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Towards defining a scallop dominant discharge for vadose conduits: some preliminary results

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Abstract: a well-established inverse relationship exists between mean scallop length and flow velocity for a given population of scallops. Previous authors have suggested that one or more 'scallop dominant discharges' can be identified at which erosion by dissolution proceeds at the greatest rate, since scallop populations usually indicate a single flow velocity whereas discharge and velocity are unsteady through time. For vadose conduits, a scallop dominant discharge is difficult to define because of the unconstrained cross-section; this causes problems in determining the discharge at which scallops are formed, although recent developments in instrumentation allow greater flexibility in monitoring flows on a continuous basis. Here the relationships between monitored flow velocity and depth are compared with the scallop velocity for an active vadose streamway in Poulnagollum, Co. Clare, Ireland. From these initial results, a complex relationship is seen to exist between the velocity and depth of flow as discharge changes. Thresholds occur over discrete depth ranges where there is little or no change in velocity; these are observed during both rising and falling stage. It is suggested that these thresholds may be related to changes in hydraulic radius, and hence flow resistance at different depths of flow. The scallop-derived velocity is related to the recorded flow data, with reference to the various controls on erosion, most notably the degree to which the flow is undersaturated with $CaCO_3$, and ongoing research is outlined.

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INTRODUCTION

Scallops are commonly-occurring dissolutional features that wholly or partly cover the boundaries of many active and fossil conduits. These concave forms are longitudinally asymmetrical, indicating the direction of the flow that formed them, and they vary in length from a few millimetres to several metres, depending upon the passage dimensions and prevailing flow conditions. A well-established inverse relationship exists between the Sauter mean scallop length and flow velocity, established by Curl (1966) using dimensional analysis and later confirmed experimentally using plaster blocks (Goodchild and Ford, 1971; Blumbeg and Curl, 1974). This relationship has been widely applied in determining flow conditions for active and fossil cave conduits.

The fact that scallop populations usually have a log-normal, unimodal distribution, while discharge and velocity are unsteady through time, has led to the suggestion that a 'scallop dominant discharge' can be defined at which dissolutional erosion occurs at the greatest rate and is therefore most effective in passage formation (Smart and Brown, 1981; Lauritzen, 1982 and 1983; Ford and Williams, 1989). The concept of an 'effective', or 'dominant', discharge was first proposed by Wolman and Miller (1960) for (surface) alluvial channels in humid temperate regions where the frequency, or return period, of a given flow is considered together with its magnitude in determining geomorphological effectiveness in terms of bedload transport rates. Whereas larger, rarer flows may individually carry out a considerable amount of geomorphological work, the infrequent occurrence of such events in comparison to the cumulative effect of lower magnitude, higher frequency flows may be more effective in determining channel capacity and form over a given period of time. This builds on the work of Leopold and Wolman (1957), who correlated meander wavelength with bankfull width and bankfull discharge, demonstrating the morphological significance of frequently occurring flows.

A rather different set of controls applies to cave conduits since, in the absence of a significant clastic load, erosion is almost entirely due to dissolution. The relationship between passage width and meander wavelength was examined by Smart and Brown (1981) for vadose streamways in Ireland and New Zealand using passage width as a surrogate for bankfull discharge (which cannot be defined for a vadose canyon). The relationship was found to be anomalous compared with the widely observed inverse relationship that exists for alluvial channels, where adjustment of channel form is accomplished through the erosion and deposition of sediment. The authors highlight the importance of local base levels in determining relative rates of vertical and horizontal incision, together with variations in the aggressiveness of the streamflow – erosion is effectively zero when the water is saturated, regardless of discharge.

Dominant discharges have been determined from measurements made by divers in phreatic conduits in marble stripe caves in Norway (Lauritzen, 1982, 1989 and 1995). Discharges calculated from scallop-derived velocities and measurements of conduit cross-section were analysed in conjunction with flow data from a gauging station. The scallop-derived discharges were found to represent flood flows that occur between 2 and 15% of the time, a flow with a magnitude three times that of the mean annual flood. By integrating flow and chemical measurements, it was estimated that half of all the chemical work occurs for only 10% of time, during the highest discharges (Lauritzen, 1989). There are a number of possible applications of the concept that include developments in understanding of erosion controls and rates of erosion and analysis of palaeoflows. Lauritzen (1989) suggested that a direct linear relationship exists between scallop dominant discharge and the corresponding drainage area – similar to the relationship observed for surface catchments – which may have potential as a powerful tool for deducing the area of palaeo-watersheds from relict caves. It is also possible to derive hydraulic parameters such as boundary friction, stream power and boundary shear stress from scallop and sediment properties (Gale, 1984).

