A study into the stream flow processes and the affecting factors in the Grainsgill Beck catchment

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This thesis is submitted in part fulfilment
of the requirements for the B.Sc. degree in Environmental Science
at the
University of Lancaster.

January 2003

Abstract

Over the past 300 years, mining in the Grainsgill Beck catchment in the Lake District National Park, has lead to the hydrology and hydrogeology of the area being altered. The extensive underground workings act as drains trapping and channelling subsurface water until it surfaces to form a stream; one such stream is known as the Mine Adit. The Mine Adit flows a short distance overland before it drains into Grainsgill Beck. In order to asses the impact of these mines and shafts on the hydrology of the area it was decided that the event characteristics of two streams would be monitored; the first stream being the Mine Adit, which reflects the altered subsurface response, and the second stream being Grainsgill Beck, which shows the response of the catchment as a whole. It was decided that the most efficient way too monitor the event characteristics would be to develop a stage discharge relationships for each stream; this would then enable a quick and accurate discharge reading to be made. Before these stage discharge relationships could be developed a small weir had to be built in the Mine Adit, the role of this weir was to generate the necessary conditions required to generate this relationship between stage and discharge. The appropriate conditions for the stage discharge relationship in Grainsgill Beck were generated by a bridge over the river which confined the flow. Discharges and rainfall were recorded in these two streams during the period 11/10/2002 till 02/11/2002. The results indicated that instead of the Mine Adit having a slow response to rainfall it actually had a very rapid, almost instantaneous, response. It is believed that this flashy behaviour is a result of “old” subsurface water being displaced into the underground stream by the arrival of “new” rainfall water at the surface. Rainfall-runoff modelling with the TFM package showed that the response of the Mine Adit and rainfall into the catchment are very closely related; it was also shown that it is possible to model and predict the response of the Mine Adit using the TFM package. Discharges from Grainsgill Beck seem to suggest that the catchment response to rainfall is less rapid than the response of the Mine Adit; however there was insufficient data collected to either prove or disprove this.

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1.0 Introduction

The Grainsgill Beck catchment is an area, which for several centuries has been of economic importance due to the minerals and ores found within the local bedrock. Mining and removal of these ores dates back to the 1720's and continued right up until the mid 1980's. Prior to the 1850's, lead, copper and arsenic were the major minerals removed from the mines; however in 1854 the tungsten ore wolframite was discovered at the site. The uses of this metal were not realised for some time, but by the First World War tungsten was of national importance due to its use in the weapons industry. Mining only occurred during periods when it was an economically viable option and so at the end of the Vietnamese War the tungsten mine finally closed (Shackleton, 1975). During these periods of mineral extraction it is likely that the hydrogeology of the area will have been affected; to measure the impacts of the mining on the hydrology of the area, and to predict future impacts, it is necessary to set up some long term monitoring so that the response of individual streams with respect to rainfall may be continuously studied. To do this, stage discharge relationships will be utilised as they are an accurate and efficient tool for determining discharges.

1.1 Location

Carrock Fell is a remote area of moorland close to Mount Skiddaw in the north of the Lake District National Park. Draining the slopes of Carrock Fell is Grainsgill Beck, which is the largest stream in the Grainsgill Beck catchment. Figure 1.1 shows the location of the Grainsgill Beck catchment. The Grainsgill Beck catchment has an area of 3.36km^2; water leaving the catchment flows into the River Caldew and eventually joins the sea at the Solway Firth, near Carlisle.

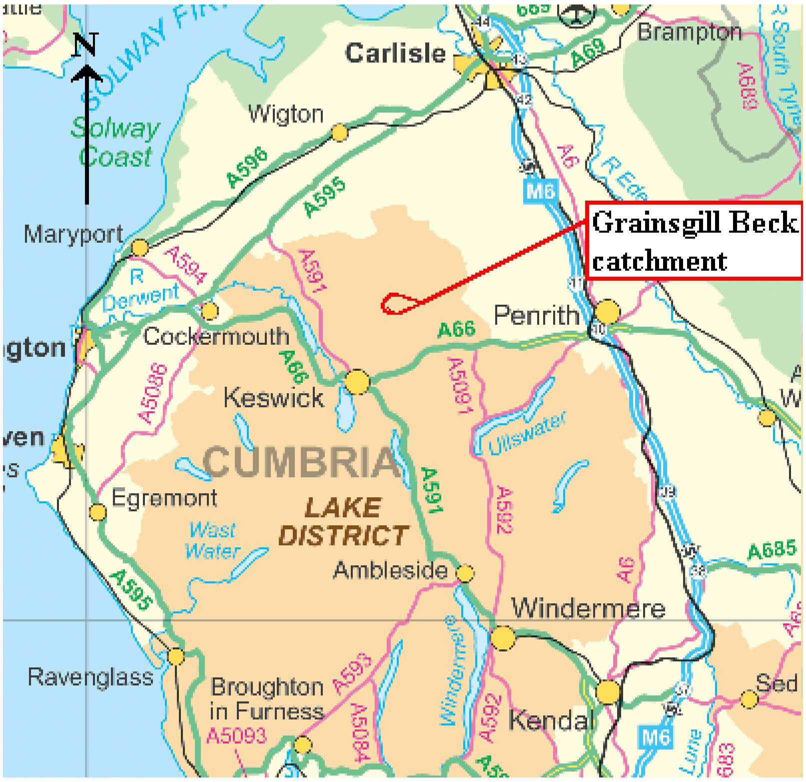


Figure 1.1, a map showing the location of the Grainsgill Beck catchment.

As Grainsgill Beck flows towards its confluence with the River Caldew it is joined by several smaller streams. These tributaries flow from and along the old abandoned mine workings. Figure 1.2 is a map of the catchment showing the course of Grainsgill Beck and some of the tributaries. Close to the centre of these mining relicts, the small Mine Adit flows into Grainsgill Beck (NGR NY322329), discharges from the Mine Adit will be measured during this project. Discharges will also be measured in Grainsgill Beck close to the confluence with the River Caldew (NGR NY327327. Both these sites can be seen on figure 1.3.

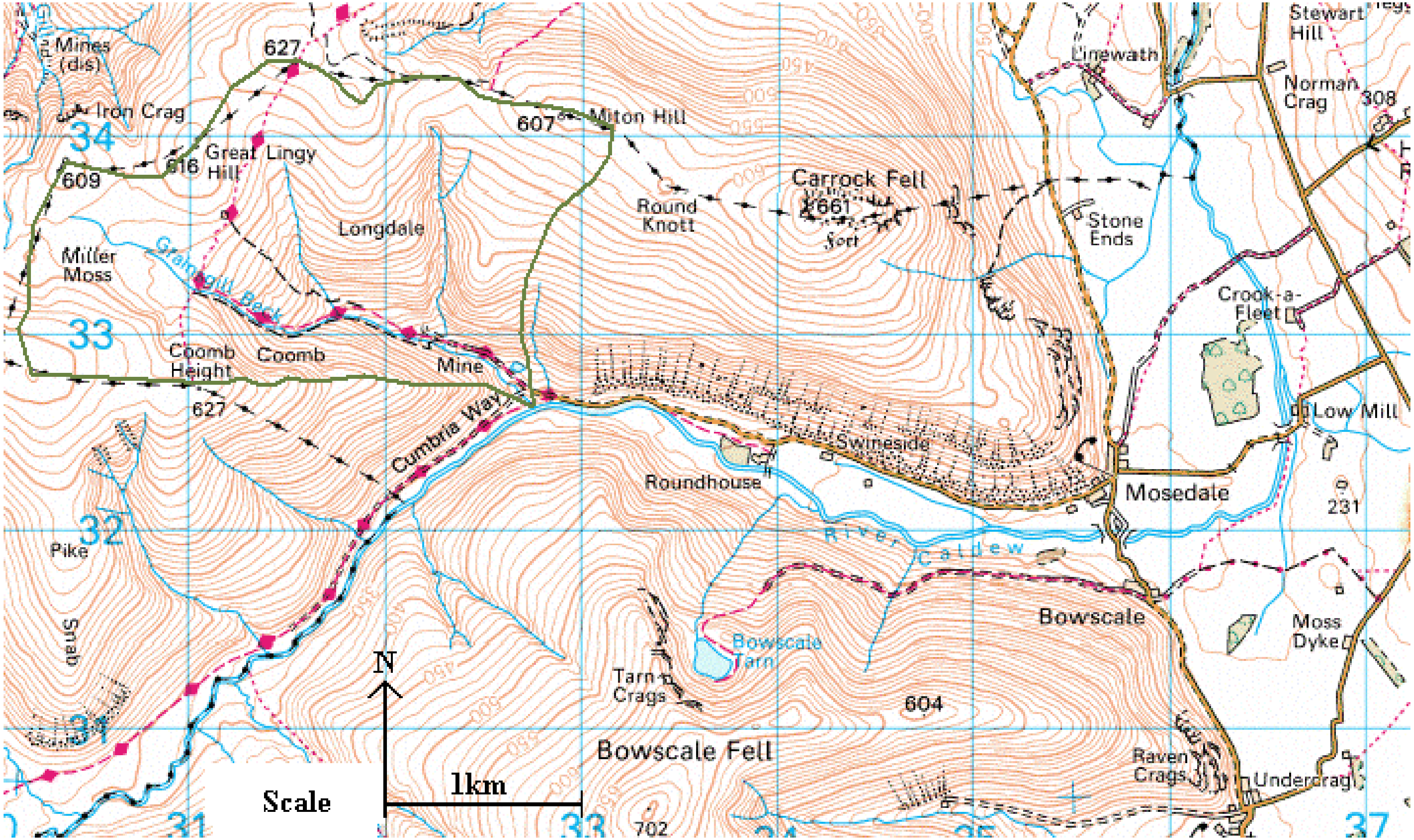


Figure 1.2, a map of Grainsgill Beck catchment and Carrock Fell, the catchment boundary is defined by the dark line. "Reproduced form Ordinance Survey maps by permission of Ordinance Survey on behalf of The Controller of Her Majesty's Stationary Office, © Crown Copyright."

