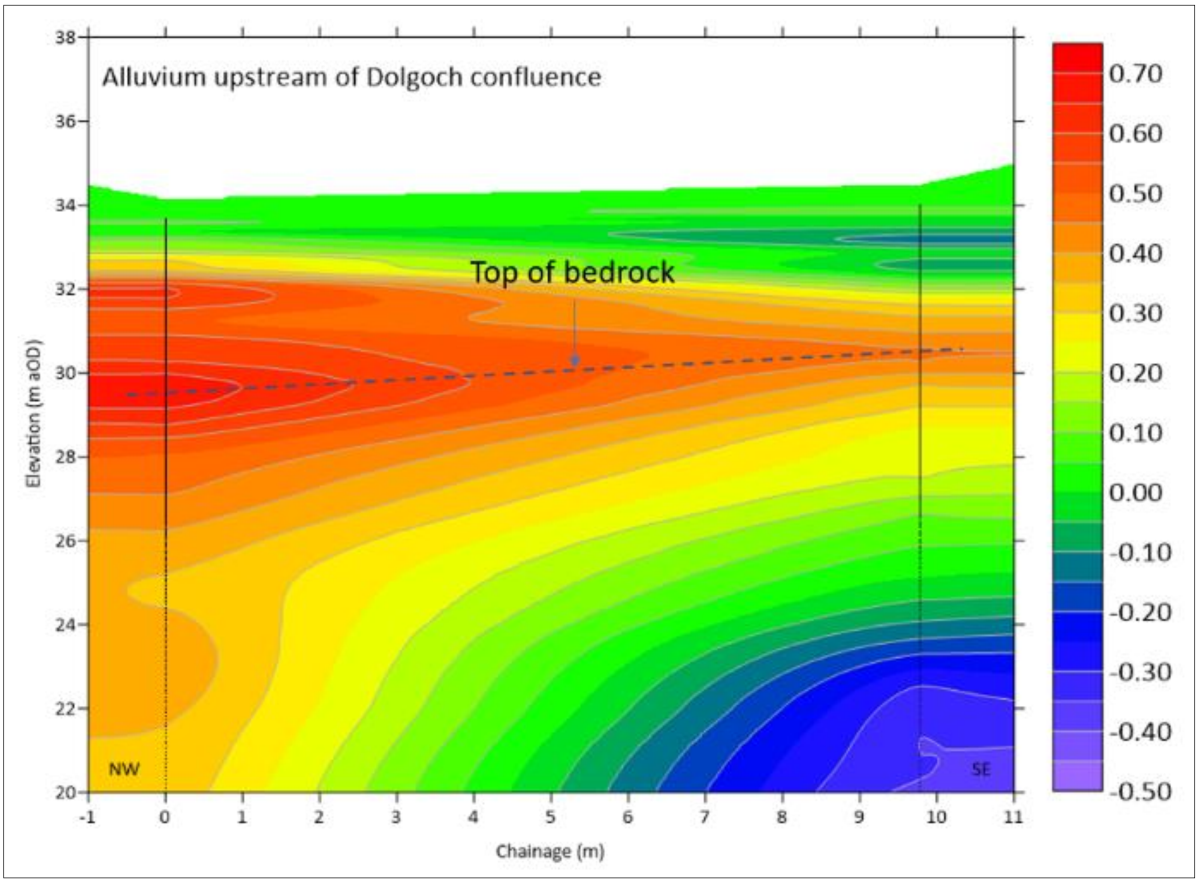


Figure 24 Colour contour plot of the H/V profile for L3 - on alluvium upstream of the Dolgoch confluence.

L4- Downstream of the Dolgoch confluence -alluvium

Again, this profile is based on two Tromino measurements. Figure 25 shows a slight peak in H/V at shallow depths at Chainage 0 m. This is interpreted as a relatively stiff layer in the alluvium – perhaps a gravel layer. Below this, at 23 m – 24 m AOD (6 m bgl) high H/V reveal a transition to somewhat stronger material, interpreted as the top of bedrock.

