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AN INVESTIGATION OF THE KARST DRAINAGE NETWORK OF AGEN ALLWEDD

by

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ABSTRACT

This study investigates the karst drainage network of Ogof Agen Allwedd, an extensive cave system underlying the plateau of Mynydd Llangattwg, South Wales. Water samples were collected between July and October 2002 from the peat moorland above the cave, drips within the cave, the Entrance Series, Main Streamway and its tributaries, and the resurgences in Clydach Gorge. Conductivity, temperature, pH, alkalinity, Ca, Mg, Mn and Fe were measured to characterize components of the hydrological system. Hydrochemical data for some of the inlets, such as Cascade Passage and Meander Passage, suggested rapid response times to recharge events, which may have important implications for flooding and pollution events in the cave. The response of the cave system to rainfall was further investigated by measuring relative changes in water-level and temperature at a major confluence in the Cascade Passage area on an hourly basis between September and November 2002. Response to rainfall was more complex than suggested by the hydrochemical data. The vadose drainage system can be described as a three-component system with (1) rapid conduit flow, (2) soil/fissure (epikarst) network flow, moderated by surface air temperatures and (3) a diffuse, percolation flow that is in equilibrium with the rock matrix temperatures at depth.

INTRODUCTION

"Agen Allwedd will warrant a close study for its unusual hydrology"
(G. Warwick in Leitch, 1960)

Karst aquifer systems exhibit a range of flowpaths from slow diffuse routes along fissures and intergranular pores to rapid routes via a network of fractures and solutionally enlarged conduits. To assess the vulnerability of karst aquifers, then, one must assess the potential for storage and transmission of contaminants through the soil, the interconnected area of fissures below this, known as the epikarst (Williams, 1983), and the rock matrix. The source, path and mixing of component waters in karstic terranes can be investigated by simple hydrochemical monitoring schemes from sink to resurgence combined with hydrographs. Storage and transport of water and potential contaminants is complex and often site-specific models are required. Here, we aim to characterise the karst hydrological system of Ogof Agen Allwedd, Powys, South Wales, which was discovered in 1957 and is currently the fourth longest cave system in Great Britain with 32 km of known passageway. Early concerns about the cause of flooding of a boulder choke in the Main Streamway prompted a call for detailed investigation (Leitch, 1960), however, no such study has been undertaken.

Ogof Agen Allwedd (entrance located at NGR SO18730 15870) lies beneath Mynydd Llangattwg (Figure 1), a gently sloping peat covered plateau, bounded by steep screes and quarried crags on the north and east. The cave is one of three major caves that comprise the Mynydd Llangattwg system. The others are Ogof Daren Cilau (SO20512 15295) and Ogof Craig a Ffynnon (SO22011 12873). All the caves lie within the Lower Carboniferous Limestone, a sequence of oolitic limestones and dolomites, overlain by the Namurian Millstone Grit and the Upper Carboniferous Coal Measures (Smart and Gardener, 1989; Waltham *et al*, 1997). Mynydd Llangattwg is susceptible to potential pollutant sources such as illegal tipping, disposal of animal carcasses, road salting and fuel spillages. The South East Wales Groundwater Study of 1979-80 (Welsh Water Authority, 1980) identified many of the subterranean flowpaths beneath Mynydd Llangattwg and these are summarised by Gascoine (1989). The recent 'Foot and Mouth crisis' further exemplifies the necessity for an understanding of the groundwater flow because the virus is known to survive best in low temperatures and damp conditions away from sunlight, and so potentially could be transmitted through groundwaters. The threat from pollution is made more acute because of the significance of Mynydd Llangattwg in terms of ecology and biodiversity: the entrance to Agen Allwedd lies within the Craig y Cilau National Nature Reserve, the major caves of the Mynydd Llangattwg system are included in a more extensive Site of Special Scientific Interest, and the resurgence of Agen Allwedd lies within the nature reserve of Clydach Gorge.

The objective of this study was to construct a simple model of the karst drainage system for Agen Allwedd by (1) characterising components of the hydrologic system on the basis of their water chemistry, (2) investigating the temporal response of these components under different recharge conditions (3), investigating the downstream pattern of water chemistry along the major vadose stream conduit and (4) examining the water level and temperature response of specific flow inlets to rainfall events. The hydrochemistry and hydraulic system were studied during a period of changing recharge conditions from July to November 2002.

In a karst system such as the Ogof Agen Allwedd catchment, conductivity, alkalinity, Ca and Mg concentrations and pH can be used as reasonable measures of the amount of dissolution of host limestone and also the extent of mixing between different water sources. Discharge at points in the cave can be used to examine the response to different recharge events. Time lag to peak flow and form of the recessional limb of stream hydrographs, for example, can be used to indicate the relative contribution of rapid conduit and slower percolation flow. Water temperature can be used as a useful tracer of source and flowpath of water. Inlets comprising waters derived from rapid flowpaths from the surface will have a temperature that is dependent on rainfall temperature, the rate of flow and the integrated temperature along the flowpath, whereas waters with a long residence time will have a temperature at or close to the surrounding rock matrix, which is generally a function of the geothermal gradient.

STUDY AREA, SAMPLING SCHEME AND METHODOLOGY

The accessible reaches of Agen Allwedd comprise formerly phreatic passages generally developed along strike and modified by vadose entrenchment at a later stage and a down-dip (south south-east) component of vadose development that is joint-controlled (Smart and Gardner, 1989). Inflow to the system occurs as concentrated recharge at large swallets or more diffuse percolation inlets or seeps. The karst network for Ogof Agen Allwedd is illustrated in Figure 1 and it can be seen that waters from Ogof Pwll y Pasg, Ogof Pwll y Gwynt and Crochan Sion Hopkin drain into Agen Allwedd, which suggests that there is significant perched water flow above mudstone rich strata (Llanelly Formation) and in most places this flow occurs above the known cave passages of Agen Allwedd. These waters penetrate through to the underlying oolitic limestones only where the impermeable strata are fractured. In such places, manganese and iron rich black deposits can be found within the cave, which suggests that flow occurs near to the contact between the Dowlais Limestone and Millstone Grit where fine-grained fossiliferous, and often pyritised, grey-black shales are observed (Gascoine, 1982).