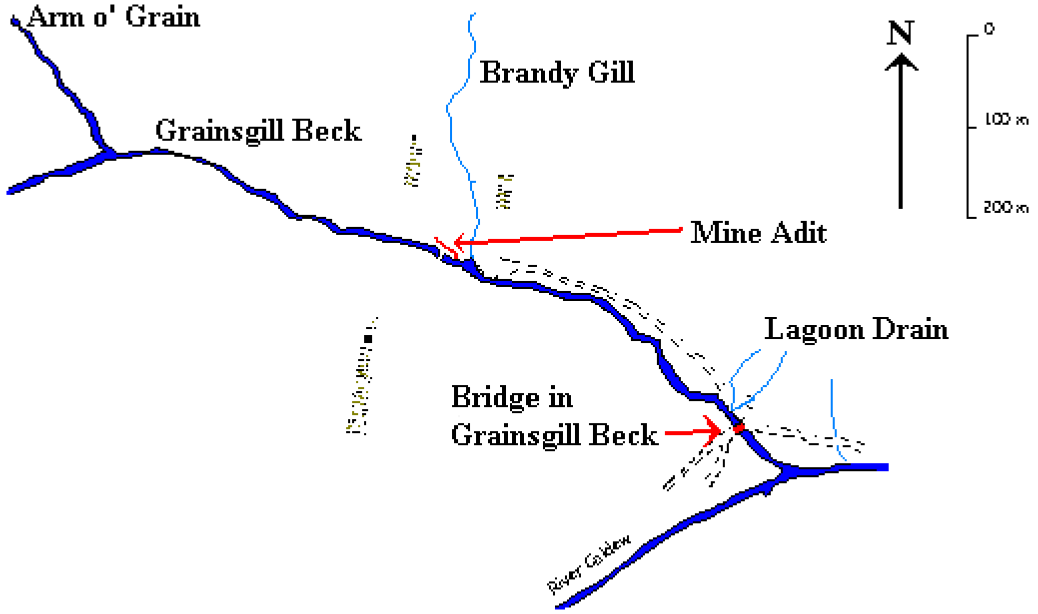


Figure 1.3, a map showing the location of the Mine Adit and the Bridge in Grainsgill Beck

1.1.1 Site 1 - The Mine Adit

The first site, which is the focus of this project, is the small Mine Adit that flows into Grainsgill Beck. The Mine Adit, which only exists as a result of the mining activity in the area, flows underground through the old mine workings until it surfaces; it then flows a short distance overland (figure 1.4) until it falls steeply towards it's confluence with Grainsgill Beck (figure 1.5).

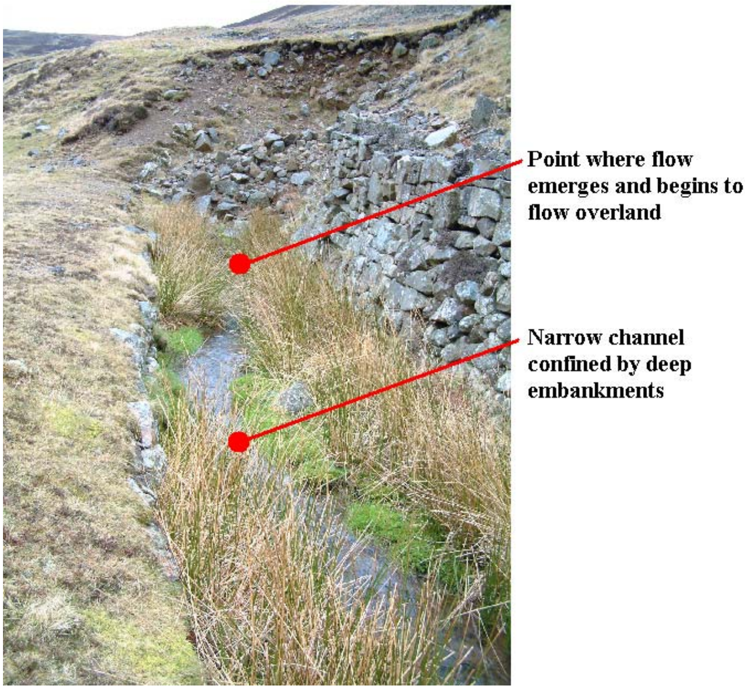


Figure 1.4, a photo showing the point where the Mine Adit surfaces.

Figure 1.5, a photo showing the steeper section of the Mine Adit and the confluence with Grainsgill Beck at the foot of the image.

Discharges in the Mine Adit were measured using a small weir positioned close to the confluence with Grainsgill Beck. A weir was used so that a long term stage discharge relationship could be created; using this stage discharge relationship it was possible to collect a continuous set of discharge data from the Mine Adit.

1.1.2 Site 2 - The bridge in Grainsgill Beck

The second site is the bridge in Grainsgill Beck, which essential marks the final out flow of the catchment i.e. there are no further lateral inputs, with the exception of bank seepage. This site is therefore perfectly located to monitor the catchment response to fluctuations in precipitation levels. The bridge in Grainsgill Beck also proves to be a convenient place for discharge measurement. As the water flows under the bridge, its width is restricted by the vertically engineered sides of the channel, therefore another stage discharge relationship can be used to obtain discharge values.

1.2 Catchment overview

The Grainsgill Beck catchment forms part of an old glacial channel which originated on the slopes of Mount Skiddaw. When the ice retreated the landscape was subjected to fluvial processes that to this day continue to affect the shape of the scenery. Water channels cut down into the hillsides gouging out the rivers and streams that are the focus of this study. As the water leaves the catchment it flows into the River Caldew, which meanders across a small flood plane, approximately 300m wide.

Grainsgill Beck falls steeply towards its confluence with the River Caldew; it descends nearly 400m, with an average gradient of 114 m/km, as it flows from its high point of 660m above sea level until it merges with the River Caldew. Several smaller lateral inputs flow into Grainsgill Beck along its course; these can all be seen on figures 1.2 and 1.3 above. The first input into Grainsgill Beck is the Arm O Grain, which drains the slopes of Great Lingy Hill (616m). The second major tributary is the Mine Adit (site 1), which only flows a short distance overland, most of its journey is along the mine shafts and levels contained within the hillsides. Approximately 15m downstream from the Mine Adit is Brandy Gill (figure 1.6), which originates high up on the slopes of Milton Hill (607m) and Drygill Head (620m). The final input is only 10m upstream of site 2, the bridge in Grainsgill Beck, and is known as the Lagoon Drain. This small stream drains from a spoil heap on the slopes of Carrock Fell.

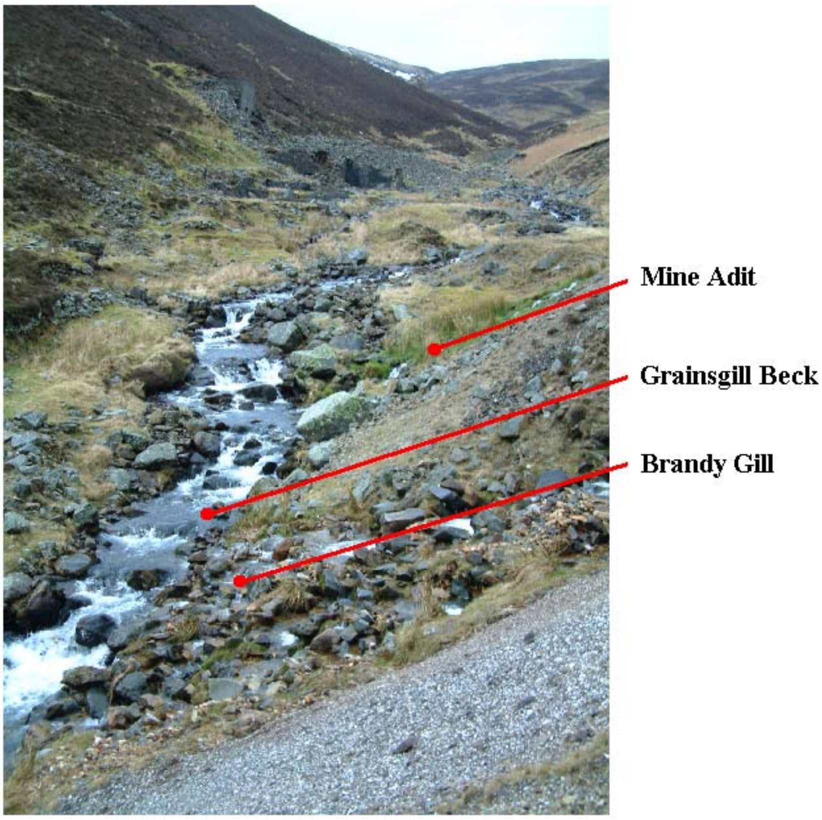


Figure 1.6, a photograph showing the short distance between the confluences between the Mine Adit and Grainsgill Beck, and also Brandy Gill and Grainsgill Beck.

The quantities of water discharged from each of these lateral inputs may vary greatly from stream to stream and day to day. Lancaster University (1998-2000 & 2002) has been measuring discharge in several of these small streams over the last five years. From these measurements it is possible to calculate the mean discharge from each stream, this information is displayed in table 1.1.

	All discharges are in litres per second			
	Lagoon Drain	**Grainsgill Beck**	**Brandy Gill**	**Mine Adit**
Mean Discharge	1.0	104.0	21	9.0
Max Discharge	5.4	291.5	48.8	14.0
Min Discharge	0.1	34.4	4.4	5.1

Table 1.1 shows the mean discharges from four streams in the Grainsgill Beck catchment, the maximum and minimum flows are also shown (Env 200, 1998-2000 & 2002).

Being located in the North West of England within the Lake District National Park, it is likely that the Grainsgill Beck catchment receives a large amount of precipitation. Environment Agency data, collected for the River Caldew at Holm Hill (NGR NY 378469), shows that the mean precipitation level for the Caldew catchment, between 1968 and 1997, is 1414mm (Environment Agency, 2001). As the Grainsgill Beck catchment is nestled in the headwaters of the Caldew catchment it is likely that the mean precipitation is higher.

1.3 Aims:

The purpose of this project is to investigate the effects that the mine workings have had on the hydrology and stream flow processes of the catchment. This will be achieved by following these aims:

- To install a small weir at site 1, in the Mine Adit, so that it yields accurate and precise discharge measurements. Once the weir is installed a long term stage discharge relationship may be established.
- To establish a long term stage discharge relationships at site 2 in Grainsgill Beck at the bridge.
- Using the above two stage discharge relationships, collect a continuous record of flows for each site in order to compare the event characteristics of the two streams.
- Evaluate the discharges at each site with respect to precipitation. This will be achieved by collecting a continuous record of rainfall
- Given the information collected, evaluate the types of processes that may be responsible for the different data produced.

By fulfilling the five aims laid out above, it will be possible to measure fluxes in discharges from both sites. The discharge data for both streams may then be compared to see what effect precipitation has on the stream hydrographs. The characteristics of any changes in discharge as a result of precipitation may then be evaluated and explained as a result of the movement of water through the subsurface, and in particular the old mine workings.

2.0 Basic fluid dynamic principles

It has been stated that this project will utilise long term stage discharge relationships to evaluate the stream flow processes in the Grainsgill Beck catchment. The project relies upon the assumption that stage discharge relationships are a useful and reliable tool for providing accurate values of discharge; a second assumption is that the weir in the Mine Adit and the bridge in Grainsgill Beck will actually generate the control conditions under which stage discharge relationships are valid. It is therefore important to give an explanation of the theory behind stage discharge relationships and an account of the conditions required for there practical implementation. Before stage discharge relationships can be explained there are some basic energy principles that must be discussed.

2.1 Hydrostatic case

Firstly the case of a fluid at rest may be considered, this is known as the hydrostatic case (figure 2.1) i.e. the pressure at any one point within the water column is matched by and equal sized pressure in the opposite direction. By looking at figure 2.1 it is possible to see that the total upward forces (pA) measured in Nm^{-2} are equal to the sum of the downward forces. There are two downward forces acting on the water; firstly the weight of the slice itself acting on the lower surface, which is defined as the density of the liquid (ρ) times the gravitational acceleration (g) times the volume of the slice (ΔzA). Secondly the pressure on the upper surface will be slightly different by a small amount (Δp), therefore the downward force acting on the upper surface is (p+ p)A (Hornberger *et al.*, 1998).