Determining the dominant discharge for a vadose streamway has always been problematical – although not impossible – because both the cross-sectional area and velocity vary with changing discharge,

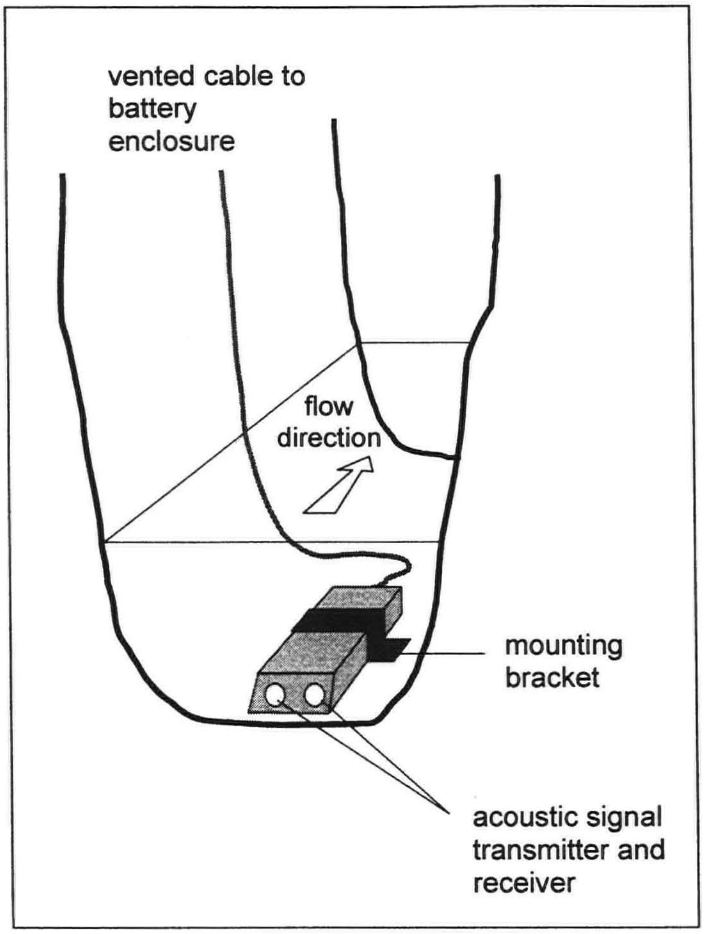

Figure 1. *The Starflow ultrasonic Doppler instrument. The dimensions of the Starflow are 290mm (L) x 70mm (W) x 25mm (H).*

making it difficult to calculate a meaningful discharge(s) from scallop measurements. However, recent developments in flow monitoring mean that it is now possible to monitor depth and velocity in vadose conduits without the need to install gauging structures. The research described here is at an initial stage, the main aims being to attempt to identify the flow conditions under which scalloping develops at the greatest rate and to determine whether a scallop dominant discharge is a valid concept in this instance.

METHODS

Flow monitoring

A Unidata 'Starflow' ultrasonic Doppler instrument (Fig.1) was selected for installation in a section of vadose canyon streamway in Upper Poulnagollum, Slieve Elva, Co. Clare, between Poll Binn Pot and Main Entrance (Fig.2). In selecting this site, several factors were taken into consideration. A straight section of actively incising streamway with a regular cross-section was chosen, care being taken to ensure that there were no obvious structural or hydraulic controls that might, for instance, cause flow to back up during high flows. Further criteria included the presence of well-developed scalloping and an absence of clastic load. The site also had to be suitable for the installation of the Starflow, which is connected via a 15m vented cable to an enclosure containing a 12V battery and computer interface, which had to be placed away from any risk of inundation. Flow monitoring is an ongoing process, with data downloaded from the Starflow at regular intervals.