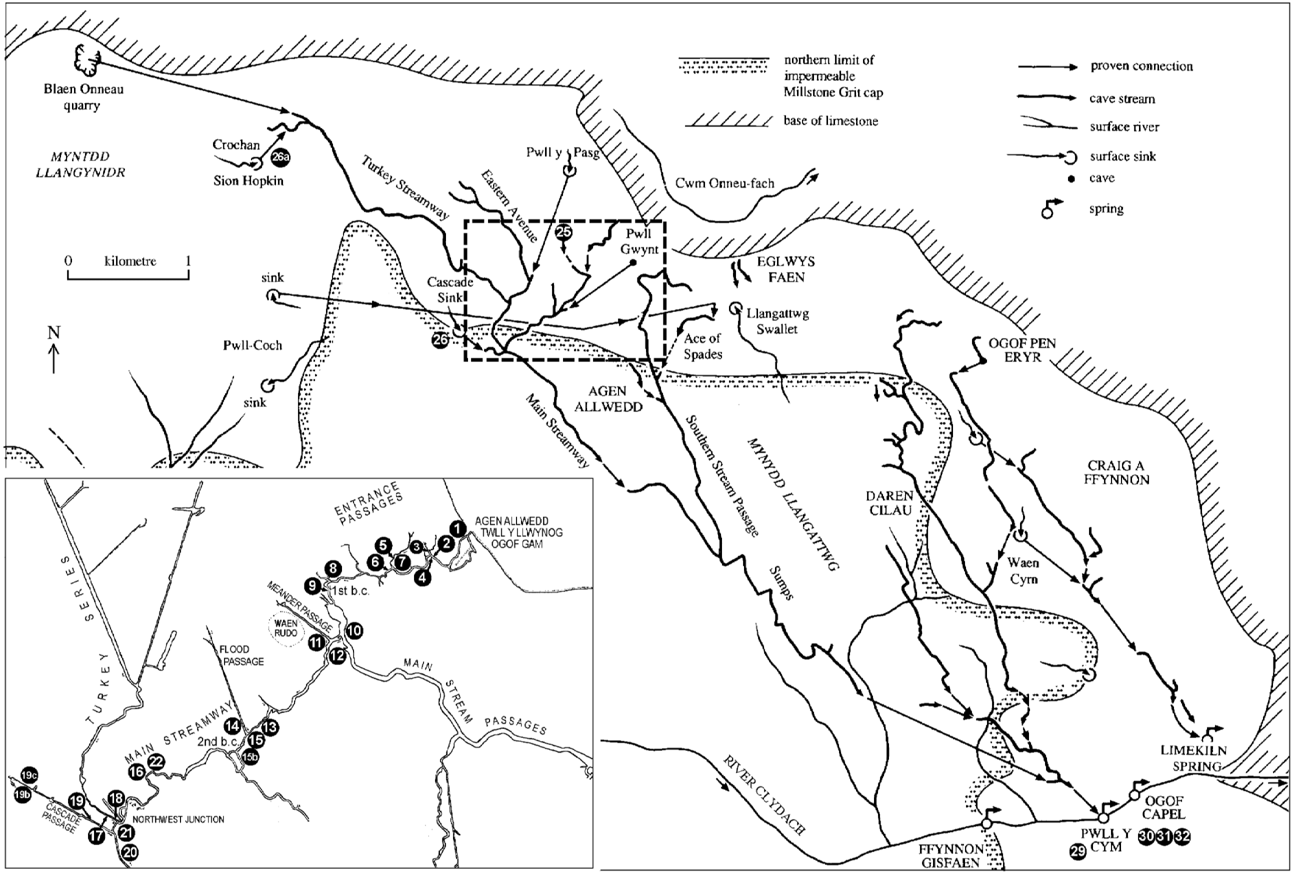

Figure 1. *Hydrology of the active stream passages of the Mynydd Llangattwg System (from Smart and Gardner, 1989). Inset is detail from the 1960 survey of Ogof Agen Allwedd (Leitch, 1960). Sample locations are numbered.*

To characterise the karst system from inputs to resurgence, water was collected from sinking streams and pools on the impermeable peaty moorland surface, drips and vadose streams within the cave, and resurgences in the Clydach Gorge to the south (see Figure 1).

Mynydd Llangattwg and Cydach Gorge water samples: Groundwater flow above the known passage of Agen Allwedd is well documented (Gascoine, 1989), thus there are no inferences (unless previously proved by dye-tracing) that samples taken on Mynydd Llangattwg are entering Agen Allwedd below where the waters are sinking. Surface samples from the peat moorland should thus be considered as representative of the approximate characteristics of waters entering the cave. Samples were collected from ponded water (e.g. Cascade Sink site 26) and sinking streams (e.g. Waen Rudd (site 25)). Samples were taken from the resurgences, Pwll y Cwm (site 30) and Elm Hole (site 31), to assess the outputs. Resurgence samples were compared with two further samples from up- and downstream within the Clydach Gorge.

Agen Allwedd water samples: Generally, vadose streams exhibit major changes in water chemistry when waters from different catchments or flow regimes are introduced, such as a tributary or fissure flow input. Between input locations, the chemistry can be considered to be relatively stable (Knights & Stenner, 2001). This assumption was confirmed during the pilot study when conductivity and temperature measurements were taken at regular intervals in the streamway. This pilot study also indicated mixing lengths downstream of confluences. At each confluence water samples were collected from the inlet (or tributary), upstream of the inlet and sufficiently far downstream of the inlet to guarantee complete mixing of the two waters.

Agen Allwedd is entered through a small entrance, Ogof Gam at the base of the Craig y Cilau escarpment (Figure 1). The stream in the entrance series is fed by a series of small tributaries (sites 2-7), which flows beneath Main Passage (sites 8 and 9), a large relict phreatic conduit, after a boulder choke. The streamway soon diverges from the Main Passage and flows into Main Streamway, which continues for approximately 700 m with a number of notable inlets: Meander Passage (sites 10-12), Flood Passage (sites 13-15) and the inlet from Pwll-y-Gwynt (site 15b). At Northwest Junction the waters from Main Streamway meet with Turkey Streamway (site 17). A short distance later Cascade Passage (sites 19-21) joins the streamway. From here the waters continue in a south easterly direction through the third, fourth and fifth boulder chokes and become Lower Mainstream Passage which meets with Southern Stream Passage. It then enters a series of sumps, emerges in Ogof Daren Cilau, and eventually resurges in the Clydach Gorge. The main resurgence, Pwll y Cwm (sites 30-32) was first confirmed in the early 1960s by dye tracing (Gascoine, 1989). Sample sites 1 (Entrance Series), 16 and 18 (both Main Streamway) were taken from fast flowing percolation drips from the passage roof.