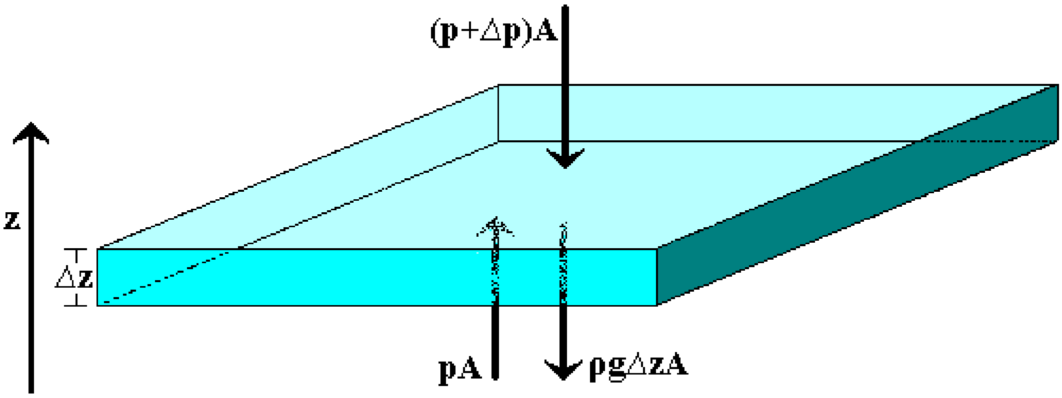


Figure 2.1, a diagram showing a thin slice of static water (Δz), as the water is at rest the upward and downward acting forces must balance (adapted from Hornberger *et al.*, 1998).

All the forces in the above diagram must balance, so:

$$pA = (p+\Delta p)A + \rho g \Delta z A \qquad \textbf{(1-1)}$$

Therefore the change in pressure (Δp) between the top slice and the bottom slice may be calculated as:

$$\Delta p = -\rho g \Delta z \qquad \textbf{(1-2)}$$

If the depth of water increases the pressure must increase as both the density and gravity are constant. As the thickness of the slice of water shrinks to an infinitesimal, this equation may then be rearranged to give the hydrostatic equation:

$$\frac{dp}{dz} = -\rho g \qquad \textbf{(1-3)}$$

The hydrostatic equation says that the rate of decrease of pressure with upward distance is the unit weight of the fluid (ρg) (Hornberger *et al.*, 1998).

Another term may now be defined, the hydrostatic pressure, consider a large body of water at rest with a free surface where density is constant e.g. a bucket (figure 2.2). Once again the pressure at any point in the bucket must balance; the total pressure acting on the bottom of the bucket must equal the pressure due to the water (p_{water}) column directly above it plus the pressure of air (p_{air}) directly above it (Chanson, 1999).

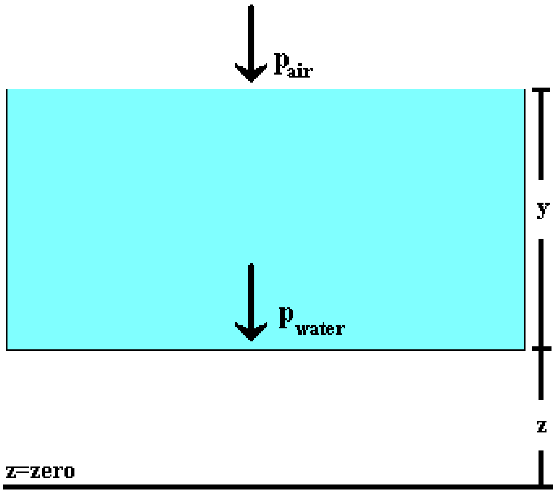


Figure 2.2, a diagram showing a large body of water at rest. The total pressure acting at the base of the bucket (Pz) is equal to the sum of the pressure of the water (p_{water}) and air (p_{air}) above it.

Therefore the pressure at elevation z (Pz) must equal:

$$Pz = p_{water} + p_{air} \qquad \textbf{(1-4)}$$

The pressure of water acting on the surface at elevation z is equal to the weight of the water divided by the sectional area (A) or:

$$p_{water} = \frac{Ay\rho g}{A} \qquad \textbf{(1-5)}$$

or,

$$P = y\rho g \qquad \textbf{(1-6)}$$

The above equation is known as the hydrostatic pressure (P) and is used to describe how pressure changes linearly with depth in a stationary water column.

By looking at figure 2.2 it is possible to see that the height of water above the arbitrary datum level (z) is simply given by:

$$\text{Head (m)} = y + z \qquad \textbf{(1-7)}$$

This head is a measure of the energy per unit weight of the water and is defined as the height to which the water can rise itself above an arbitrary datum level (Price, 1996)

2.2 Total energy head of flowing water

The pressures acting on a stationary water column have now been described; however the principles of the stage discharge relationship are still to be discussed. To do this the movement of water from a region of high potential pressure to a region of low potential pressure must be considered.

This may be illustrated by altering the bucket example from above. If the bucket were split in two and the water in the left hand side were raised (figure 2.3), water will begin to flow from left to right or from a point of high potential energy to a point of lower potential energy, as the water flows this potential energy is converted to kinetic energy.

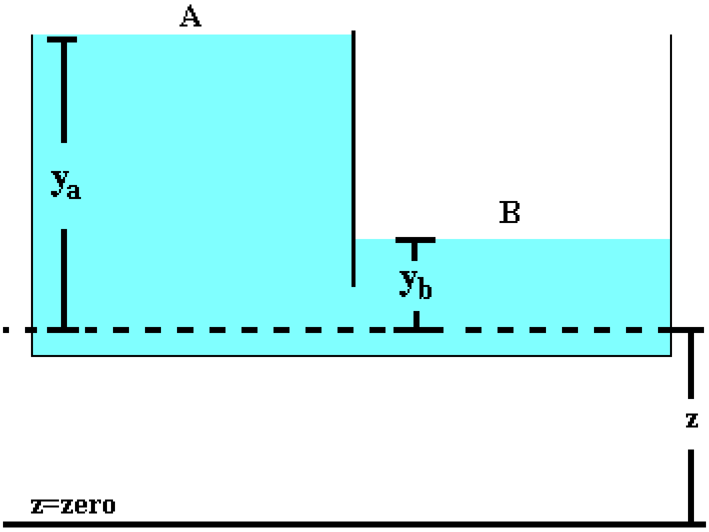


Figure 2.3, a diagram showing the bucket split in two, the higher potential energy at point A will cause the water to flow towards point B.

The head at point A is equal to the elevation above the arbitrary datum level plus the depth of water at point A, i.e.

$$H_A = Z_A + y_A \qquad \textbf{(1-8)}$$

The head at point B is equal to the elevation above the arbitrary datum level plus the depth of water at point B, i.e.

$$H_B = Z_B + y_B \qquad \textbf{(1-9)}$$

As Z_A and Z_B are equal and y_A is greater than y_B, H_A must be greater than H_B. This means that the water at point A has more energy per unit weight than the water at point B and so the water will flow from A to B. This is represented in figure 2.4, which shows the water flowing from the point of high potential energy to the point of low potential energy.

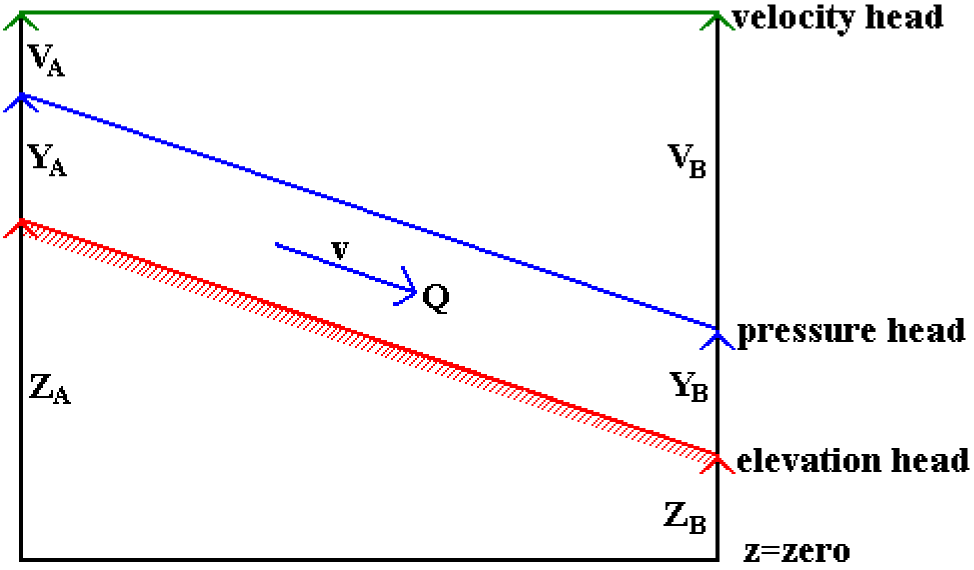


Figure 2.4, a diagram showing the three energy components of flowing water. Frictional losses are ignored in this diagram and so velocity head remains constant.

The three energy components of flowing water are known as the elevation head, the pressure head and the velocity or kinetic head. Elevation head has already been defined as the height above an arbitrary datum level to which the water will rise itself. The pressure head has been defined by equation (1-6). The velocity head is defined as:

$$\text{Velocity head (m)} = \frac{v^2}{2g} \qquad \textbf{(1-10)}$$

Therefore the total head of water flowing down a slope is given by the sum of the elevation head, pressure head and velocity head, and is described in the following equation:

$$\text{Total Head (H)} = \frac{v^2}{2g} + \frac{P}{\rho g} + z = \text{constant} \qquad \textbf{(1-11)}$$

Consider the case in figure 2.4 where water is flowing down slope from left to right, the total head must be conserved and so as the elevation head decreases and the pressure head remains constant the velocity head must increase for equation (1-11) to be true.

Equation (1-11) is also known as the Bernoulli equation, for this equation to apply there are several important assumptions, these are:

a. There are no frictional losses.
b. The fluid is homogeneous.
c. The fluid is incompressible.
d. The flow is steady with time.

The solution to the Bernoulli equation is only valid along a streamline (Hornberger *et al.*, 1998).

2.3 Specific energy and specific discharge

Now that the forces and energies of flowing water have been described, the specific energy and specific discharge may be defined. The specific energy can be thought of as the average energy per unit weight of water at a channel section as expressed with respect to the channel bottom (Bos, 1990). The equation describing the specific energy can be written as:

$$\text{Specific Energy (E)} = \frac{v^2}{2g} + y \qquad \textbf{(1-12)}$$

In the above equation it is important to remember that the average flow velocity ($\bar{u}$) is not a measurable quantity but is determined by the equation:

$$Q = \bar{u} A \qquad \textbf{(1-13)}$$

Where the sectional area of the channel (A) is rectangular the discharge is equal to the velocity times the depth of water (y) times the channel width (B) and may be derived from:

$$Q = \bar{u}yB \qquad \textbf{(1-14)}$$

If the channel width is assumed to be constant, equation (1-14) may be rearranged to give the specific discharge (q_w), which is defined as the discharge per unit width of channel and applies when the channel width is constant, it can be written as:

$$\text{Specific Discharge } (q_w) = \frac{Q}{B} = \bar{u}y \qquad \textbf{(1-15)}$$

The specific discharge may be substituted into equation (1-12) to give:

$$E = \frac{q_w^2}{2gy^2} + y \qquad \textbf{(1-16)}$$

This equation allows the calculation of the depth of a frictionless channel flow of known discharge and specific energy (Hornberger *et al.*, 1998). Equation (1-16) may be solved directly or graphically. The graphical solution allows a specific energy diagram to be drawn (figure 2.5), which shows the specific energy versus the depth of water for a given value of specific discharge.