The Starflow is able to record flow data for a period of up to three months, and was set to scan at a rate of once a minute, logging time-averaged data every ten minutes. Depth is measured by means of a hydrostatic pressure sensor that is vented via a cable to the atmosphere, while velocity is determined by means of an incoherent, or continuous, ultrasonic Doppler. During a scan, a continuous ultrasonic signal is transmitted at a fixed frequency in an upstream direction. The centreline of the beam is aligned at an angle of 30° from horizontal and the beam has a width, or spread, of 10°. The transmitted signal is reflected by particles and air bubbles carried in the flow, and the frequency of the signal is changed as a result of the Doppler shift. A measuring circuit detects changes in frequency in the reflected signal arriving at a receiver and a processing system accumulates and analyses frequency changes to calculate a representative Doppler shift from the range received. Since the Starflow is an incoherent Doppler, velocity is depth-integrated and it is not possible to obtain a velocity profile; instruments with this capability are not widely available. The operating ranges of the instrument are, for depth, 0m to 2.0m at a 2mm resolution; and velocity, 21mm s^{-1} to 4500mm s^{-1}, at a resolution of 1mm s^{-1}, with an accuracy of 2% of the measured velocity.

Determining scallop velocity

Scallops form at a stable scallop Reynolds number (Re*) of ~2200 (Curl, 1974; Blumbeg and Curl, 1974), where Re* is related to the mean boundary shear velocity $\bar{u}*$ (obtained by dividing boundary shear stress by fluid density), Sauter mean scallop wavelength ($\bar{\lambda}$)fluid density (ρ_f) and fluid dynamic viscosity (μ) by:

1. $$\mathrm{Re}* = \frac{\bar{u}*\bar{\lambda}\rho_f}{\mu}$$

Where:

D = passage width

$\bar{u}*$ = friction velocity

$\bar{\lambda}$ = Sauter mean scallop length

B_L = Prandtl's bed roughness constant

A theory of scallop formation was proposed by Curl (1966). The layer of fluid next to the boundary is slow moving and saturated with respect to $CaCO_3$. However, dissolution can start to occur once a critical scallop Reynolds number has been reached – assuming the bulk fluid is not saturated. At this scallop Reynolds number, flow separation starts to occur at the site of small surface irregularities, forming a jet of fluid that undergoes a transition to turbulent flow, becoming unstable after a certain distance, at which point reattachment occurs. This allows aggressive bulk fluid to reach the boundary at the point of reattachment, where erosion proceeds at the greatest rate. The frequency of detachment increases with increasing velocity, thus reducing the erosion length available to each individual scallop. The characteristic scaling of scallops is a hydrodynamic mechanism, and fluid dynamic equations can be used to describe their formation and the flow conditions under which they were formed (Curl, 1966 and 1974).

Velocity conditions near the wall depend on the conduit size for a given mean conduit velocity and may be described by a 'law of the wall' type turbulent analysis, where the velocity distribution within the boundary layer (the thickness of flow affected by boundary drag) is assumed to be semi-logarithmic. Curl (1974) used a modified version of Prandtl's universal velocity distribution law, from which the mean velocity ($\bar{u}$) in a channel may be computed by substituting values in the equation for parallel-walled conduits:

2. $$\bar{u} = \bar{u}*\left[2.5(\ln\frac{D}{2\bar{\lambda}} - 1) + B_L\right]$$

Scallop dimensions were measured on both sides of the passage below the depth of the maximum flow and within an area on each wall that was delimited upstream from, and within range of the beam of the Starflow. This was determined by calculating the distance from the Starflow at which the beam, inclined at an angle of 30° from horizontal, would intersect the water surface at different depths of flow; this varies from 0.12m for a depth of 0.1m to 0.84m for a depth of 0.7m. Although the Starflow was installed during low flow conditions (approximately 0.1m depth), the water depth was greater