Conductivity and temperature were measured *in situ.* Alkalinity was determined by repeated titrations within 24 hours of sampling. Dissolved trace metal concentrations (Ca, Mg, Fe and Mn) were determined for filtered waters by atomic adsorption spectrometry. Not all major ions were measured, the potentially important SO_4^{2-} , Na^+ and K^+ ions, for example, were not included in this survey, which means that thorough geochemical modelling or assessment of ion-balance errors could not be undertaken.

Initial survey of the water characteristics in the Main Streamway suggested that Cascade Passage had a relatively rapid flux time from the surface. To estimate relative changes in discharge, two calibrated pressure sensors were installed at unguaged sites upstream of the junction with Main Streamway (Northwest Junction, Site 21) and downstream at Cascade Passage Pool (Site 20). Water level estimates are compared with rainfall measurements from a tipping bucket raingauge at Tretower (SO 200200), 5 km north of the cave entrance. Relative water temperature changes were also recorded at Cascade Passage Pool. All measurements were recorded by data loggers on an hourly basis from 09/09/02 to 14/11/02.

RESULTS AND DISCUSSION

General chemical results

The waters samples exhibit a tenfold range of electrical conductivities from 30 to 350 μS cm^{-1} across the catchment (Figure 2a) and, as expected for a karst aquifer, they covary with the Ca and Mg concentration, or total hardness. The range of conductivities was similar throughout the period of study. As recognised in other studies (Bray, 1969; 1971), there is a non-zero intercept on the y-axis of Figure 2a which is probably explained by the contribution of K+ or Na+ ions to the total dissolved cations.

Water sample sites have been categorised to facilitate comparison between different components of the karst drainage system. These categories include *drips,* which would be expected to have the longest residence time in the system; *sinks,* which are the surface waters taken from sinking streamways, *resurgence* samples as examples of the outputs of the system. Vadose stream waters are categorised as *inlets* (tributaries to Main Streamway), *entrance* (from Entrance Series) and *Main Streamway*. Component waters were expected to have different chemistries, and this is readily illustrated in Figure 2b, where pH is plotted against alkalinity. Drip sites have the highest alkalinities (up to 150 mg L^{-1} HCO_3^-) and pH values (~ 8.0), whereas sinks have low pH (< 6.0) and low alkalinity (< 25 mg L^{-1} HCO_3^-). Vadose stream waters and resurgences have pH (~7.0 to 8.0) and alkalinity (35 to 90 mg L^{-1} HCO_3^-) values that lie somewhere between the two end-member values for drips and sinks, the absolute value being a function of the extent of water-rock interaction and mixing between different source waters.

Monthly data

For the period July to October, when chemistry data were collected, the amount of recharge to the system varied considerably: September was the driest month, while October was the wettest month. Hence, it was possible to investigate the response of water chemistry to differing recharge conditions. Data for each category can be investigated in terms of the absolute values and range (or variance) by month. Sample sizes were insufficient for formal analysis of variance.

The overall pattern of high conductivities and alkalinities in drips, low conductivities and alkalinities in sinks and intermediate values in vadose stream waters and resurgences is clearly shown in Figure 3. This pattern was maintained for each month, but there were differences in the absolute values and range of data. Most categories had their highest values during the driest month September. Of the drip samples, sample 18 was particularly notable for its high and consistent alkalinity (127 to 140 mg L^{-1} HCO_3^-). Samples from the sinks were often below the detection limit, which distinguished them from those samples taken within the karst system. Samples from the Entrance Series, the five samples in the first 450 m of the cave, had a smaller range in values than the rest of the vadose water categories. October values exhibited both lower values and a greater range in alkalinities. The greatest variability by month was observed for samples taken from inlets. The alkalinities obtained for samples from the Main Streamway were very similar to the resurgence values.

Generally, the same pattern was observed for variation in conductivity by source of water and month as observed for alkalinity. Unfortunately, no data was reported for September because the conductivity meter malfunctioned. What is particularly evident in Figure 3a is the