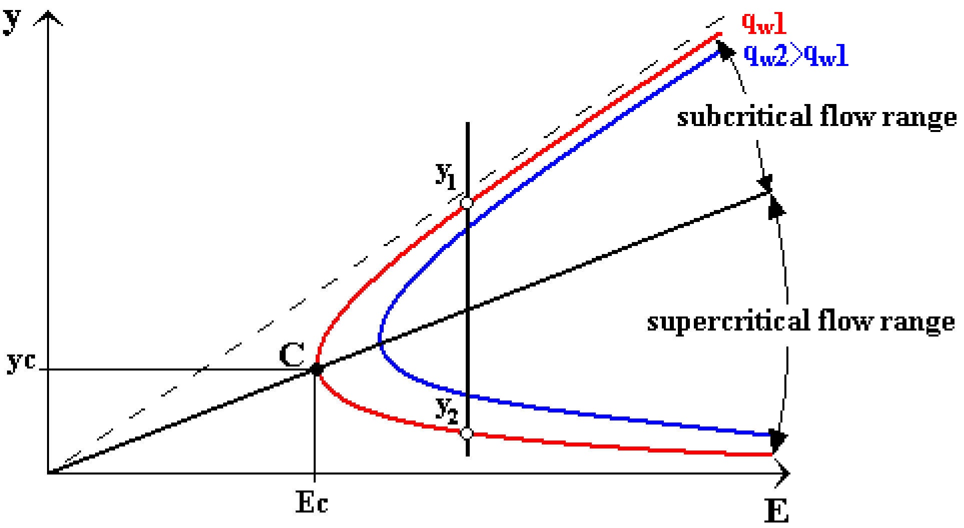


Figure 2.5, a specific energy diagram. The diagram shows that there are two alternative flow depths for each specific discharge (y_1 & y_2).

When the depth of water is greater than the critical depth the flow is said to be subcritical, this type of flow is characterised by slow deep tranquil water. When the depth is less than the critical depth the flow becomes supercritical, this type of flow is shallow and fast (Beven, 2002).

By looking at the above diagram it is possible to see that at the point C the two alternate flow depths merge and that the specific energy is at a minimum, this point is called the critical depth. This critical depth is vital for stage discharge relationships because at the point when the critical depth is reached there is a unique relationship between stage and discharge (Ackers *et al.*, 1978), the basic form of this relationship may be expressed as:

$$Q = C_D B H^{1.5}$$

Where:

Q is the discharge in cubic metres per second (m^3/s).

C_D is the coefficient of discharge which may be made up of several factors.

B is the cross section width in metres (m).

H is the hydraulic head in metres (m) (BS ISO 1100-2, 1998).

2.4 Critical flow and the control of stage discharge relationships

A stage discharge relationship occurs when flowing water is forced to switch flow from subcritical to supercritical, at some point between the switch the water will flow critically (figure 2.6). To be able to use a stage discharge relationship for the long term study of discharge in a channel it is important to know exactly where this switch is occurring. The best way for doing this is to engineer a channel so that complete control of the upstream conditions are obtain, the point of critical flow is then located in a known position that will not change in time.

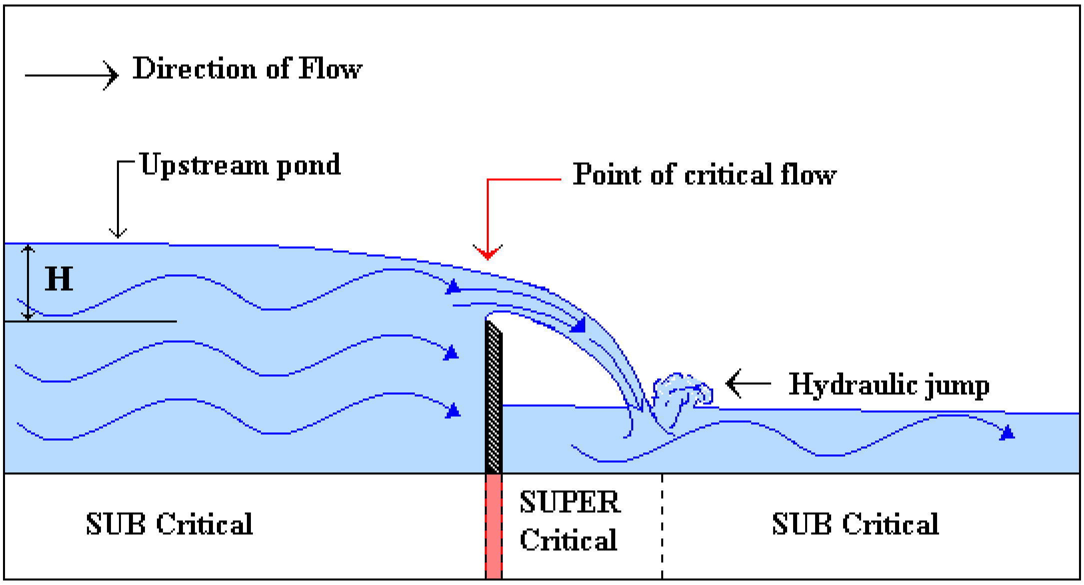


Figure 2.6 a diagram showing how the energy of the water varies as it flows over a weir.

This point of critical flow is only reached when the channel conditions change so that the specific energy of the water is at a minimum (Hornberger *et al.*, 1998). The law of the conservation of energy states that the energy of the water must be conserved; therefore there are two ways of lowering the specific energy:

1. Increasing the velocity head of the water by forcing it through a constriction causes a drop in specific energy.
2. Forcing the water to flow over a step increases the elevation head; the specific energy is therefore lowered, this is shown in the above diagram.

Stage discharge relationships are controlled by the physical channel conditions immediately downstream from the point where stage is to be measured. There are three types of these controls these are; section, channel and combination controls. Each type of control describes a slightly different approach to establishing a stage discharge relationship. The environment in which the work is to be carried out usually dictates the type of control adopted. In this project both stage discharge relationships will adopt section controls. A section control is defined as a natural or manmade feature such as a weir or flume, which produces a riffle or drop in water level (BS ISO 1100-2, 1998).

If the bed is raised or if a step is placed in the channel, as in the case of a weir, the water ponds up on the upstream side of the structure and becomes subcritical (White, 1988). To flow over the obstacle the velocity of the water must increase, in doing so the depth of water must decrease to maintain the total head. This reduces the specific energy to a minimum and creates critical flow. This is the technique that is used to provide the section control and to generate a stage discharge relationship at site 1 in the Mine Adit.

By measuring the stage through a range of discharges a rating curve may be developed; it is recommended that at least 12 measurements are made within the desired range of stage (BS ISO 1100-2, 1998). Future measurements of stage may then allow the discharge to be calculated.

3.0 Design and construction of the weir

Having decided to use a weir to create a stage discharge relationship in the Mine Adit it is important to design and build this structure so that it yields accurate, precise and reliable results. There are many variations on the design of a thin plate weir, which have all been created to deal with different channel conditions. It is therefore important to select the correct design for the channel conditions likely to be encountered in the Mine Adit. A review of the likely flow conditions was carried out in the catchment overview (section 1.2 table 1.1); using this information a variety of suitable thin plate weir designs were considered. Once the final design was decided upon the construction of the weir was planned and carried out.

3.1 A review of the different thin plate weir designs

There are many different designs of thin plate weir; to maximise the efficiency and accuracy of the weir it is important to use the shape of weir which best suits the channel conditions. Before the weir could be designed for the Mine Adit several weir shapes were investigated:

3.1.1 Rectangular notch thin plate weirs

The profile of this weir as suggested by its name is a rectangle. The rectangular thin plate weir may be divided into two sub types, the full width weir and the rectangular notch weir. The difference being the full width weir spans the width of the entire channel whereas the rectangular notch weir (figure 3.1) is constricted at the sides. This restriction allows the nappe to fully develop side contractions (BS 3680, 1981). Under low flows the water level may fall so low that the nappe does not develop at all and instead the water simply runs down the face of the weir.

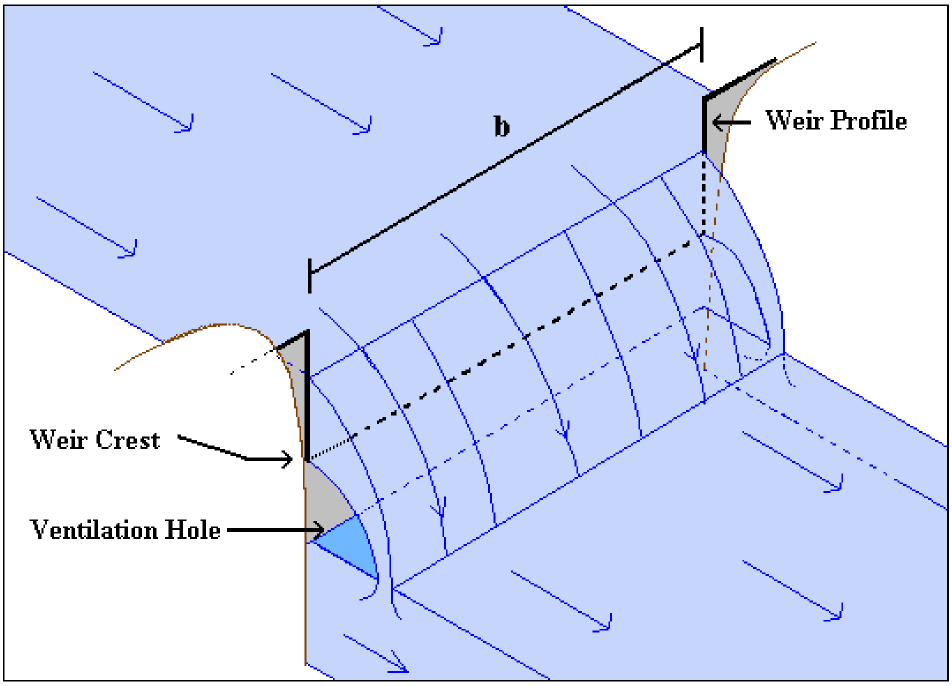


Figure 3.1, a diagram showing a rectangular thin plate weir, the actual weir is drawn in thick black with a crest given by b.

Although the weir is stable for a large range of operating conditions, measurements of low flows are less reliable (Webber, 1968). The most practical application for this weir is in a relatively wide stream where the head is large and the flow is steady and constant but where there is occasional submergence of the weir. If this design were to be implemented at the Mine Adit the width of the weir would have to be very small whilst the height of the weir would have to be very large. This would be necessary to increase the sensitivity of the structure to changes in discharge.