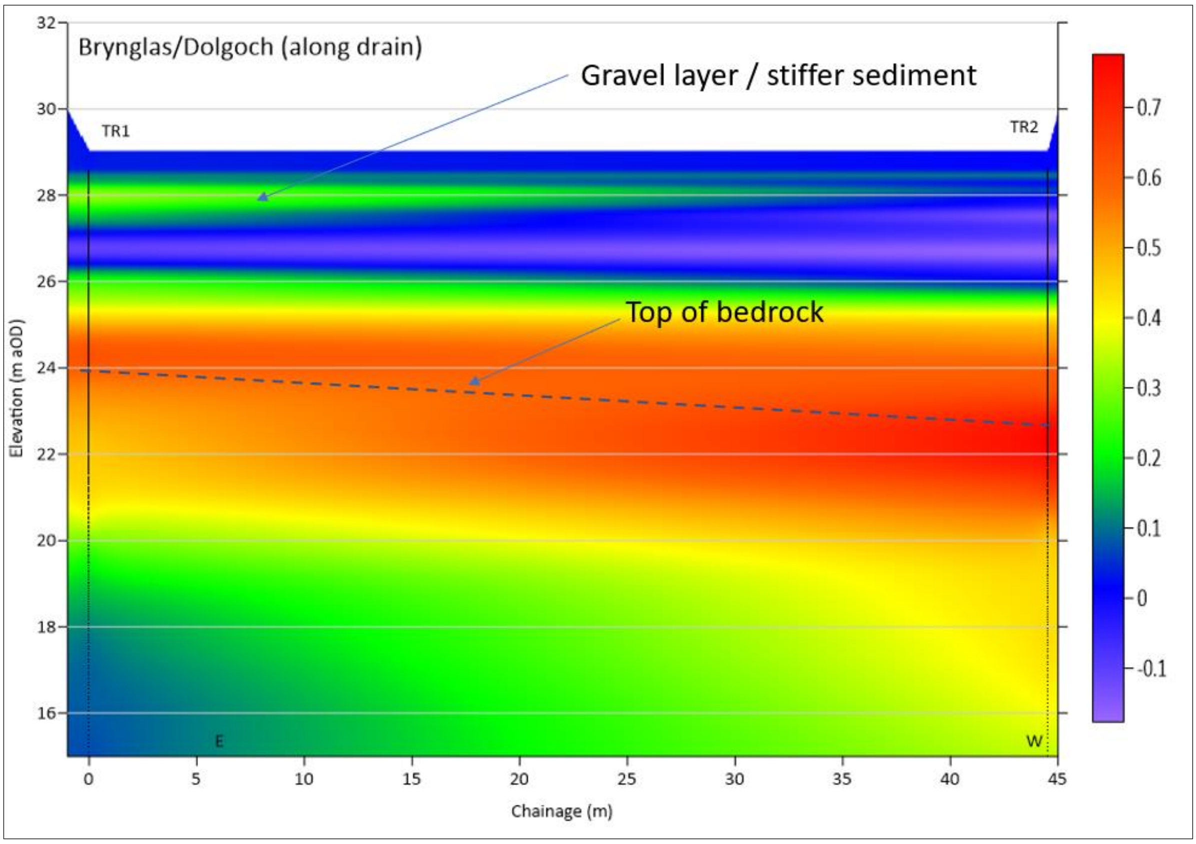


Figure 25 Colour contour plot of the H/V profile for L4 - on alluvium downstream of the Dolgoch confluence.

3.5.3 Brynglas

L5 – Brynglas farm, alluvium, peat, outcrop

The H/V profiles have been produced using an assumed shear wave velocity (Vs) of 200 m/s for the near-surface sediments, which is typical for alluvium. However, because Vs for peat is much lower (<50-100 m/s), this will have the effect of distorting the depth range seen on the profile, with the base of peat appearing deeper than it is in reality. Forward modelling of individual Tromino readings suggest that the depth of peat is 3 m to 10 m. Figure 27 shows two examples of this.