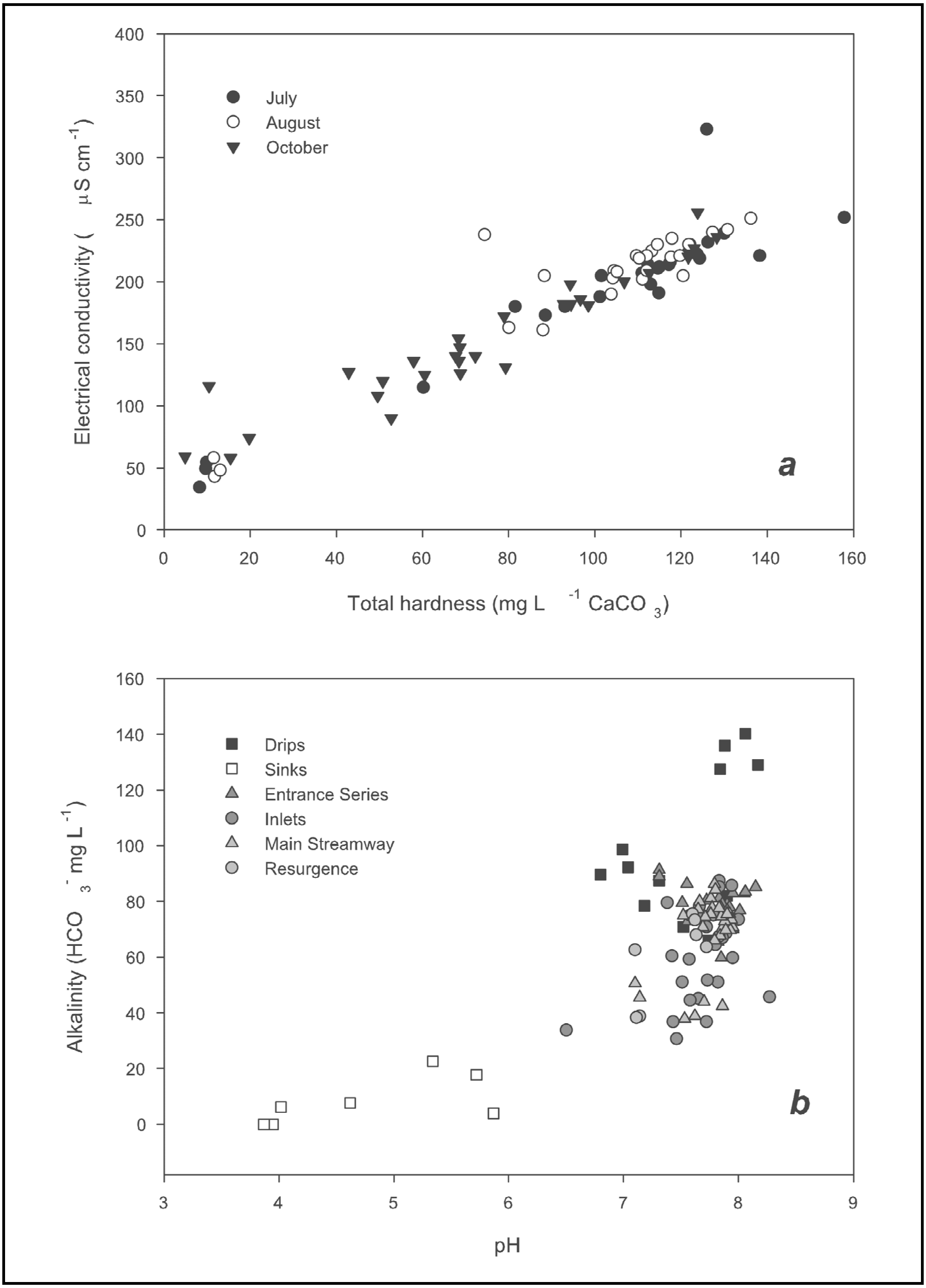

Figure 2. *a. Total hardness vs. electrical conductivity by month of sampling; b. pH vs. alkalinity for different water categories.*

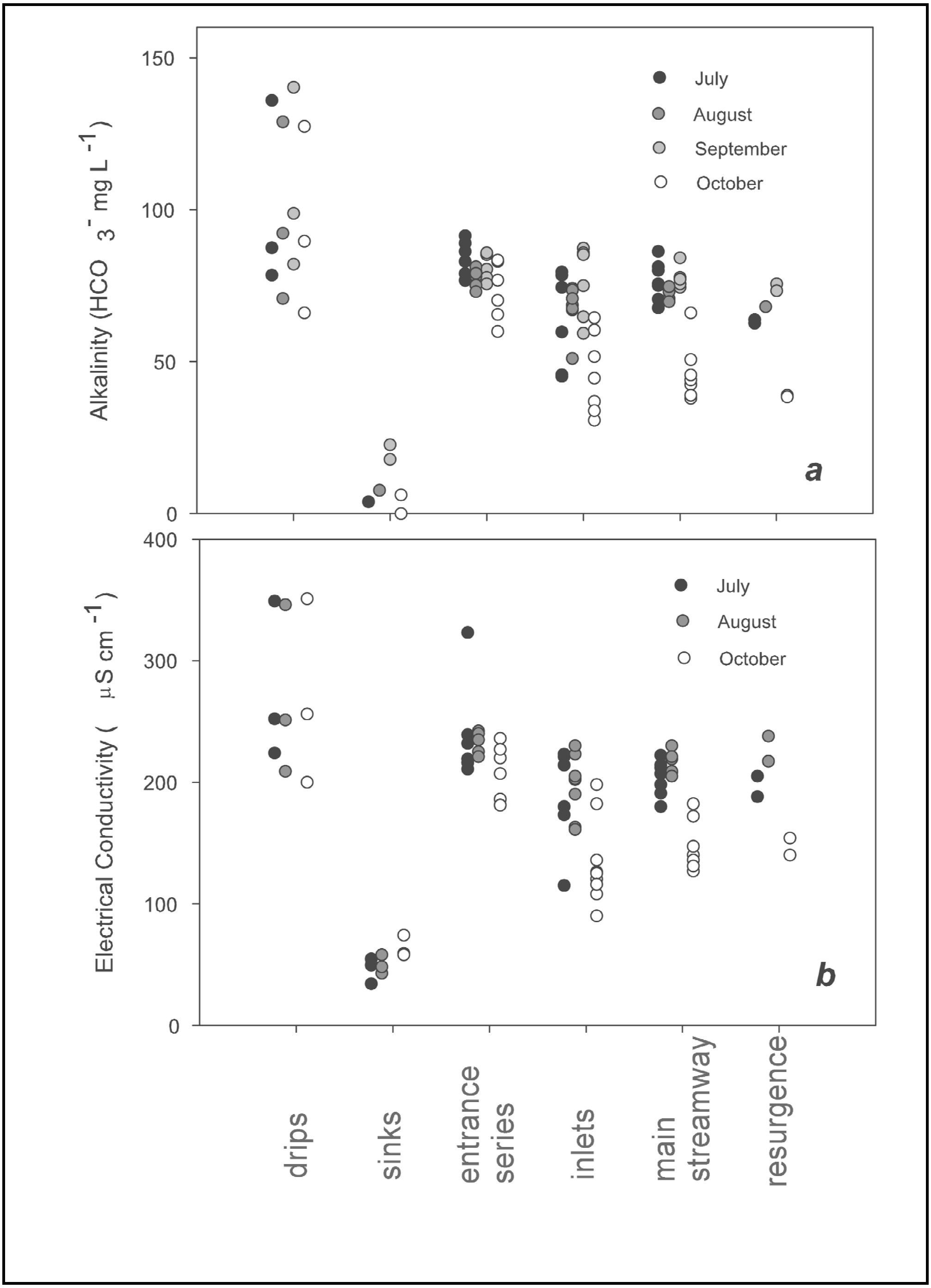

Figure 3. *a. Conductivity and b. alkalinity for different water categories by month.*