3.1.2 Triangular V-notch thin plate weirs

The V-notch weir (figure 3.2) can be made through a range of notch angles (θ) depending upon the sensitivity required. Due to the smaller sectional area through which the water must flow the weir becomes more sensitive to changes in stage height with smaller notch angles.

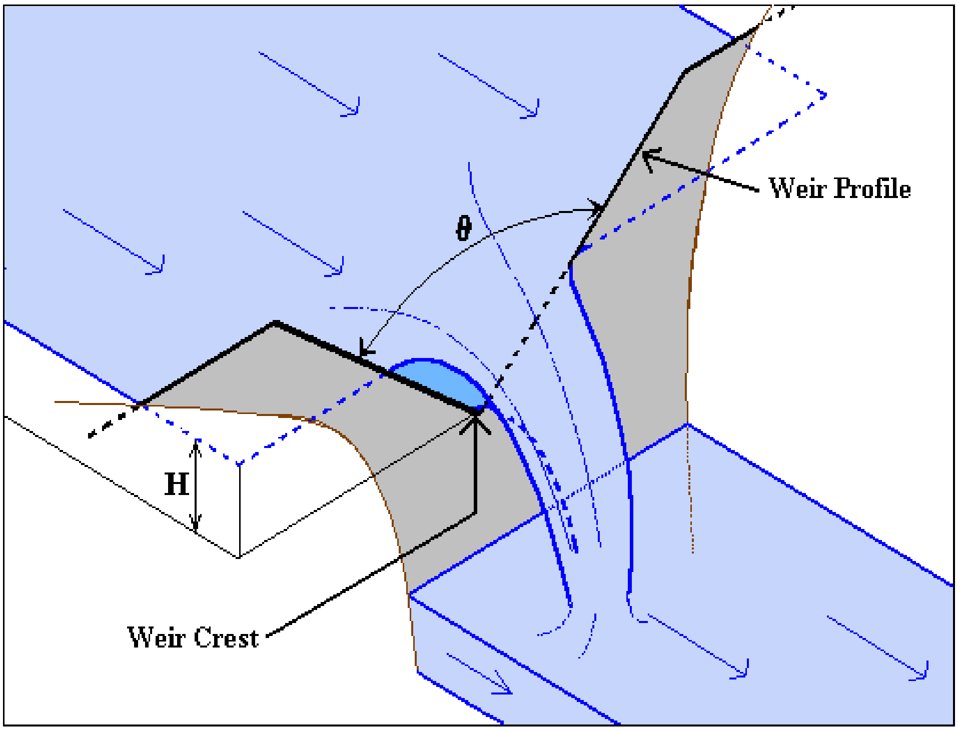


Figure 3.2, a diagram showing a triangular thin plate weir, the angle of the crest is given by θ.

In small streams, which are subject to rapid and large variations in stage, a V-notch weir is suitable for measuring discharge. This weir is sensitive to a wide range of flows and is particularly sensitive to small changes in stage, which may occur during the rising and descending limbs of a storm hydrograph (Kay, 1998). When installing and operating a V-notch weir it is important to ensure that the downstream water level does not reach the base of the notch as this leads to uneven discharges (Ackers, *et al.,* 1978).

The major drawback of this weir is that under extreme events it may become submerged and unlike the rectangular weir, which can still be used to obtain a rough measurement of discharge, the V-notch weir is inappropriate in such conditions.

3.1.3 Compound thin plate weirs

The compound thin plate weir utilises the best features of both the rectangular and V-notch thin plate weirs (figure 3.3). By inserting a V-notch weir into a rectangular notch weir, a huge range of flows, both approach conditions and submergence can be accurately measured (Novak, 1996); during low flows the water is forced to flow through the small section of the V-notch, this maintains accurate measurements of stage height (Bos, 1990). If submergence occurs during an extreme event, the discharge can still be estimated with the rectangular notch weir.

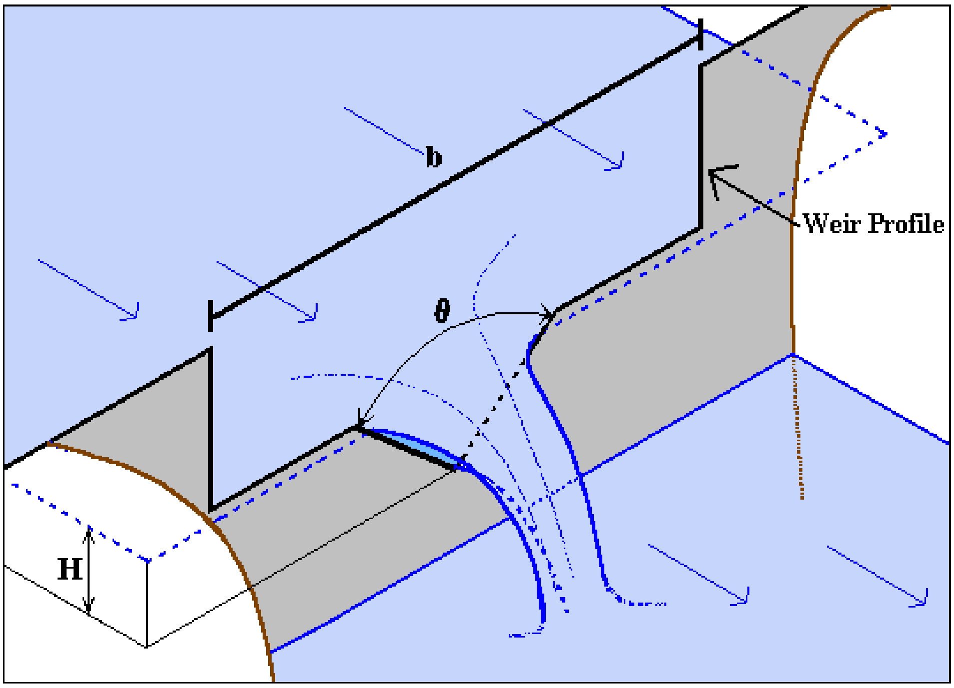


Figure 3.3, a diagram showing a compound weir, the width of the crest is given by b, the angle of the V-notch is given by *θ*.

The stage discharge relationship of a compound weir does not follow a simple smooth relationship and so it is important to get calibration data for a range of flows, which include both the V-notch and the rectangular notch.

This method of calibration using results from *in situ* site measurements ensures that the stage discharge relationship remains accurate through the entire range of flows (Webber, 1968).

3.2 The chosen thin plate weir

After viewing all the options as to which design of thin plate weir would best suit the channel conditions likely to be experienced in the Mine Adit, it was decided that the compound thin plate weir would provide the most accurate and sensitive data. By narrowing the angle of the notch (θ), it is possible to make smaller changes in discharge appear as larger changes in stage, however if the angle of the notch is too small there is a danger that the larger, less frequent flood may completely submerge the weir. Therefore a suitable notch angle must be decided upon, which provides sensitive values but that will not be flooded too frequently.

A range of notch angles (θ) were investigated with the final angle being set at 53˚8'. By looking at appendix A, which is a table showing the head (m) for V-notch weirs, where the notch has an angle equal to 53˚8', through a range discharges (m^3s^{-1}), it is possible to see that as the discharge changes there is an appreciable change in head (BS 3680, 1981).

3.3 Location of the weir

When choosing exactly where to locate the weir it is important to envisage what the end result will look like, the expected variation in head also needs to be taken into account. To make the stage discharge relationship as accurate as possible it is important that even a small change in discharge causes the water level to rise or fall. To do this, a narrow and steep section of channel should be used as the approach to the weir. This way the head is maximised and any small change in discharge will be measurable.

Another important consideration when locating the weir is the visual impact that it will have. The Mine Adit is in a remote location and is quite well concealed by spoil heaps, however to ensure that there is minimal impact the concrete flanks of the weir will be set into the hillside, close to the confluence with Grainsgill Beck (figure 3.4). Stones will then be laid down around the weir both for camouflage and to provide some support.

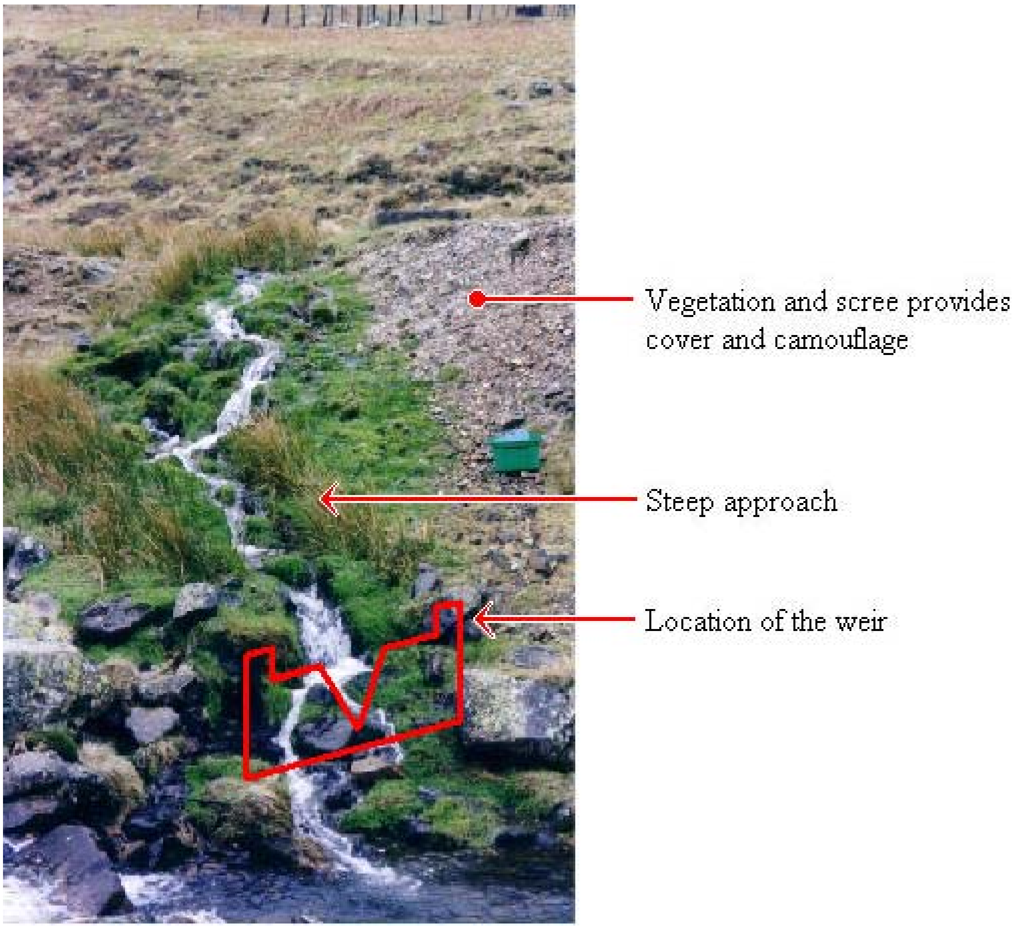


Figure 3.4 a photograph showing the Mine Adit and where the weir will be located, the concrete flanks of the weir will be set into the bank and therefore remain hidden by the scree and vegetation.