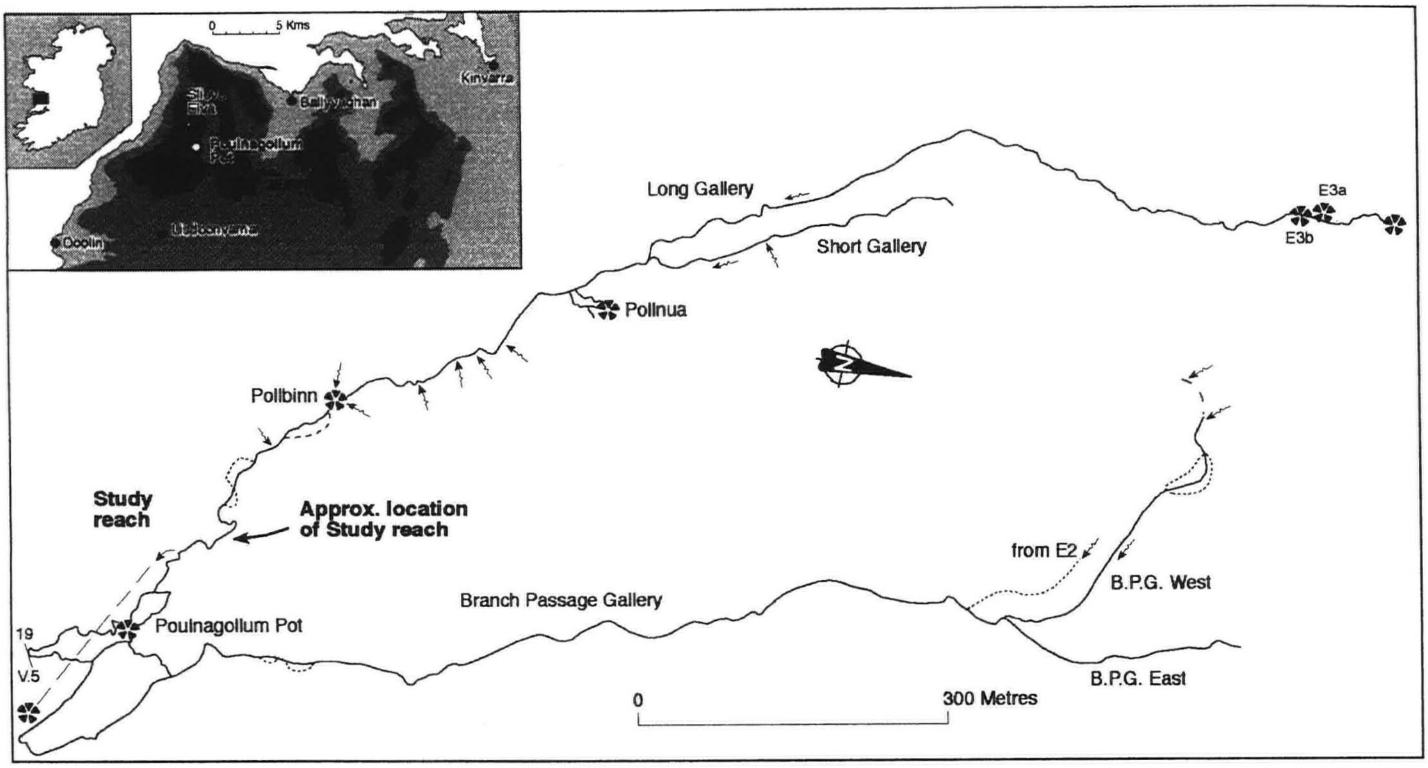

Figure 2. Map and survey showing the location of the study site.

than 0.2m on subsequent visits so it was not possible to measure the dimensions of scallops below this level. The width of the passage was measured at vertical intervals of 0.1m for a cross-section located at the Starflow and within the range of flow depths recorded. From these measurements an average width of 0.67m was calculated. These width measurements also enabled an estimate to be made of the discharge from recorded velocity and depth data, although width measurements alone do not provide sufficient information about the cross-section to calculate accurate discharge values. For this reason depth hydrographs are referred to in the following section. The friction velocity was calculated from Equation 1 using a value of 0.013cm^2 s^{-1} for μ/ρ_f (kinematic viscosity), which assumes a temperature of 10°C (the range of water temperatures recorded by the Starflow was between 5.8°C and 12.1°C). The mean conduit velocity was then calculated using a value of 9.4 for B_L (Blumberg and Curl, 1974).