lack of temporal variation for each drip sample: samples 16 and 18 vary from 251 to 256 μS cm^{-1} and 346 to 351 μS cm^{-1}, respectively, during the sampling period. The sinks show different temporal pattern from the other samples, with October showing the highest conductivity. Except for a single outlier, (site 4, July, 323 μS cm^{-1}), samples from the Entrance Series exhibited generally low within-category variance (180 to 241 μS cm^{-1}). In both the entrance samples and inlets October samples tend to have lower conductivity and are more variable than the other months. As with alkalinity, the most variable waters were those from the inlets, sample site 19 has the lowest conductivity in both July and October with conductivities of 115 μS cm^{-1} and 108 μS cm^{-1} respectively. The lowest conductivity recorded in the system was that of site 19b which had a conductivity of 90 μS cm^{-1}, in October.

The conductivity of the Main Streamway varies as expected over the sampling period, with the lowest conductivities in October, indeed the measured conductivities along the Main Streamway in October are statistically different to the rest of the sampling period. The resurgence conductivities are similar to those of the Main Streamway and display the same temporal variance.

Water characteristics along the Main Streamway

Sampling occurred up and downstream of confluences from the Entrance Series to downstream of Cascade Passage. Transects plotted in Figure 4 show the effect of inlets on the composition of the Main Streamway.

Conductivity: The profile for July and August transects indicate a gradual decline in conductivity suggesting progressive dilution by inlets with lower conductivity. This is apparent in July when waters from Cascade Passage, which has a low conductivity (115 μS cm^{-1}) reduces the conductivity of the Main Streamway from 222 μS cm^{-1} upstream to 180 μS cm^{-1}downstream of the inlet. Although conductivities recorded in October are lower than the other months, the shape of the October profile is similar to the other months.

Mg/Ca molar ratio: Mg/Ca ratio is a sensitive tracer for different source waters. It is affected by lithology and water-rock residence times. It is clear that different inlets have different Mg/Ca ratios and these influence the Mg/Ca of the Main Streamway. The wettest and driest months, October and September, respectively have very different profiles downstream of Meander Passage. Higher Mg/Ca in September likely to be related to a slower percolation feed, which becomes diluted in October by a rapid, conduit flow.

Temperature: All the profiles follow a very similar pattern, progressively warming along the transect, downstream. Notably, in July the warm waters from Cascade Passage cause the temperature of the Main Streamway to rise. This is perhaps related to the influence of waters that have warmed at the surface and have short routes to the Main Streamway and insufficient time to equilibrate with the ambient cave temperatures.

Description of water characteristics in relation to flowpaths

Each karst drainage system is unique and inferences to the physical structure of the drainage system can only be suggested relative to specific examples from Agen Allwedd. Discussion of the suggested structure of the aquifer will be based upon the two end-members; percolation feed, characterised by water from site 18, and rapid conduit flow, typified by waters

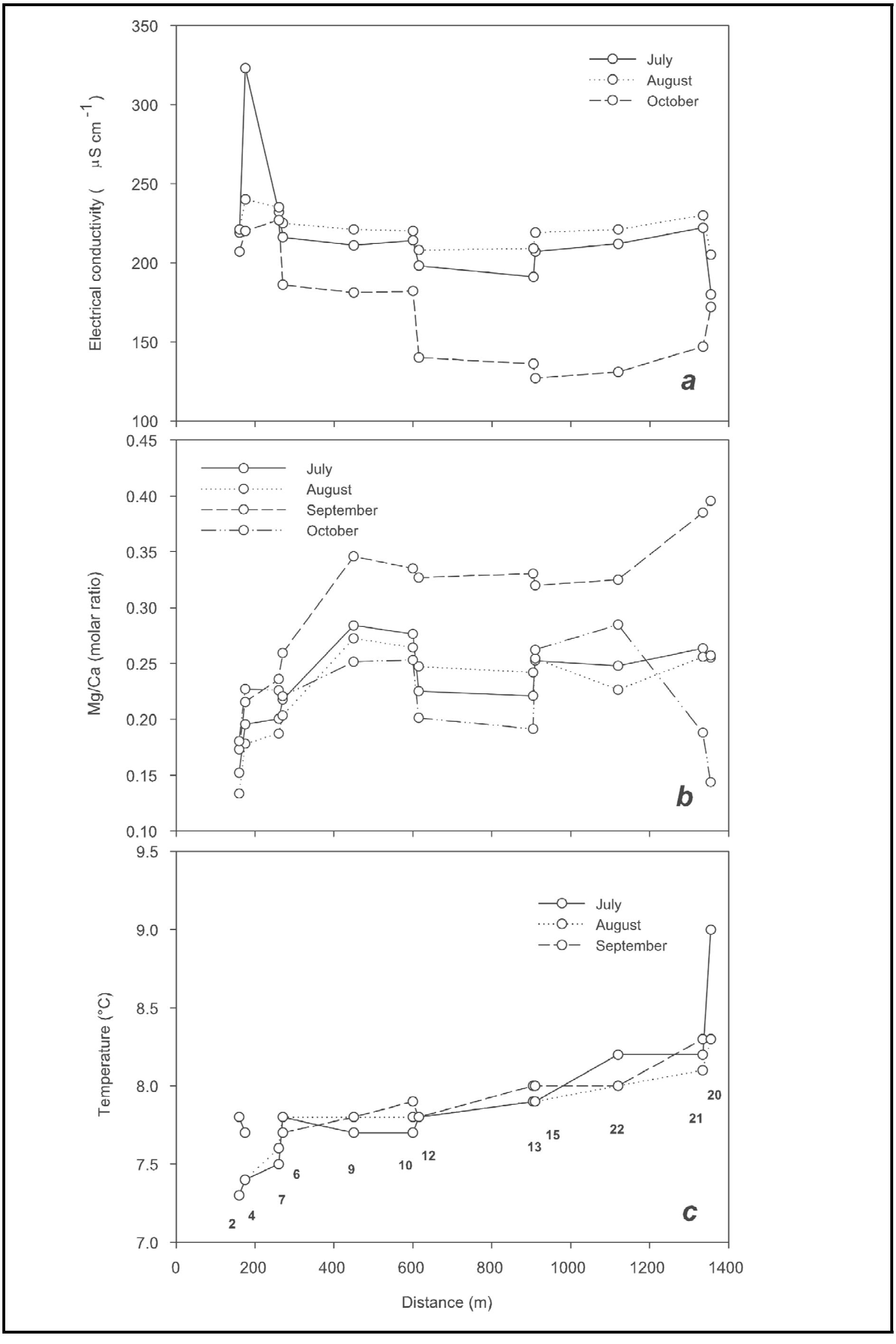

Figure 4. *Monthly water characteristics along Entrance Series and Main Streamway: a. Electrical conductivity; b. Mg/Ca; c. temperature (and site numbers).*