3.4 The design and construction of the thin plate weir

With the final design of thin plate weir settled upon, it had to be fitted into the channel in which it would operate. Two parallel concrete walls were used to provide an artificial channel; the thin plate weir was then fitted to the front of these walls so that water flowing between the concrete was forced to pond behind and flow over the thin plate. The weir was designed and constructed using the procedure detailed below.

3.4.1 The design of the weir

When designing the weir every effort was made to work with the natural features of the existing channel. The maximum length and width of the channel used were dictated by the physical characteristics of the site. It was decided that the natural topography would be used where possible to contain the flow and cut down on the use of building materials. The basic shape of the structure is a rectangular box where water can flow in easily at one end but is forced to flow over the thin plate at the other. Two small concrete walls are used to channel and contain the water (figure 3.5).

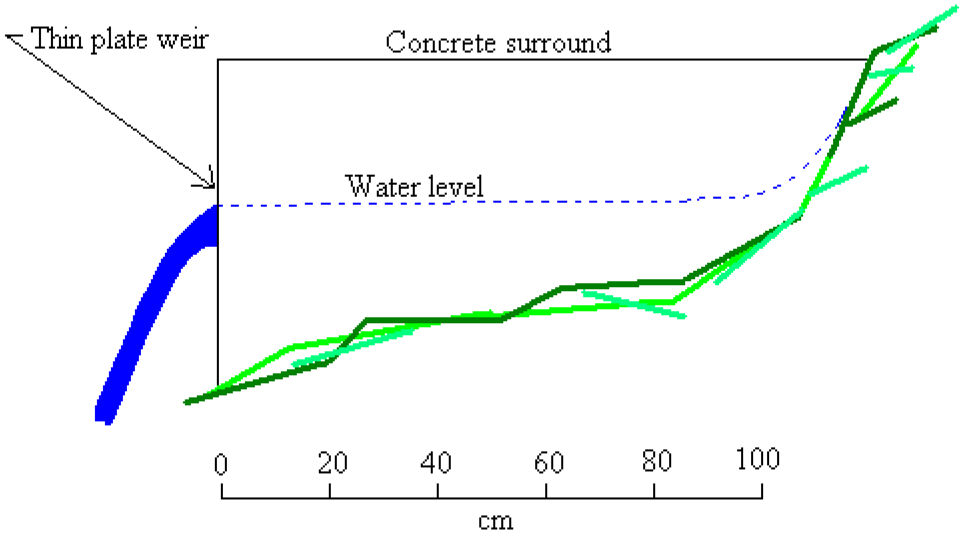


Figure 3.5, a diagram showing the side view of the weir, the concrete walls provide vertical, parallel and uniform sides to the flow.

Appendix B is a scale diagram showing the design plans for the weir; this includes all measurements and annotations where appropriate.

3.4.2 Site preparation and construction

The first step in the construction of the compound thin plate weir in the Mine Adit was to divert the flow around the construction site. This was essential as the concrete would not set in a flooded environment. The stream was diverted by building a small dam (made of rubble and organic debris) just upstream of the location of the weir. With the flow diverted around the construction site, the next stage was to remove all loose material so as to expose solid ground on which to lay the concrete.

Before the concrete walls could be laid wooden shuttering was built, the wet concrete would then simply be poured into the shuttered boxes, compacted and left to set. To provide strength to the structure and to help the concrete walls bind to the floor, small metal rods were driven into the ground inside the shuttered areas (figure 3.6). The concrete was then poured in between the shuttering to make too walls. The concrete was layered, with each fresh layer being constructed after the previous layer had been compacted and fully set.

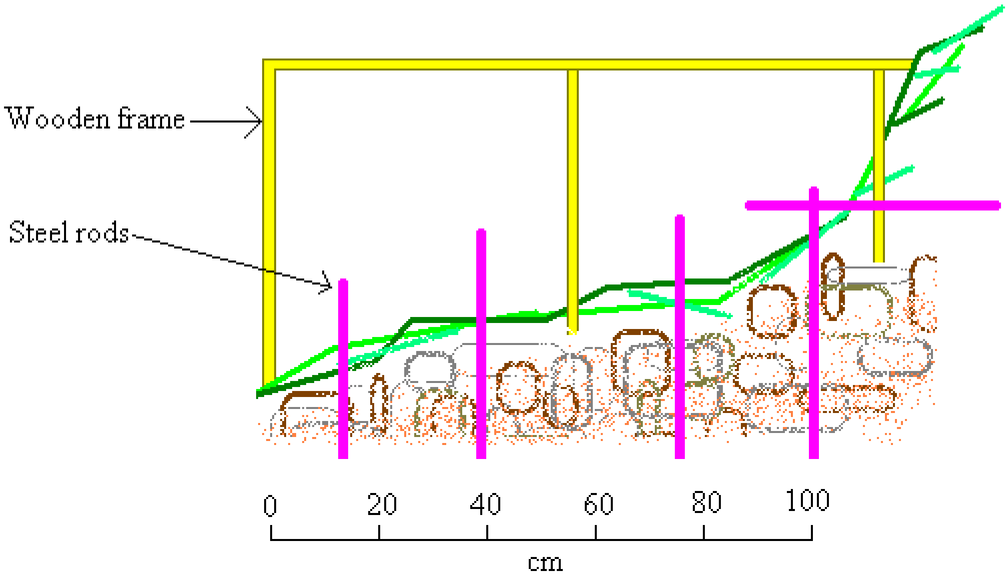


Figure 3.6, a diagram showing the wooden frame for the shuttering and the possible location of the metal supports.

When the concrete walls were finished and the shuttering had been removed, the thin plate compound weir had to be fitted to the face of the structure. To do this four bolts were drilled through each side of the weir plate into the concrete wall. Just before the bolts were tightened the gap between the concrete and steel plate was flooded with sealant; this was to help ensure a water tight seal.

The final step was to lay a skirt of concrete underneath the thin plate weir to join the steal plate to the ground. A ruler was then glued to the inside of the concrete channel so that the zero centimetre mark on the ruler corresponds with the level of the V-notch. Once done the final weir was water tight and ready to be calibrated.

4.0 Methods

During this project flows were observed and measured at two separate sites, the Mine Adit and the bridge in Grainsgill Beck (see figure 2.3). Each site required its own different set of field techniques to measure and record these discharges. What follows is a description of the methods used at each of these two sites, there is also a description of the method used for collecting and measuring rainfall.

4.1 Methods used at the weir in the Mine Adit

As mentioned above, discharge was measured in the Mine Adit using a small thin plate compound weir. Once installed as described in section 3, accurate measurements of discharge and stage were required to calibrate the weir and allow the stage discharge relationship to be produced. Once this stage discharge relationship had been established and a rating curve drawn, a chart recorder was used to collect a continuous record of stage; this provided a series of discharge measurements over a given period of time.

4.1.1 Volumetric gauging of discharge over the weir

Volumetric gauging allows the volume of water flowing over the crest of the weir in a given time to be measured. This is achieved by collecting an amount of water in a suitably sized container whilst measuring the time taken to do so. The discharge is then given by the formula:

$$\text{Discharge (l sec}^{-1}\text{)} = \frac{\text{Volume (litres)}}{\text{Time (seconds)}}$$

This method is only suitable for low discharges; typical discharges over the weir in the Mine Adit are approximately 10 litres per second. This makes volumetric gauging a suitable method for determining discharge at this site (figure 4.1).

Figure 4.1, a photo showing volumetric gauging being carried out at the weir in the Mine Adit.

Discharge was measured over the weir a minimum of three times at each stage height; the average discharge for that stage was then taken. These discharge and stage measurements were then used to create a stage discharge relationship. To ensure that the relationship is accurate at high and low flows it is important to take physical readings rather than extrapolate a small data set. By diverting some of the flow from the Mine Adit around the weir it was possible to artificially produce the low flows. High flows can not be artificially produced without the aid of a pump and so it is simply the case of waiting until the stage naturally rises.

4.1.2 Measurement of stage at the weir in the Mine Adit

Measuring stage gives a record of the level of water flowing out of the Mine Adit. Using the rating curve for the weir discharge can be calculated by simply measuring the stage. It is important that the stage is always measured from the same datum level; this level is the notch of the compound weir. By fixing a ruler to the channel wall a short distance upstream of the weir so that zero of the ruler is at the same level as the notch of the weir, stage may be accurately and easily measured

Flow through the channel on the upstream side of the weir may not always be calm; the surface of the water may be covered in ripples and small waves. When measuring stage on the ruler it may be necessary to take the mean value of the peaks and troughs of any ripples (figure 4.2). The stage will be measured to the nearest half centimetre.

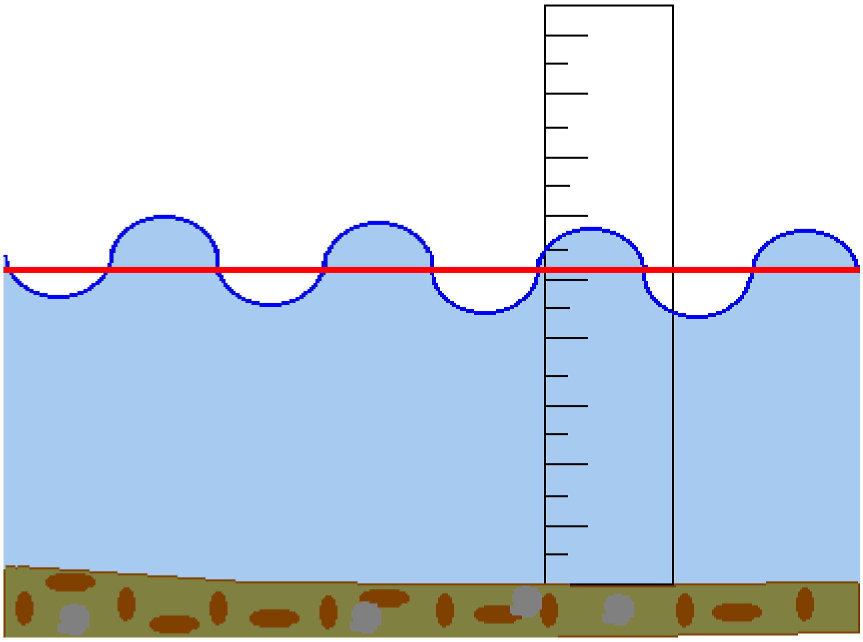


Figure 4.2, a diagram showing the effect of ripples and waves on the measurement of stage. The red line is the actual measured stage.

4.1.3 Chart recorder to measure stage

To collect a continual record of stage and therefore discharge, a chart recorder was installed in the channel upstream of the weir. The chart recorder (figure 4.3 a&b) uses a float sitting in a stilling chamber to measure the water level, variations in water level cause the float to either rise or lower, this motion causes the drum to turn. Paper is secured around the drum and a pen is fixed on a rail. As the motor turns the pen is pulled along the rail, this is a reflection of time. As the pen moves along the time axis the drum is free to rotate in the stage axis. The pen marks on the paper any changes; by measuring the stage at certain times and marking this on the paper, the discharge at any point can be determined. Discharges were measured daily in litres per second.