RESULTS AND DISCUSSION

Flow data have been analysed for the eight-month period between September 2002 and May 2003. The peak flow recorded, approximately 1.2m^3 s^{-1}, occurred on 5/12/02, with a maximum depth of 0.76m and a maximum velocity of 2.27m s^{-1}. The minimum depth was 0.02m, but it is not possible to define a minimum discharge because a value of zero is recorded when the mean velocity falls below 0.022mm s^{-1}; problems also arise when the flow depth falls below the level of the acoustic transmitter and receiver. It should be noted that measurement of velocity at very low flows is difficult using most instruments. Fig.3 shows depth and velocity hydrographs for a one-month period from 18/12/02 to 18/1/02, selected as being representative of the high and low flow conditions recorded over the monitoring period. Each of the data points on

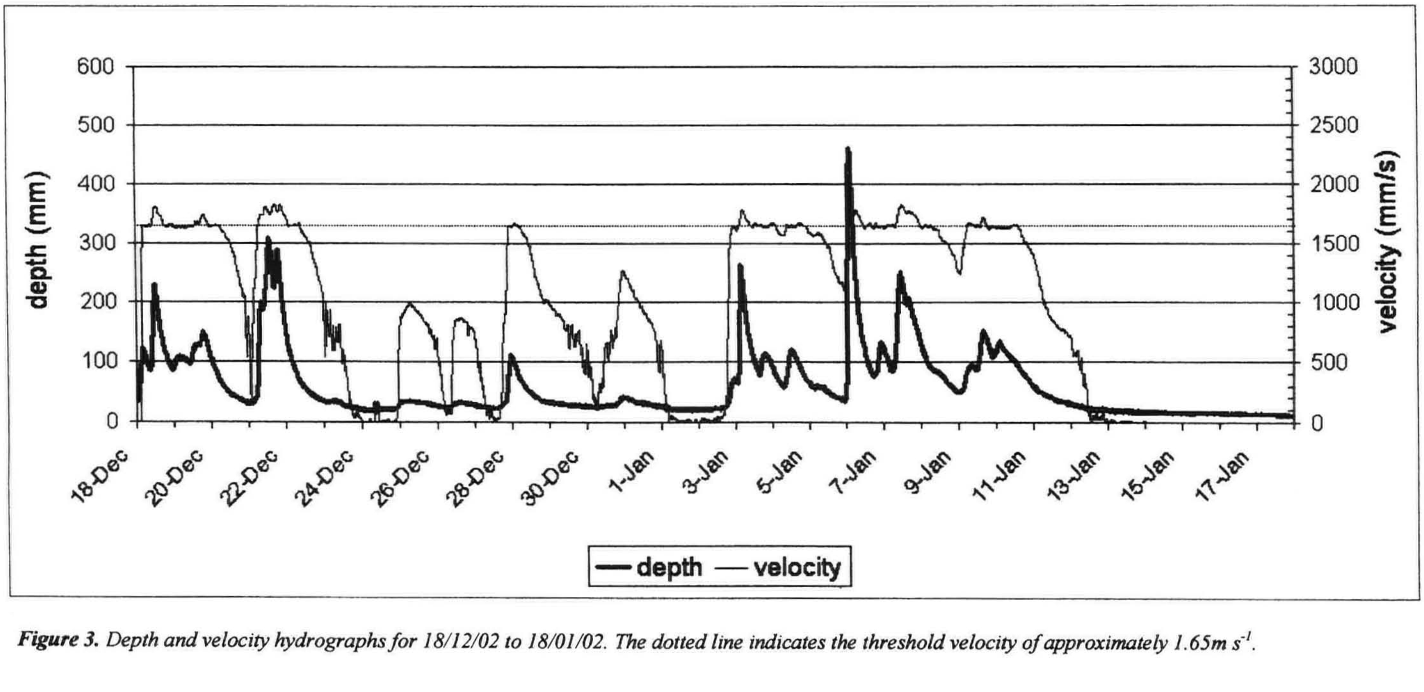

Figure 3. Depth and velocity hydrographs for 18/12/02 to 18/01/02. The dotted line indicates the threshold velocity of approximately 1.65m s^{-1}.