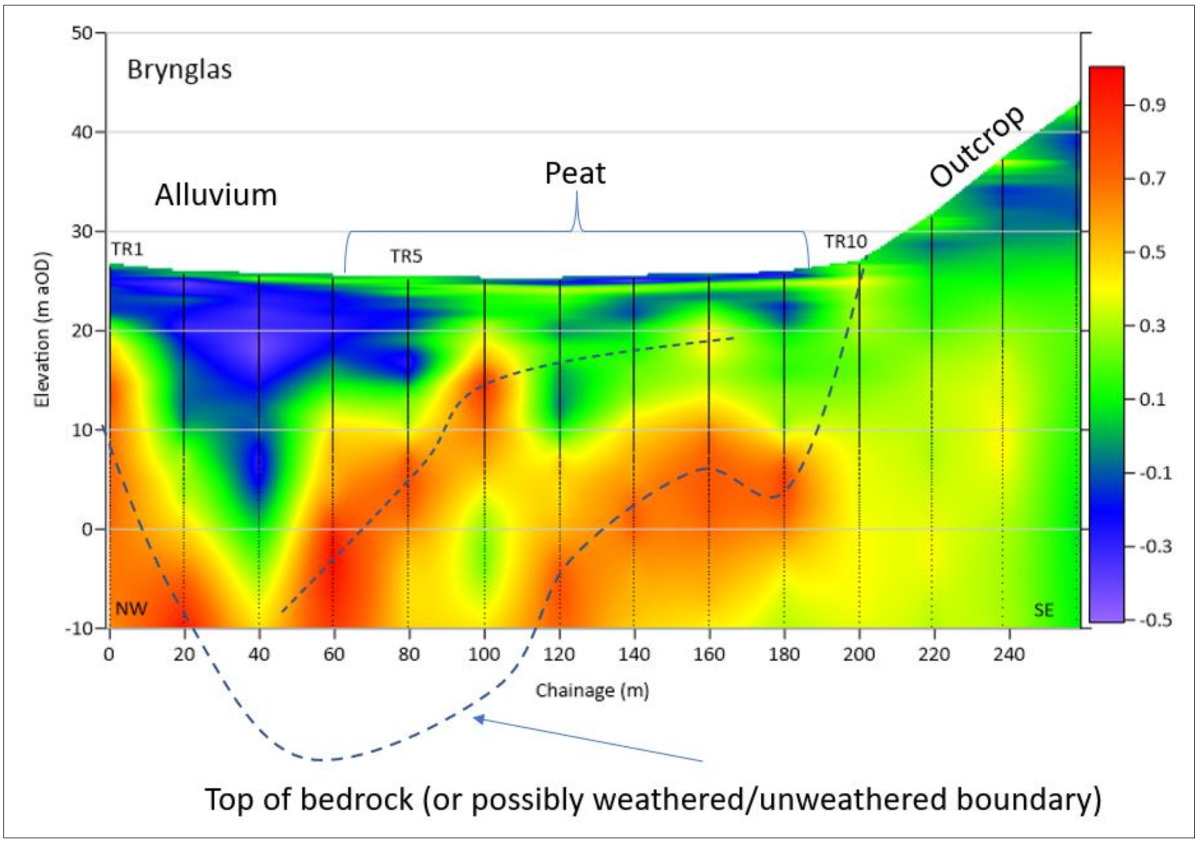


Figure 26 Colour contour plot of the H/V profile for L5 at Brynglas Farm - on alluvium, peat and bedrock outcrop.

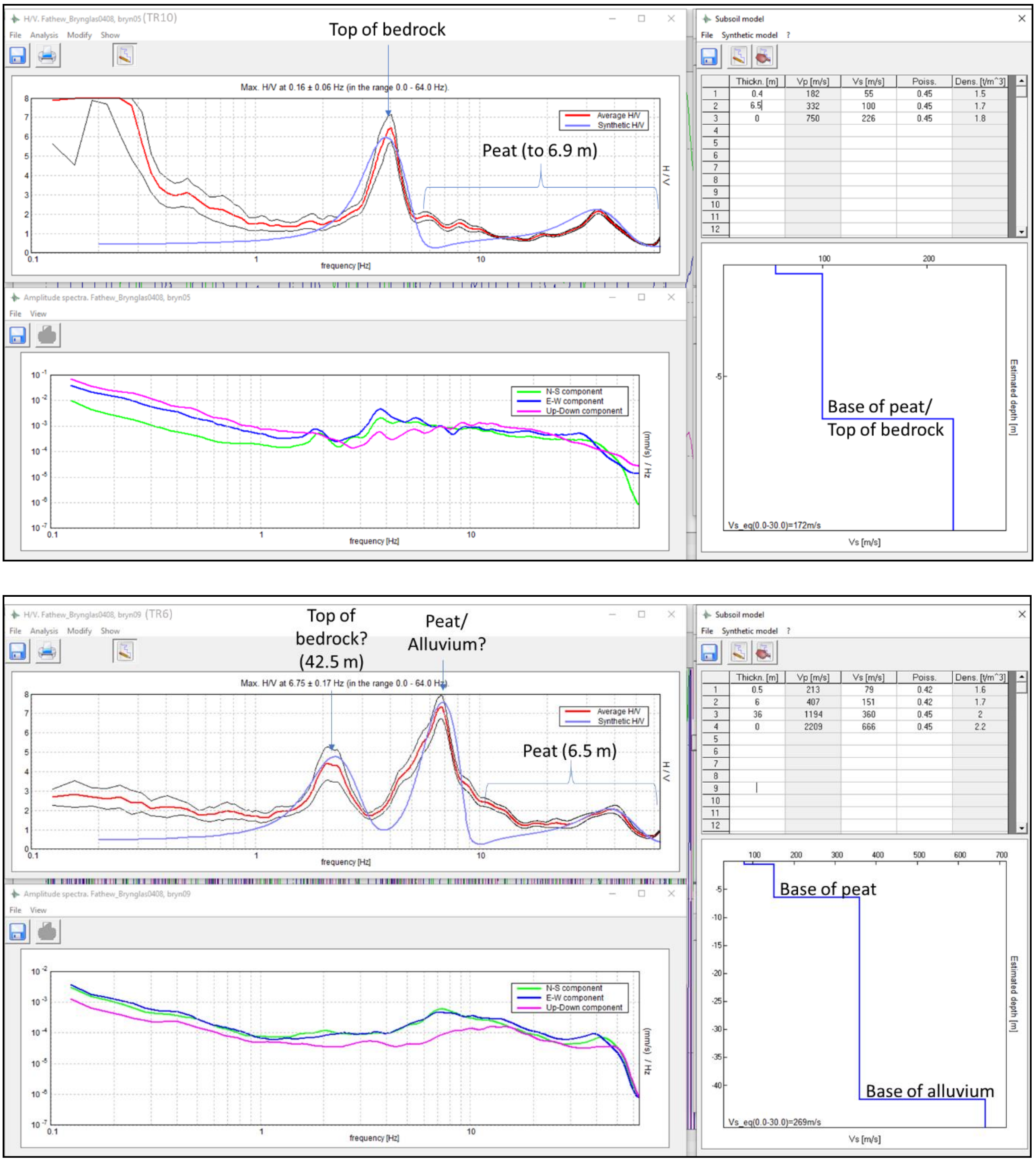


Figure 27 Forward modelling of Tromino data from TR10 (top) and TR6 (bottom) on the Brynglas profile, showing modelled depth to base of peat and top of bedrock. Average H/V (red line) is the measured data, and Synthetic H/V (blue line) is the model.