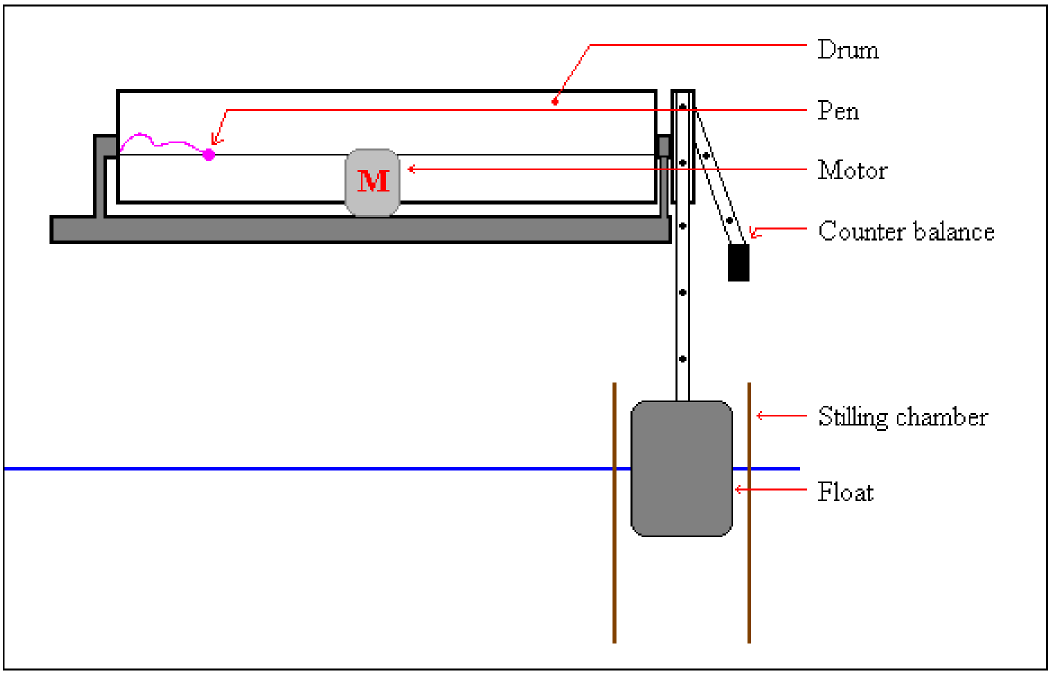


Figure 4.3.a, a diagram showing the layout of the chart recorder.

Figure 4.3.b, a photo showing the chart recorder installed at the weir.

4.2 Methods used at the bridge in Gainsgill Beck

Discharges at the bridge in Grainsgill Beck are much larger than at the Mine Adit, once again a stage discharge relationship was used to allow a quick and accurate measurement of discharge to be made. Instead of constructing a structure to provide this stage discharge relationship the natural shape of the river bed together with the artificially engineered bridge was used. The site was calibrated with respect to stage and discharge; fortunately there has already been a substantial amount of stage and discharge data collected at the bridge in Grainsgill Beck. By collating this data together with some new results the stage discharge relationship was established. As the discharge at the bridge in Grainsgill Beck is at least ten times larger than in the Mine Adit volumetric gauging would be unsuitable and so dilution gauging was used. Stage was once again measured by simply placing a ruler in the stream and reading the level of water above the river bed.

4.2.1 Dilution gauging at the bridge in Grainsgill Beck

Dilution gauging involves the injection of a known volume of tracer into the flow, the concentration of this tracer may then be measured at some point far enough down stream so that complete mixing has occurred. The tracer used is a dye known as Rhodamine WT, which is toxic in high quantities. The dye is mixed with around five litres of river water and is then injected into a particularly turbulent section of flow, to allow complete mixing at the downstream point of measurement, approximately forty metres upstream (White. 1988). The time of injection is noted and the downstream concentration is logged using the 10AU fluorometer, manufactured by Turner Designs.

The change in concentration of tracer between the upstream and downstream locations is a measure of the discharge, which may be calculated as follows:

A known mass of tracer (M) is injected into the stream with a background concentration of C_0 (ML^{-3}). This background concentration is determined by logging concentration for five minutes prior to the tracer being injected. The downstream change in tracer concentration with time (t) is given by C_1 (ML^{-3}). Discharge Q (L^3T^{-1}) is:

$$Q = \frac{M}{\int (C_1 - C_0)\, dt}$$

Where the term $\int (C_1 - C_0)\, dt$ is the area under the chemograph and is estimated using the trapezium rule:

$$\text{Area} = t \times \left(\frac{C_1}{2} + \sum_{i=2}^{N-1} C_i + \frac{C_N}{2} \right)$$

Where the time axis has been split into N-1 intervals of time Δt.

Dilution gauging was used at the bridge in Grainsgill Beck to support data, which was collected from a range of other sources. Stage and discharge had previously been measured at this site by Buist (1998), Conning (2002) and Lancaster University field courses (1998, 1999 and 2000). The results from these studies were combined with the discharges measured using the above dilution gauging technique to produce a stage discharge relationship for the bridge in Grainsgill Beck.

4.2.2 Measurement of stage at the bridge in Grainsgill Beck

The height of water above an arbitrary datum level must be accurately and precisely recorded. To measure this stage a ruler was placed against the wall of the bridge in Grainsgill Beck, the same point was used each time (figure 4.4). Any sediment in this area had to be removed before the stage was read; the water level was then measured from the river bed to the nearest half centimetre.

Figure 4.4, a photo showing the point of stage measurement at the bridge in Grainsgill Beck.

4.3 Methods used to collect rainfall:

A tipping bucket rain gauge was installed in the Grainsgill Beck Catchment, the bucket was set to tip every 0.2mm of rainfall. A site was found (GR NY 327328) that would be safe from vandalism whilst reflecting the catchments rainfall.

As well as this rainfall data, other information was collected from the Environment Agency.

5.0 Results

The results were collected using the methods laid out above. Once the results were collected the stage discharge relationships for both sites had to be drawn, and statistically analysed to check there accuracy. Next the discharge and rainfall data collected for the sites could be analysed.

5.1 Stage discharge relationships

5.1.1 Stage discharge relationship at site 1, the Mine Adit

The stage and discharge data collected for the weir in the Mine Adit, site 1, can be seen in appendix C. Using these results the stage discharge relationship for the Mine Adit was drawn, and is shown in figure 5.1. Error bars are included on the plot; these are equal to the standard error of the discharge measurements made.

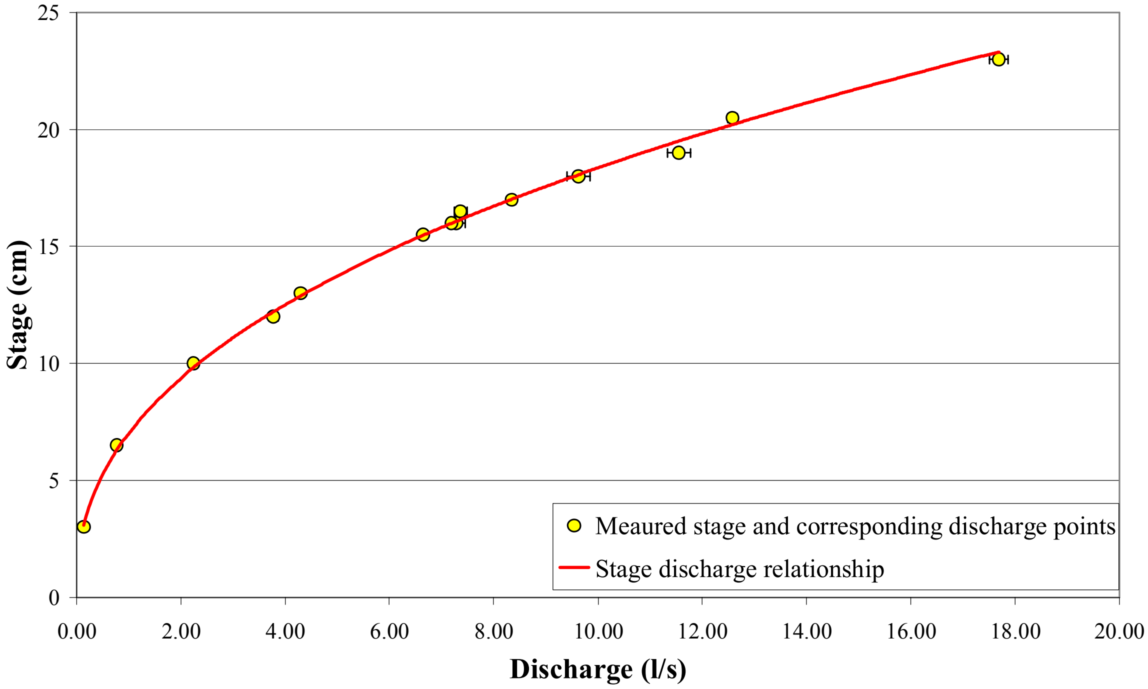


Figure 5.1, an arithmetic plot showing the stage discharge relationship at site 1, the Mine Adit.

This simple arithmetic plot is very useful in that it is convenient and easy to read; by using this type of plot it is possible to display the discharge at zero stage, even though this is not measured. However for analytical purposes a logarithmic plot must be drawn (BS ISO 1100-2, 1998), this can be seen in figure 5.2. The figure below also shows the 95% confidence limits for the weir.

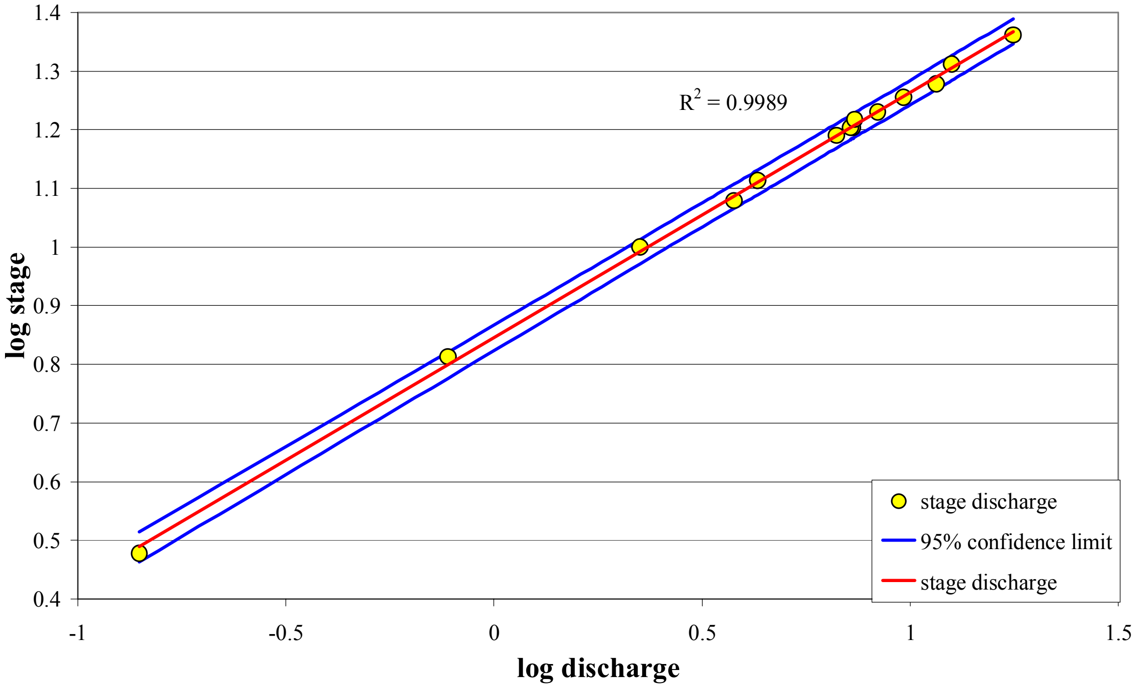


Figure 5.2, a plot showing the log stage discharge relationship at site 1, the Mine Adit.