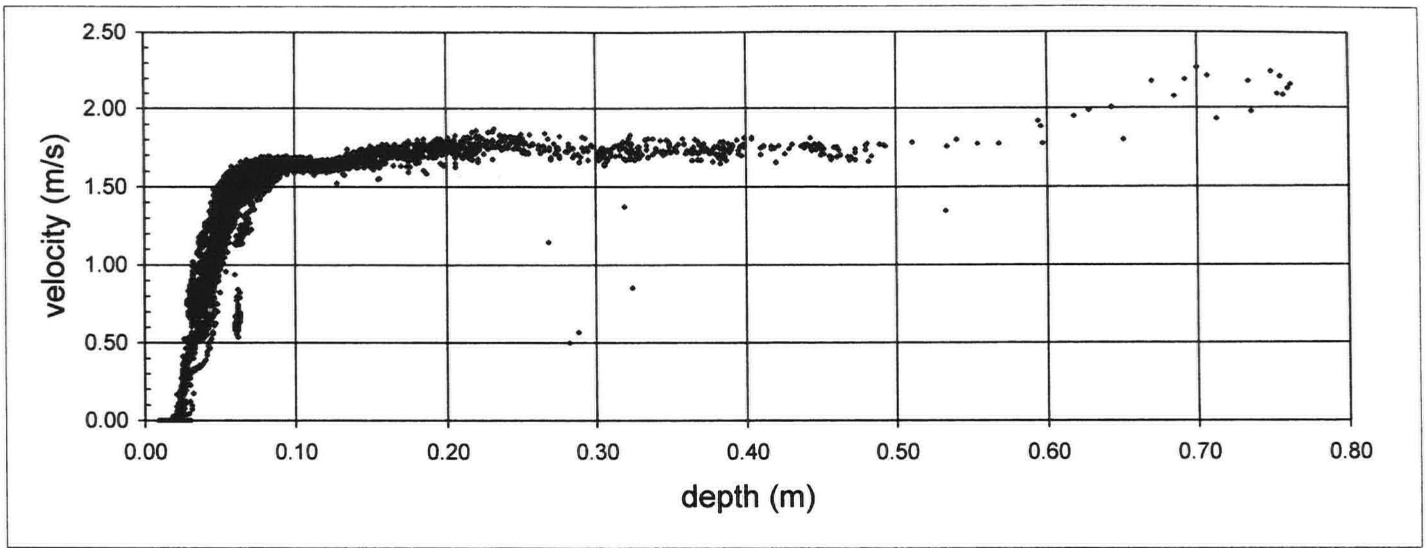

Figure 4. *Graph of velocity against depth. The data include the rising and falling limbs of selected storm hydrographs.*

these graphs is the logged 10-minute time-averaged value derived from scans made at one-minute intervals. Although rainfall data are not currently available, the depth hydrographs indicate a catchment with a rapid or 'flashy' response to rainfall. This might be expected, as the catchment is small (less than 1km^2), underlain by shale, and covered by blanket peat in which drainage channels have been cut for forestry.

An interesting characteristic of the velocity hydrographs is a 'plateau' that occurs once the velocity reaches a value of approximately 1.65m s^{-1}; this is in contrast to the rapid increase in velocity with discharge (depth) up to this point. This 'plateau' is indicated by a dashed line in Fig.3, and the effect can be seen for several of the events shown, where it appears that some threshold must be reached for further increases in velocity to occur. The multi-peaked events from 03/01/03 to 13/01/03 are a good example, with the velocity exceeding the velocity threshold where there are corresponding peaks in the depth hydrograph, although the duration of these peaks is relatively short. On the rising limb of hydrographs, the velocity appears to stop increasing once the depth exceeds a value of approximately 0.1m, and further increases in velocity do not occur until the depth is greater than about 0.15m. Examination of all hydrographs for the monitoring period indicates that further thresholds exist, although these are not so distinct and are difficult to define because of the relatively short duration of the higher velocities. The relationship between depth and velocity can be seen more clearly in Fig.4, which shows the relationship between depth and velocity for a number of selected events. The data include values from the rising and falling limbs of each hydrograph, and over 6000 data points are shown (many are superimposed on the graph). Here the thresholds in velocity can be seen, despite the fact that there is a hysteresis effect (this can be seen from Fig.3) where, for the same depth, the velocity is greater on the falling limb than it is on the rising limb of the hydrograph. In Fig.4 the isolated points at the upper end of the distribution correspond to the event of 5/12/02, for which an anticlockwise hysteresis occurred, with lower velocities on the rising limb. It is suggested that the velocity thresholds observed may be due to variations in total boundary resistance. Although the roughness of the actual boundary itself, defined by B_L in equation 2, can be assumed to be constant, the amount of contact between the body of flowing water and the boundary – the hydraulic radius – changes with discharge. The hydraulic radius is calculated by dividing the cross-sectional area of the flow by the wetted perimeter (the combined length of bed and banks in contact with the flow), with higher values indicating a greater hydraulic efficiency. If the depth of the stream shown in Fig.1 were doubled, the cross-sectional area would more than double. However, the wetted perimeter would increase by a lesser amount, leading to an increased hydraulic radius. The enhanced hydraulic efficiency reduces the proportion of total energy expended in overcoming boundary friction, enabling water to be transmitted more rapidly. At very low flows, flow resistance would be considerable, and it is suggested that for flows of less than 0.1m depth any variation in depth results in a substantial change in flow resistance, accounting for the large variations in velocity with depth in this range. For flow depths greater than 0.15m, it is likely that changes in flow resistance for a given change in discharge are not so great, although variations in channel width with depth would affect the cross-section and may affect the different rate at which velocity changes with depth seen in Fig.4. From the approximate cross-section shown in Fig.5 it can be seen that as flow depth increases from 0.2m to 0.5m there is a gradual widening of the passage, with an increase of more than 50% between 0.6m and 0.8m. Flows with depths in this range have only been recorded for one event so far: that of 05/12/02. At these flows, a given increase in depth represents a proportionately greater increase in discharge than at lower flows. Additionally, the cross-sectional area increases at a much greater rate than the wetted perimeter, increasing the hydraulic radius, and may account for the high velocities recorded for this event.