3.5.4 Pandy

L-6 Pandy, alluvium, outcrop, alluvial fan (gravel)

Bedrock outcrop was observed close to the measurement point T10 on this profile – see Figure 28. Moderately high H/V values at TR2 to TR5 at around 15 m AOD have been interpreted as bedrock. Tromino data at TR1 are typical of a measurement taken on bedrock. High H/V values from TR14 to TR18 suggest that bedrock may be close to the surface, although this could also be interpreted as a bed of gravel in the alluvial fan. The high H/V values towards the SE end of the line at 0 m AOD to 22 m AOD have been tentatively interpreted as stronger bedrock.

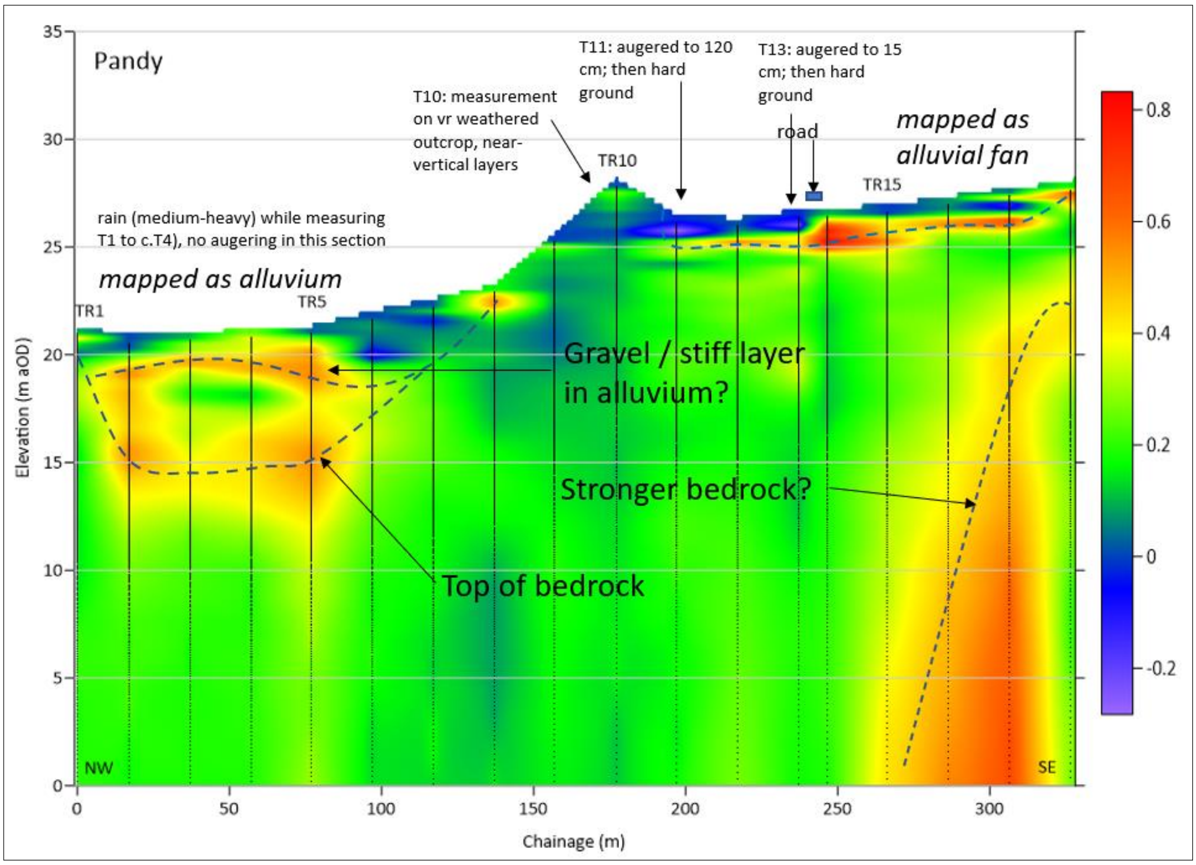


Figure 28 Colour contour plot of the H/V profile for L6 at Pandy - on alluvium, bedrock outcrop and alluvial fan (gravel).

3.5.5 Summary of Tromino Survey

The Tromino data showed H/V peaks at a range of frequencies, indicating interfaces with contrasting physical properties at various depths. These have been interpreted as base of topsoil; gravel layers within alluvium; base of superficial deposits; base of bedrock and/or top of bedrock.

Table 6 summarises the results of the Tromino survey. It should be noted that it has not been possible to verify the processing parameters by calibrating the measurements against borehole data. Instead, typical values for alluvial deposits have been used. This limits the interpretation of the Tromino data, and thicknesses should be considered to be relative and with an uncertainty of +/- 5 m. Further work to validate the Tromino results is outlined in section 5. Based on the parameters used in processing the data, it would appear that the bedrock is considerably closer to the surface at profiles L3 and L4 (close to the Dolgoch confluence) compared to the profiles both upstream and downstream. However, note that L3 and L4 both each have only two measurement points.