from site 19, which according to Penney's (1976) dye trace can have a rapid flux time from the surface of 1 hour 20 mins. A summary of the network is presented in Figure 5.

Inputs to Agen Allwedd: The samples typically had a low conductivity (50µS/cm^{-1}), a temperature similar to air temperature, low pH (between 3.87-5.87), calcium contents lower than the detection limit to 5.43 mg L^{-1} and magnesium contents ranging from 0.09 mg L^{-1} to 0.75 mg L^{-1}. The surface samples broadly matched those results found by Newson (1970) for the aggressive waters of Waen Fignen Felyn sink on the peat moorland above Dan-yr-Ogof.

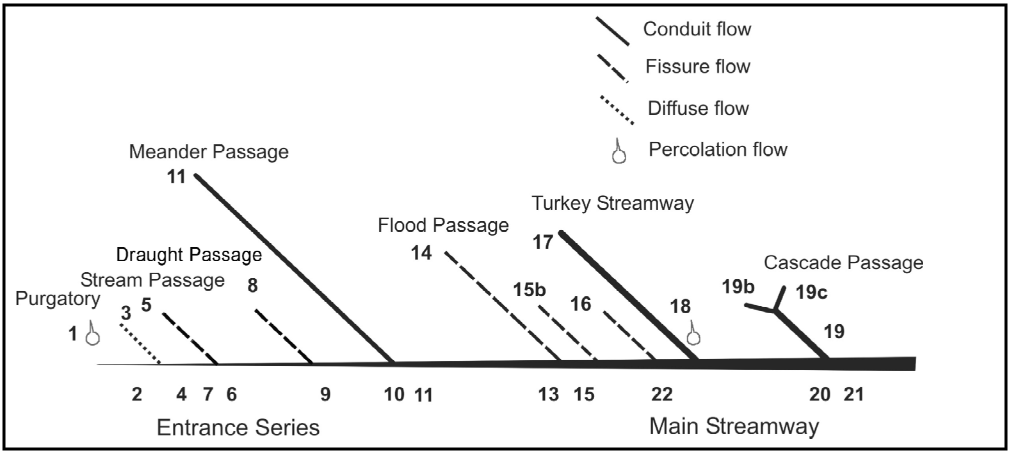

Figure 5. *Schematic diagram of the vadose karst network sampled during the study based on water chemistry data. Samples are mostly conduit streams and inlets with isolated percolation (diffuse or fissure) fed water sources.*

Drip samples: Site 1, near the entrance, had a slightly greater observed variance in water characteristics with seasonal changes than that of sites 16 and 18 from deeper in the cave. This might be explained by the fact that there is no overlying Millstone Grit at site 1, and there is a shorter distance between the cave and the surface. Variations in the drip rate were noticeable at site 1. The conductivity, alkalinity, Ca and Mg in samples taken from site 16 and 18 are high and consistent, indicating a relatively slow flowpath. These waters have been in the system for a substantial period, are not notably influenced by surface conditions and thus represent percolation flow. Site 16 is distinguished from other drip sites by the presence of silt-sized sediment, which suggests that, while a major component of the percolation feed here is slow, some proportion may be more rapid *via* solutionally enlarged fissures.

Entrance Series samples: At site 2 (the start of the vadose stream transect) discharge was variable. The water characteristics varied as expected, with the highest conductivity, alkalinity and ionic composition in September, which was the driest sampling month and thus the waters had spent longer in the aquifer. Following rainfall in October, vadose waters had the lowest conductivity, alkalinity, calcium and magnesium contents. During this month, longer residence time waters must have been diluted by waters from more rapid flowpaths. At site 3, the water characteristics (in particular the high magnesium content and flow consistency) show a long residence time in the drainage system, which is characteristic of feed from diffuse waters.

Sample site 7, upstream of the convergence with Stream Passage is consistently different to that of site 4, and yet there are no known inlets into the cave between them. It is likely then that there is some fissure flow intercepting the streamway between these two sites. Extremes in parameters at Site 5 (Stream Passage) are in September and October the driest and wettest sampling periods respectively. The water characteristics support expectations of fissure flow and relatively slow flow.

Waters from Draught Passage (site 8), indicate relatively rapid transfer through the system and change with recharge conditions. The stability of calcium and magnesium ratios shows that the flowpaths do not change over the sampling period and the high magnesium content suggests a network of fissures.

Main Streamway samples: Penney's (1976) dye trace from Waen Rudd to Meander Passage (site 11) took 2.75 hours. Here, the water characteristics confirm a rapid flow rate. In July, August and September, Waen Rudd sink was dry, but samples from Meander Passage still suggested short residence times. According to Gardener (*pers comm*.) two separate inlets feed Meander Passage, which explains why the Mg/Ca ratios differ by nearly a third; under different climatic conditions different flowpaths prevail. The data suggests that both of these inlets have rapid flowpaths indicative of conduit flow.

Flood Passage (site 14) exhibits the black deposits described by Gascoine (1982). Although samples had been filtered, some iron and manganese was detected in site 14 waters during October. Significant residues were observed on filtering suggesting a slow, fissure-fed path rather than diffuse (intergranular) network.

Pwll y Gwynt is a cave above Agen Allwedd in the upper Dowlais Limestone (Smart and Gardener, 1989) and flows into Agen Allwedd at site 15b. The water characteristics are similar to Flood Passage and the site also has black deposits (Gascoine, 1982). These waters also have detectable manganese contents and periodically measurable Fe content (October).