A scallop mean velocity of 1.43m s^{-1} was derived for the conduit and was compared with the distribution of recorded velocities. Each ten-minute velocity record was assigned to a class with a range of 0.09m s^{-1}. The 1.40 to 1.49m s^{-1} class had a relative frequency of 2.1%, and flows within this range were equalled or exceeded 10.0% of the time. The most frequently recorded flow velocities were those less than 0.1m s^{-1}, which were logged for 43.6% of the time. All other classes had a frequency of less than 4.0%, with the exception of flows with velocities between 1.60 and 1.69m s^{-1}, for which the frequency was 11.6%; the main velocity threshold observed (between depths of 0.1m and 0.15m) falls into this class. In comparing the scallop mean velocity with recorded flows several factors must be taken into consideration, such as the possibility that the scallops were formed under hydraulic and hydrological conditions that are outside the range of the recorded data. A critical control on rates of dissolution is the concentration of $CaCO_3$ and the way in which this varies with discharge. Limited water chemistry data exist for upper Poulnagollum although the $CaCO_3$ content of flow from individual swallets in the Poulnagollum system has been observed to decrease with increasing discharge (Ingle Smith *et al.*, 1969). The same authors found that in the central part of this system, the $CaCO_3$ content of streams with no direct surface feeders can be much higher, with aggressive flows only occurring during flood conditions. The mixing of water from these two different types of source leads to a complex pattern of variation between sites. In order to examine variations in $CaCO_3$ at the research site, a conductivity logger has recently been installed to provide data at ten-minute intervals, and will allow the range of scallop forming conditions to