Table 6 Summary of Tromino survey results

Line reference	**Catchment location**	**Mapped geology at land surface**	**Estimated ranges of depth to bedrock in valley bottom (m)**	**Comments**
L1	Tan-y-coed-uchaf	Bedrock, head and alluvial fan	>20	Bedrock outcrop observed
L2	Tan-y-coed-uchaf	Alluvial fan	>20	
L3	Dolgoch	Alluvium	<10	Only two measurements
L4	Dolgoch	Alluvium	<10	Only two measurements
L5	Brynglas	Alluvium, peat, bedrock	>20	
L6	Pandy	Alluvium, bedrock, alluvial fan	<10	Bedrock outcrop observed

4 Conceptual model

The conceptual model of groundwater flow in the Fathew catchment is presented in Figure 29 and Figure 30 and can be summarised as follows:

- The Fathew is underlain by a bedrock of silty mudstones, with occasional sandstone bands. These formations are traditionally considered to be poor aquifers. However, in the Fathew catchment there is evidence for groundwater flow (at least at the local scale) in the bedrock within fractures and other discontinuities. Borehole records indicate the presence of extensive fracturing within an upper weathered layer of bedrock. This upper weathered layer, in combination with faulting and folding patterns, and permeability variations between bedrock units (e.g higher permeability in sandstones and the weathered Nod Glas formations in comparison to lower permeability in the Broad and Narrow Vein), is likely to control the geometry and magnitude of bedrock groundwater flow systems. These systems are likely to be relatively local in nature. The extent of deeper regional groundwater flow systems in less weathered bedrock is largely unknown, but is considered to be less significant.
- Agreement between groundwater residence time indicators suggests that a “piston flow model” may be occurring, where groundwater recharge and discharge occur at discrete locations, which corroborates the localised groundwater flow systems postulated above. The residence time indicator data suggest that groundwater in the bedrock is over 40 years old.
- The superficial deposits in the catchment are highly heterogeneous in the valley bottom. At the head of the catchment there is alluvial fan which may have moderate permeability, causing any upstream drainage to disappear. The Tromino survey suggests the superficial deposits are relatively thick (> 20 m) in this reach. At the source of the Afon Fathew, low permeability lacustrine deposits are present, which causes spring emergence. Further downstream of the Dolgoch there is a section with increased permeability associated with well drained alluvial gravels. In this reach the combined flow of the Dolgoch and upper Fathew appears to be losing into the superficial deposits. It is likely that the alluvial gravels provide some storage in this reach. Given that the superficial deposits in this reach are relativity thin (<10 m), (estimated by Tromino survey), it seems likely the alluvial gravels are highly permeable. That there may also be additional storage in the small number of dug field drains in this reach. From near Bryngias to downstream near the confluence with the Pandy, the superficial deposits become narrower, less permeable and of

shallower depth. This corresponds with increased river flows as groundwater discharges into the river.

- A small number of springs discharging from the bedrock on the hillside were recorded in the field survey. Their location is likely to be controlled by fracture network geometry and orientation, and the interface between different bedrock formations and between the bedrock and the superficial deposits. A number of these springs are captured and used for supply by local farms. The estimated total flow of these springs (< 2 l/s, 0.17 Ml/day) is very low relative to the total flow in the Fathew and the contributions from Dolgoch and Pandy tributaries. Colloquial information from local farmers suggests that the reliability of these springs is somewhat intermittent, and an increasing number of boreholes have been drilled in the catchment to augment private water supplies.
- The catchment appears to be hydraulically isolated from the Dysynni due to geomorphological changes that occurred before the landslip on the Fathew-Dysynni col. The increases in flow recorded in the Dysynni accretion profile, together with the likelihood of topography driven groundwater flow in the superficial deposits (if in physical continuity in any case) at Fathew-Dysynni col, suggests that it is highly unlikely that there is groundwater flow from the Dysynni to the Fathew within the superficial deposits.
- In the Fathew, c. 60% of low flow inflows are coming directly from upland tributary inflows (Pandy and Dolgoch) where very limited superficial deposits are present. In these upland settings during dry periods it is likely that the majority of discharge is coming from baseflow from bedrock. Extensive peat coverage (often associated with spring lines) and dug channels makes it difficult to identify discrete springs within the two sub-catchments, and groundwater discharge to surface water may be more diffuse. It may also be that the overlying peat deposits act as a temporary store of water, though the extent of this is unknown at this time.

Based on the evidence gathered in both the desk study and field investigations in this project, we posit that baseflow in the Fathew is predominantly derived from groundwater discharge to the river. In general, the level of baseflow support to the Fathew during drought periods can be conceptualised as a two-phase system:

- Discharge from the superficial deposits to the river, particularly associated with the down-catchment variability in the permeability and thickness of the deposits.
- Discharge from the weathered bedrock aquifer into the river, from both springs and tributary (the Dolgoch and the Pandy) inflows

The contribution of these two processes is likely to vary as drought conditions develop. Previous work in the nearby Dyfi catchment conceptualised that discharge from the superficial deposits (Glendining et al., 1981) dominated river flows during the early-time dry weather period, with discharge from the weathered bedrock controlling river flows during more extreme drought conditions. In the Fathew we postulate that a similar temporal sequence may be occurring, although at present the evidence base for this is weak. Further, contribution of flows in springs and tributaries to downstream storage within the superficial deposits is likely to complicate the deconvolution of the Fathew river flow hydrograph into different flow components. This temporal sequencing requires further investigation.