Turkey Streamway (site 17) is composed of many different waters and responds to seasonal variation in the expected manner. Cascade Passage (site 19) was distinct from all the other inlets in July and October, in August and September (the driest months) these differences were not as exaggerated. This is as expected considering that in both August and September, Cascade Sink, which drains to Cascade Passage, was virtually empty. By October this had refilled and resumed its 'normal' appearance as a pool. In August and October samples were collected from the two inlets at the top of Cascade Passage, the water characteristics agree with Penney's (1976) dye trace which found that site 19b rather than 19c is directly linked to the Cascade Sink. Sample 19b has detectable iron content derived from surface sources. Although both flowpaths are rapid and transitional, the relative influence of inlets 19b and 19c on Cascade Passage waters varies seasonally, this is confirmed by the variation in Mg/Ca ratio at site 20 and 21 during September and October.

Outputs of the system: The samples taken from the resurgences Pwll y Cwm and Elm Hole have very similar characteristics and show similar variance in parameters to the samples from the cave system. So, by site 20 the streamway is representative of mature cave waters. The waters of the Clydach Gorge upstream of the resurgences have a higher pH, alkalinity, conductivity, calcium and magnesium than the resurgence samples. Despite the differences in characteristics, the downstream samples are not noticeably influenced by the entry of cave waters.

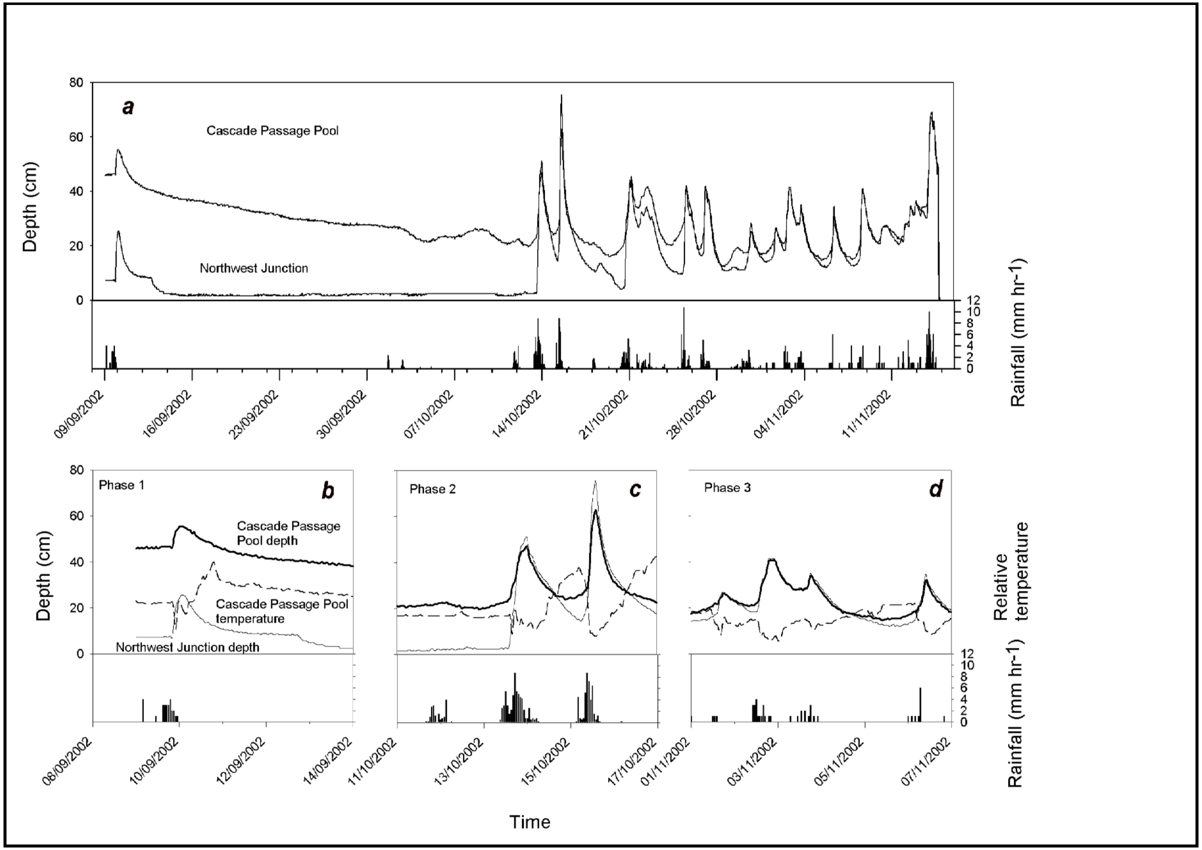

Figure 6. *a. Water depth at Cascade Passage Pool (CPP) and North West Junction (NWJ) (equivalent to sites 21 and 20 respectively, see Figures 1 and 5) for the period 09/09/02 to 14/11/02. b. Water depth and temperature at CPP and water depth at NWJ from 08/09/02 to 13/09/02 ; c. Water depth and temperature at CPP and water depth at NWJ from 11/10/02 to 16/09/02; d. Water depth and temperature at CPP and water depth at NWJ from 01/11/02 to 06/11/02.*

Stream hydrographs, temperature and flowpaths

The observation of large shifts in temperature, Mg/Ca and conductivity between sites 20 and 21 on a monthly basis prompted detailed high-temporal resolution investigation of the nature of flow from the surface to the major confluence of Cascade Passage with the Main Streamway. Pressure transducers were installed to monitor the relative changes in discharge. A thermistor was used to obtain information about flow routes using heat as a tracer. Unfortunately, recorded depths cannot be related to discharge in a simple manner because the cross-section of the passage was not measured. Hence, we discuss relative changes in discharge only. Temperature data also remains uncalibrated.

Cascade Passage Pool (CPP) depth, Cascade Passage Pool temperature, Northwest Junction Pool (NWJ) depth and precipitation at Tretower are plotted in Figure 6a on an hourly-basis for the period 9/9/2002 to 14/11/2002. Three distinct phases are recognised (Figures 6b-d); a long period of recessional flow after a late summer storm (Phase 1), a significant recharge period in mid-October (Phase 2) and then sustained periodic recharge during late October and November (Phase 3).