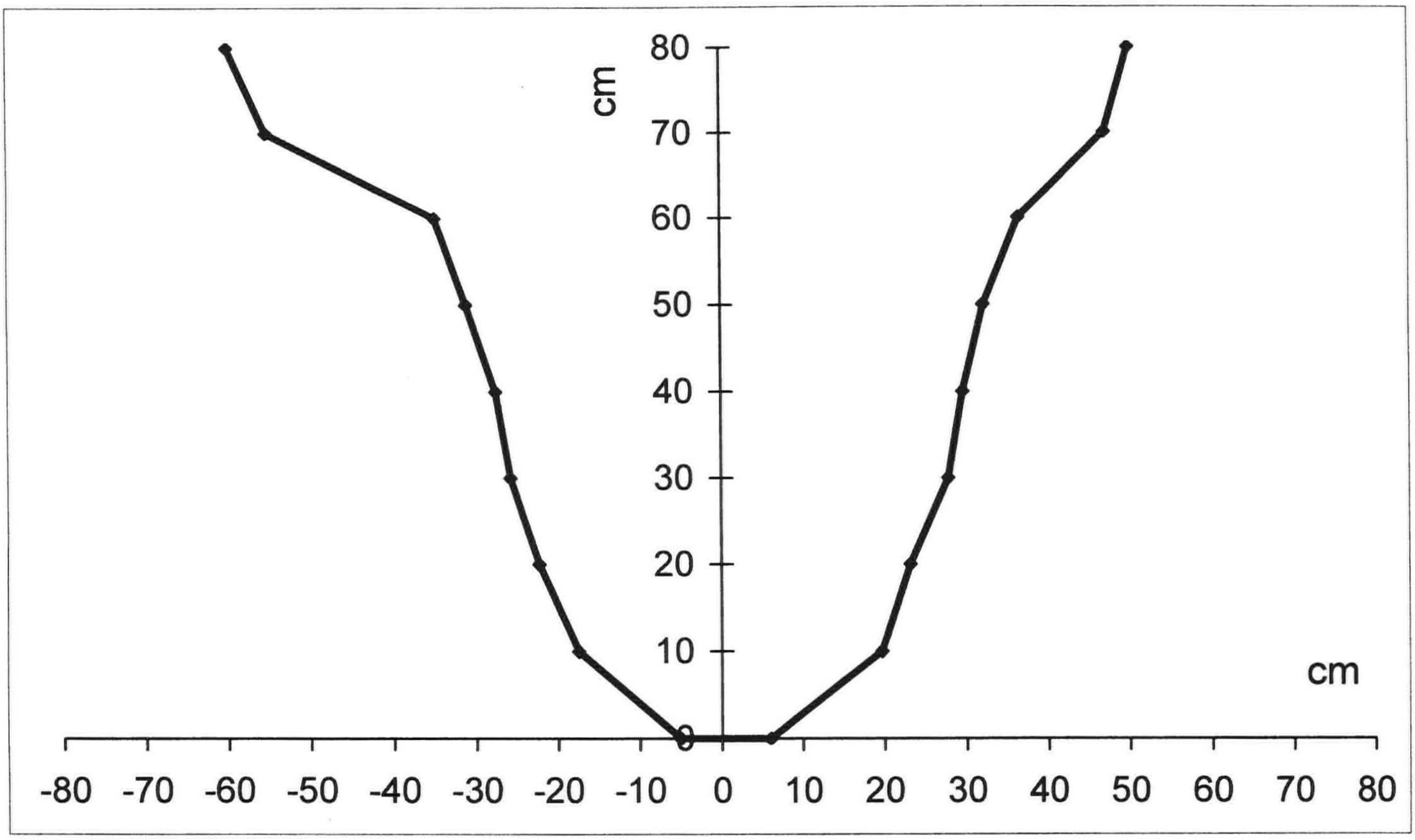

Figure 5. *Approximate cross-section derived from measurements of passage width made at the installation site.*

be refined. Further measurements of scallop dimensions are necessary as the original sample size was relatively small (100 scallops), although care will be taken to ensure that individual scallops are not included twice in the sample. At the same time, the size distribution corresponding to different depths of flow should be examined as it is not known if the scallops found at a given height are fossil features or are formed by contemporary high flows. Visual observations made at the site suggest that the scallop size does not change with increasing height above the floor of the passage, but this has not been confirmed quantitatively.

CONCLUSIONS

Determining a dominant discharge for vadose conduits is problematical because of the unconstrained cross-section, which makes it difficult to identify the depth(s) of flow at which the scallop dominant velocity occurs. The preliminary results of the monitoring programme described here indicate that the relationship between velocity and depth with changing discharge is complex, and appears to be controlled by the shape of the passage cross-section and the resultant variations in flow resistance with depth. The depth-velocity relationship is characterised by thresholds, with a similar velocity occurring over a range of depths. This could mean that it is not possible to define a single dominant discharge on the basis of scallop measurements, rather a range of discharges. The calculated scallop velocity was found to lie towards the upper end of the flows monitored, being equalled or exceeded approximately 10% of the time and corresponding to a flow depth of less than 0.1m. Although this flow velocity was exceeded by many of the hydrograph peaks recorded, its value was less than that of the main threshold observed in the depth-velocity relationship. However, it is not really possible to determine the flow conditions leading to the development of scalloping in the absence of $CaCO_3$ concentration data. A conductivity logger has recently been installed at the site to address this.

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