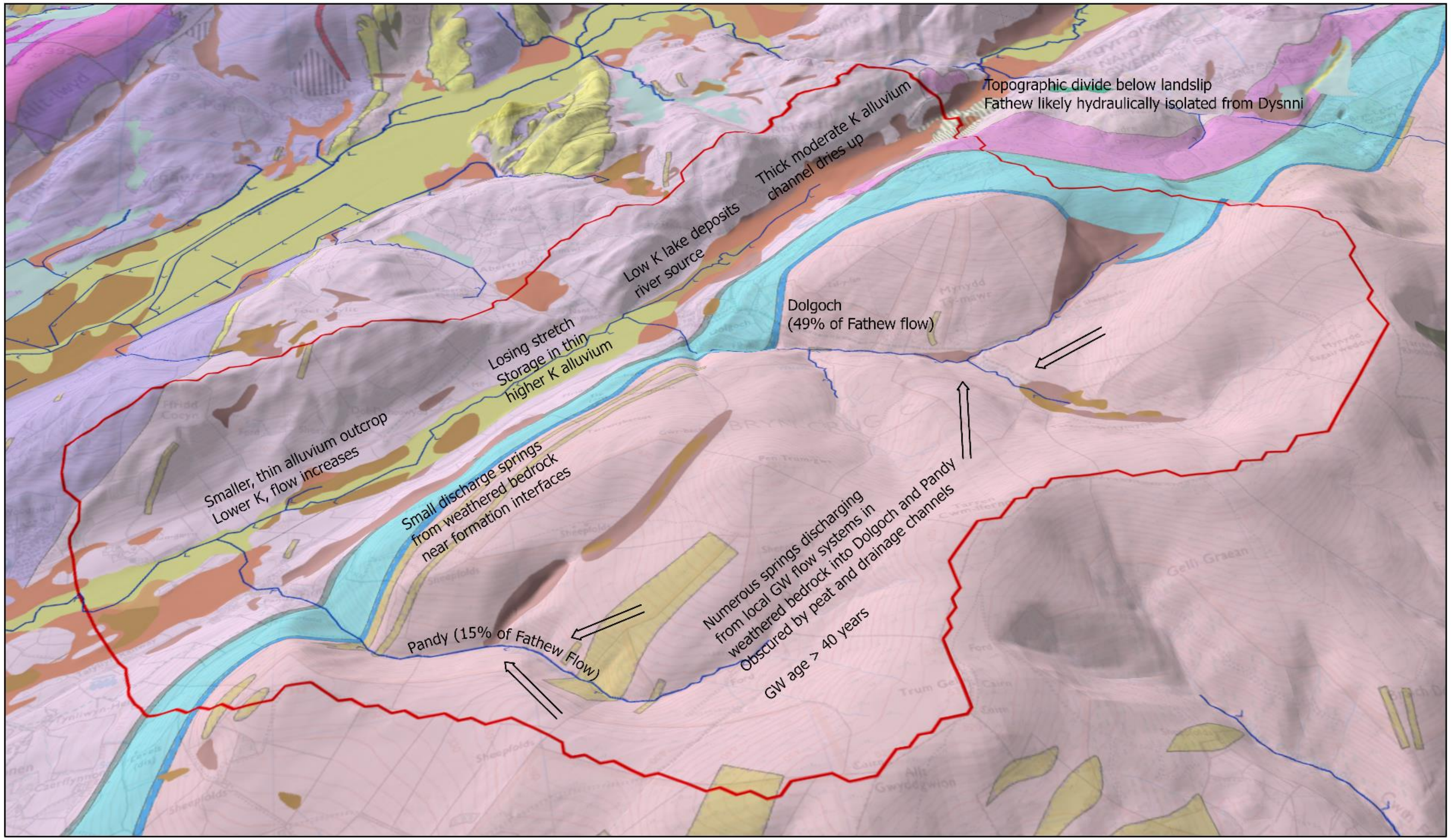


Figure 29 3D conceptual model of groundwater flow in the Afon Fathew catchment. Colours are bedrock and superficial geology as shown in Figure 1 and Figure 3. Contains Ordnance Survey Data © Crown Copyright and database rights 2022. Ordnance Survey Licence no. 100021290. Contains BGS materials © UKRI. All rights reserved.