Phase 1: Mynydd Llangattwg experienced a large rainstorm over many hours during 09/09/02 and no further precipitation event was recorded until 01/10/02 (Figure 6b). Water levels at CPP and NWJ react at the same time, some 12 hours after the onset of rain and it is not until 0.00 on 10/09/02 that Cascade Passage Pool reaches its peak depth. Lag time is indicative of the structure of the drainage system and the waters stored in the system. CPP is known from Penney's (1976) dye tracing and the water characteristics to be a fed by a rapid conduit flow from the surface. At this time, both NWJ and CPP had long lag times suggesting that storage in the fissures of the epikarst was being recharged by much of the storm waters. Relative temperature recorded at CPP provides additional information. Temperature fell during the rising limb of the storm hydrograph, probably because the relative contribution from the two catchments upstream of Cascade Passage and North West Junction changed. The configuration of the sensors was such that CPP included contribution from both catchments, NWJ only one of the catchments. Waters from upstream of NWJ must have had colder temperatures because as soon as these waters dominated the downstream (CPP) water levels, temperatures rapidly dropped. Prior to the peak discharge, there was a progressive increase in temperature until some 18 hours after the peak. It would appear that the recessional limb was increasingly dominated by slow, residence waters that had sufficient residence times in the near surface soil and epikarst zone to produce temperatures greater than ambient cave temperatures. These waters may have had a horizontal flow component of flow towards points of rapid transmission at shafts and short residence times within the colder conduit environment, such that the water have not achieved equilibrium with the ambient cave air temperatures. It is interesting to note that two minor rainfall events on the 01/10/02 and 02/10/02 prompt a rise in depth some 24 hours later, however there is no recorded change in temperature. Because these pulses take many hours to reach Cascade Passage, the water must have been fed as percolation feed or deeper seated epikarst flow that has equilibrated with the ambient rock temperatures during its slow flow path.

Phase 2: Short rainfall events on 01/10/02, 02/10/02 and 12/10/02 had a small effect on water levels in CPP and little or no effect on NWJ levels (Figure 6a,c), probably because the moorland and epikarst storage zone below was relatively dry and able to 'absorb' this precipitation. The two large rainfall events on the 13/10/02 and 15/10/02, however, prompted a dramatic water level response (Figure 6c). Water levels at CPP rise before NWJ, which is indicative of the shorter average flow path for the catchment of Cascade Passage compared with that of the Main Streamway at NWJ. After recharge during the early October storms, the response of Cascade Passage is near immediate. The temperature pattern for the storm of 13/10/02 is interesting. At the time of early water level rise (first few hours) no change in temperature is observed, which suggests that the first waters from Cascade Passage must have been in equilibrium with ambient rock temperatures (dewatering of stored water with long residence times?), temperatures then fell at the beginning of the rising limb, when colder waters from Main Streamway catchment above NWJ dominated the response, and then increased again through the peak discharge as longer residing waters arrived. Temperatures increased during the recessional limb probably because the contribution from waters sourced from shallow routes affected by warmer daytime temperatures become dominant. It is expected that eventually water temperature would have fallen to mean rock matrix temperatures as slow-percolation feed waters dominate. In addition to the continuous monitoring results, it is noted that the temperatures recorded each month increased downstream (Figure 4c), likely a result of addition of water with shorter residence times and higher temperatures at this time of year. Surface waters and sinks were between 14 and 18 ºC from July to September, compared with cave waters temperatures 6.6 º to 8.8 ºC.

Phase 3: The final phase illustrated here is characterised by similar responses in both passages, CPP and NWJ (Figure 6d). Whereas increases in water level in the two passages were separated by nearly 24 hours in response to the storm event on the 19/10/02, by 11/11/02 the responses are separated by less than 2 hours. Transmission times were much shorter during mid November because much of the storage capacity of the soil and epikarst zone was saturated. A simple inverse relationship between temperature and water level is evident for this phase, which suggests that temperatures are dominated by the contribution of waters from the Main Streamway.

CONCLUSIONS

Water chemistry and hydrograph data for the upper reaches of Agen Allwedd for the period July to October 2002 reveal something of the complex hydrology of karst terranes. Measurement of standard parameters, such as conductivity, alkalinity, Ca, Mg, temperature and pH indicate that different waters within the cave have different residence times and there is a range of mixing relationships between water sources. There are large differences between the chemistry of waters from surface sinks, percolation drips and vadose streams, and while the pattern is generally similar on a month to month basis, different recharge conditions affect the overall concentrations of dissolved ions because of dilution and changing residence times. With increasing rainfall intensity and frequency, the alkalinity and conductivity of downstream waters were much reduced indicative of dilution by waters with short residence times from inlets with shorter mean paths from the surface.

Hydrograph data from a major confluence in the Main Streamway demonstrates that different catchments within the cave have different response times and mean travel times. The temperature response in a vadose stream is complex and a function of integrated temperature along the flow path, surface temperatures and discharge rates and mixing relationships between different upstream, catchments. A first attempt to deconvolve the temperature and discharge data in Agen Allwedd confirms the short mean path from Cascade Sink to Cascade Passage

Pool and hints of a three-component (fast concentrated recharge, shallow horizontal transport, slow diffuse percolation) system.

The hydrographs suggest that although Cascade Passage may initially respond slightly earlier, Northwest Junction and Cascade Passage Pool have their peak depths the same time after a rainfall event. From this limited data in this area of the cave the response and maximum in flooding is essentially uniform and does not vary in association with 'rapid' flowpaths. The 'wetter' the antecedent conditions, the more rapid and greater the response to rainfall events. Thus, with respect to flooding the antecedent conditions are as important as rainfall intensity and duration.

This represents a preliminary attempt at understanding the 'unusual' karst drainage network of Agen Allwedd. It relies on a short sampling period for hydrochemical and hydraulic data. Future studies should encompass a more comprehensive survey of major ions to calculate useful summary parameters such as saturation indices with respect to calcite. It is hoped that further analysis of hydraulic data for a complete yearly cycle will add to the current simplistic model.

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