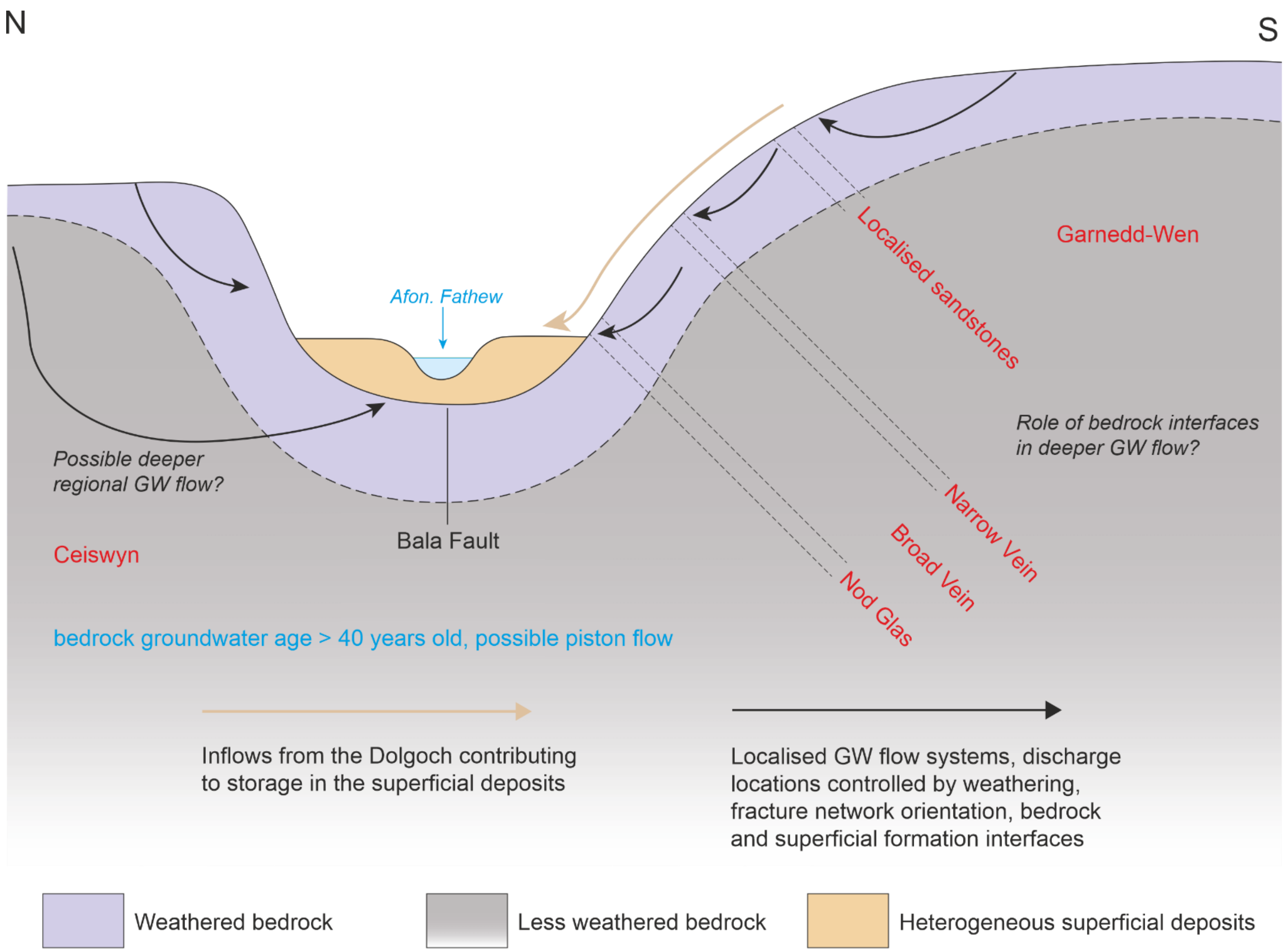


Figure 30 Conceptual cross section of groundwater flow in the Afon Fathew catchment. Red names are bedrock formations and italics indicate areas of greater uncertainty.

5 Further work

The conceptual model reported in section 4 is based on a desk based assessment of sparse existing data and the limited fieldwork that was able to be completed in Summer 2022. There are a number of uncertainties in the conceptual model which could be addressed through further targeted field and analytical work:

- Analysis of the streamflow hydrograph at the Fathew intake. Undertaking a master recession curve analysis similar to that undertaken by Glendining et al. (1981) in the nearby Dyfi catchment would be of benefit. This could be used to assess the relative contributions of the superficial deposits and the bedrock to drought flows.
- Further streamflow and spring monitoring. Continuous monitoring of levels in the Pandy, and Dolgoch during a drought would support an assessment of the temporal sequencing of drought flow contributions
- Accretion profiling in the Dolgoch and the Pandy. Given these inflows form a large component of the catchment water balance, undertaking accretion profiles during drought conditions in these sub-catchments may better constrain the inflows to these tributaries.
- Installation of monitoring boreholes in the superficial deposits. Based on the accretion profiles and superficial geology, it seems likely that there is significant storage in the alluvial deposits downstream of the Dolgoch confluence. Drilling of monitoring boreholes and associated hydraulic testing and instrumentation with paired groundwater and surface water level loggers would be of benefit to assess how storage in the alluvial deposits contributes to baseflow during drought.
- Additional benefits of borehole drilling would be the opportunity to take water samples for groundwater residence time indicators from the superficial deposits, and to verify the superficial thicknesses estimated from the Tromino survey. Groundwater residence time indicator data would improve our understanding of if there are differences in the age of groundwater (and hence drought vulnerability) between the bedrock and the superficial deposits.
- Additional Tromino and/or other geophysical profiling (e.g. Multi-Channel Analysis of Surface Waves (MASW) and/or Electrical Resistivity Tomography (ERT)) along the axis of the valley. The Tromino results in this study showed substantial variability in the depth to bedrock along the valley floor. Understanding this variability would inform our understanding of the potential for groundwater storage in the superficial deposits. In particular, ERT, whilst more time consuming than Tromino surveying, may also provide information on saturated thicknesses.

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Appendix I – Borehole logs

DRILLING LOG

LOG NUMBER 9WB 474

DRAGON DRILLING (WATER & ENERGY) LIMITED
GRAIG LELO INDUSTRIAL ESTATE
CORWEN
LL21 9SD
TEL: 01824 707777

SITE: Ty Gwyn JOB REFERENCE: 3531 SITE BH NUMBER: 1 BGS No: SN22/128 GRID REF: SH65440510 DATE: 13/05/2022

OPERATION	SIZE (MM)	FROM DEPTH (M)	TO DEPTH (M)	TOTAL
Set up				1
Symmetrix Drilling	198	G. L	30	30
Open Hole Drilling				
Mud Drilling				
CFA Drilling				
Airlift				1

DEPTH (M)	DESCRIPTION	MATERIAL & DEPTH (M)
G.L – 2	Clay, silt and sand	
2 – 30	Extremely fractured dark grey and brown mudstone.	Solid casing size – 113mm
	Very high-water productivity.	Bentonite type - Pellets
		Slotted casing size – 113mm
		Gravel pack size – 6mm
	Water strike depths – 5, 10, 15, 20, 25 metres.	Glass media Size – N/A

PREDICTED DEPTH (M)	ACTUAL DEPTH (M)	WATER STRIKES (MBGL)	LITRES PER MINUTE	SLOTTED CASING (M)	PLAIN CASING (M)	END CAP	GRAVEL/GLASS PACK (MBGL)	BENTONITE (MBGL)
60	30	5, 10, 15, 20, 25	200	18	12	Yes	30 – 11	11 – G. L

Dates on site: 10/05/2022 – 13/05/2022
DRILLING FOR: Water supply

NAME: [redacted] (LEAD DRILLER)

Date: 01/04/2019 R24 Issue:01

Figure S 1 Ty-Gwyn borehole log. British Geological Survey © UKRI 2022.

Appendix II – Information on Hydro Power Schemes

Figure S 2 Information on Hydro Power Schemes.

Ac No 47754

ENVIRONMENT AGENCY

Form WR – 38	*Ref: formwr381*	Agency No.

BOREHOLE RECORD

SH60/3
SH60NE/

A. ***SITE DETAILS***

Borehole drilled for:	[redacted]		
Location:	[redacted]		
N.G.R.:	SH 659 063		
Ground Level (if known):	SURFACE		
Drilling Company:	W.B. & A.D. MORGAN LTD., PRESTEIGNE, POWYS. LD8 2UF		
Date of Drilling:	**Commenced:** 23/06/08	**Completed:**	26/06/08

B. **CONSTRUCTION DETAILS**

Borehole datum (if not ground level) GROUNDLEVEL
(Point from which all measurements of depth are taken e.g. flange, edge of chamber, etc.)

Borehole drilled diameter................		200	mm from	0	to	80	m/depth
			mm from		to		m/depth
			mm from		to		m/depth
Casing material: u.P.V.C and type (e.g. plain steel, plastic slotted)	diameter	103	mm from	0	to	78	m/depth
Plain	diameter	103	mm from	0	to	15	m/depth
Slotted	diameter	103	mm from	15	to	21.1	m/depth
Plain	diameter	103	mm from	21.1	to	27.2	m/depth
Plain	diameter	103	mm from	27.2	to	39.4	m/depth
Slotted	diameter	103	mm from	39.4	to	45.5	m/depth
Plain	diameter	103	mm from	45.5	to	57.7	m/depth
Slotted	diameter	103	mm from	57.7	to	63.8	m/depth
Plain	diameter	103	mm from	63.8	to	76	m/depth
Slotted	diameter	103	mm from	76	to	78	m/depth

Grouting details:	12m	to surface
Water struck at:	9	m (depth below datum – mbd)
Rest water level on completion:	12	m (depth below datum – mbd)
Estimated blowout yield:	1400	Gallons per hour

C. **STRATA LOG**

Description of Strata	**Thickness (m)**	**Depth (m)**
Drift	1	1
Grey and black mudstone	9	10
Grey clay	3	13
Grey and black marl	67	80

Other Comments (e.g. gas encountered, saline water intercepted, etc.)			
Gravel Pack Quantity:	87 x 25kg = 2,175kg	Temp Steel Casing: Depth and Diameter	230mmx 2m
Cement:	14 x 25kg = 350kg		
Rig & Crew:	A Evans, S Powell, Berretta 2		

Figure S 3 Rhiwerfa BH log. British Geological Survey © UKRI 2022.