The logarithmic plot follows a straight line; therefore it is also possible to extrapolate this line. The graph will remain straight with this same gradient until the angle of the notch in the weir changes. Using the gradient of this line it is possible to predict discharges for any stage up to 45cm, at this point the 'V' notch is replaced by the rectangular notch.

The close proximity of the 95% confidence limits to the stage discharge relationship, and the high goodness of fit (R^2) value, indicate that there is very little scatter of the data. The above graph shows that with 95% confidence, for a given discharge, the range in observed stage will be small.

By looking at figure 5.3 it is clear that for a given stage height, at 95% confidence limits, the range in discharges is small. The equation of the log discharge stage relationship is shown on the graph below (figure 5.3).

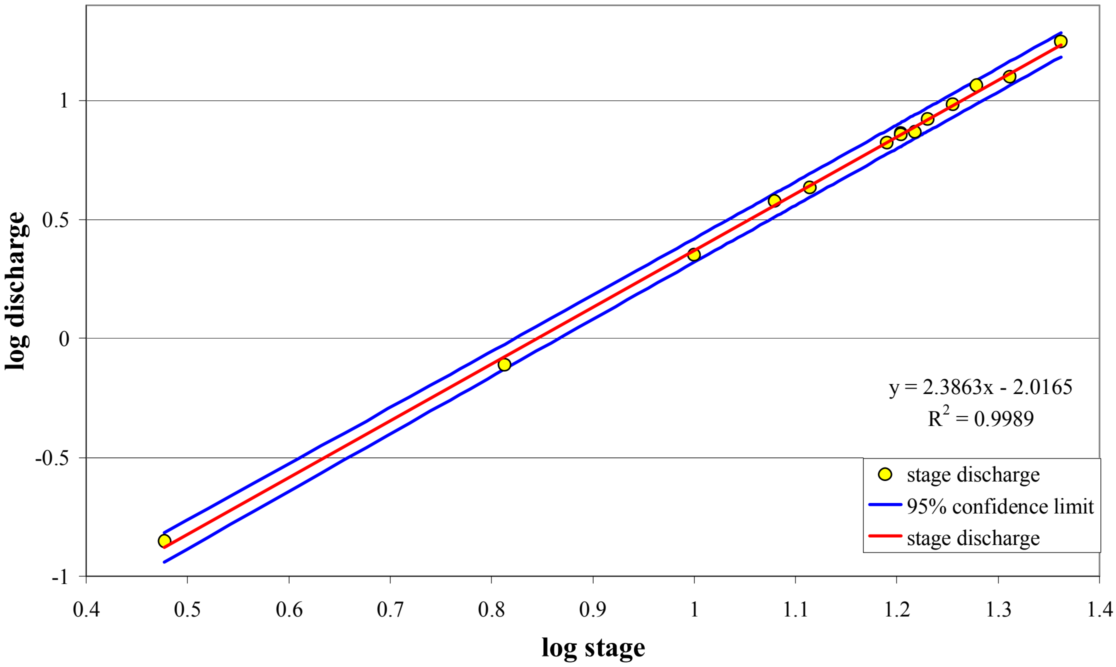


Figure 5.3, a plot showing the log discharge stage relationship at site 1, the Mine Adit. The equation of the stage discharge relationship is shown as a log linear relationship.

Using the equation of the line in the above figure, which represents the stage discharge relationship, it is possible to calculate the best estimate of the discharge for a given stage; this was done for each of the measured stage heights. The log stage and log best estimate of discharge were then converted back to the original arithmetic form; error bars were plotted on the graph to check how the confidence in the stage discharge relationship varied as stage increased. These error bars show the 95% confidence limits in the individual best estimate. Figure 5.4 shows this measured stage versus the best estimate of discharge, based on the gradient of the stage discharge relationship in figure 5.3.

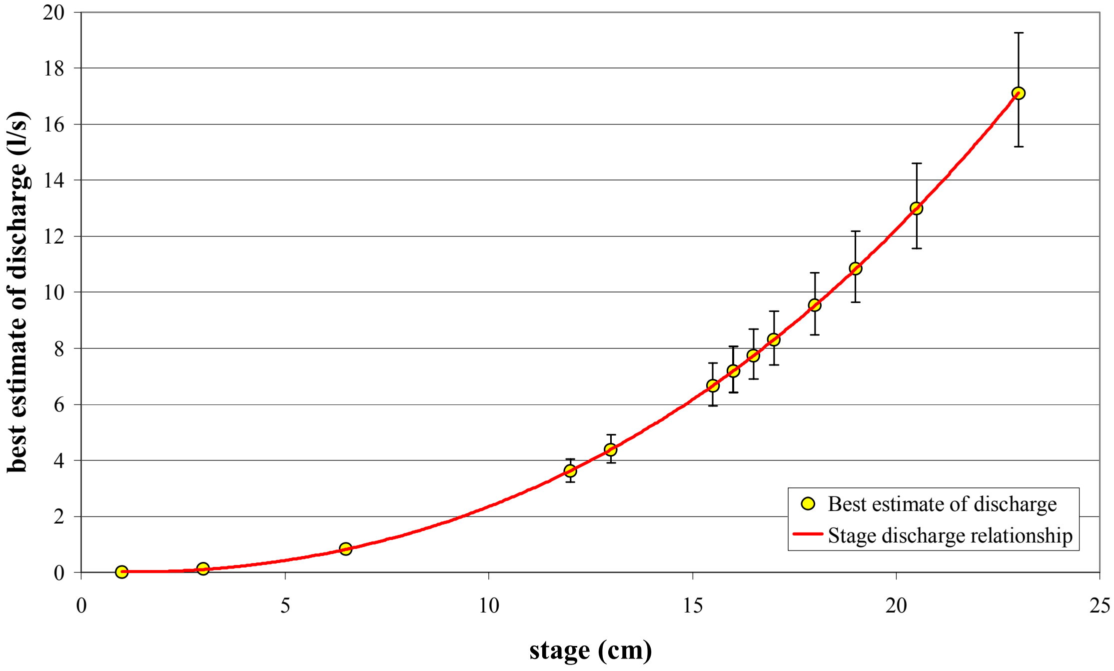


Figure 5.4, the best estimate of discharge stage relationship for site 1, the Mine Adit showing the 95% confidence limits of discharge for a given stage.

It was expected that the best estimate of discharge would exhibit very small error bars, this is because the 95% confidence in the trend line from figure 5.3, which this graph is based on, is so high. By looking at the above figure it is possible to see that errors in the best estimate of discharge get larger as stage increases, however even for the largest stage of 23 cm the error is still small, approximately plus or minus 2 litres per second.

The 95% confidence in the individual best estimates is high; to check that the 95% confidence in the actual stage discharge relationship is high the observed stage may be plotted against the observed discharge (figure 5.5). This is done by taking the anti log of the values from figure 5.3 and is used to show how the actual confidence in the observed stage discharge relationship may vary as stage increases.

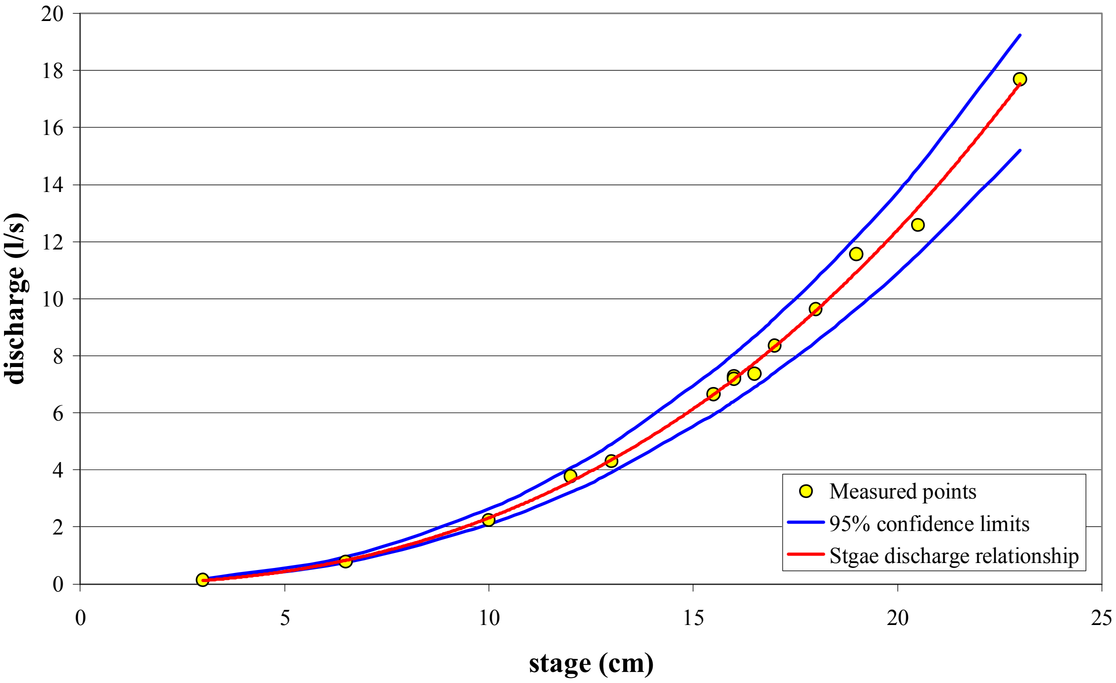


Figure 5.5, an arithmetic plot of the raw data showing the 95% confidence limits for the stage discharge relationship at the weir in the Mine Adit, site 1.

The above diagram shows the completed stage discharge relationship for site 1, the Mine Adit; it shows the 95% confidence in the discharge through a range of stage heights. From this diagram it is possible to determine the discharge from a measurement of stage, made at the weir. The confidence in the discharge obtained can also be quoted for any value in the discharge range.

To ensure that the above stage discharge relationship is not just down to chance the significance of the correlation must be tested. If the calculated value of r from the above graphs is larger than tabulated Pearson's correlation coefficient the stage discharge relationship is significant (Owen & Jones, 1989).

Calculated r = 0.999 n = 14

Tabulated r with 12 degrees of freedom and α = 0.01 = 0.661

Therefore as the calculated r is much greater than tabulated r there is a significant relationship between stage and discharge at the 1% level.

5.1.2 Stage discharge relationship at site 2, the bridge in Grainsgill Beck

The stage discharge relationship at the bridge in Grainsgill Beck, site 2, was constructed using data collected by Buist (1998), Conning (2002) and Lancaster University field courses (1998, 1999 and 2000). This data can be seen in appendix C. Once again the stage discharge relationship was drawn on an arithmetic and logarithmic scale; these are shown in figures 5.6 and 5.7 respectively. The logarithmic plot in figure 5.7 also shows the 95% confidence limits in the data.

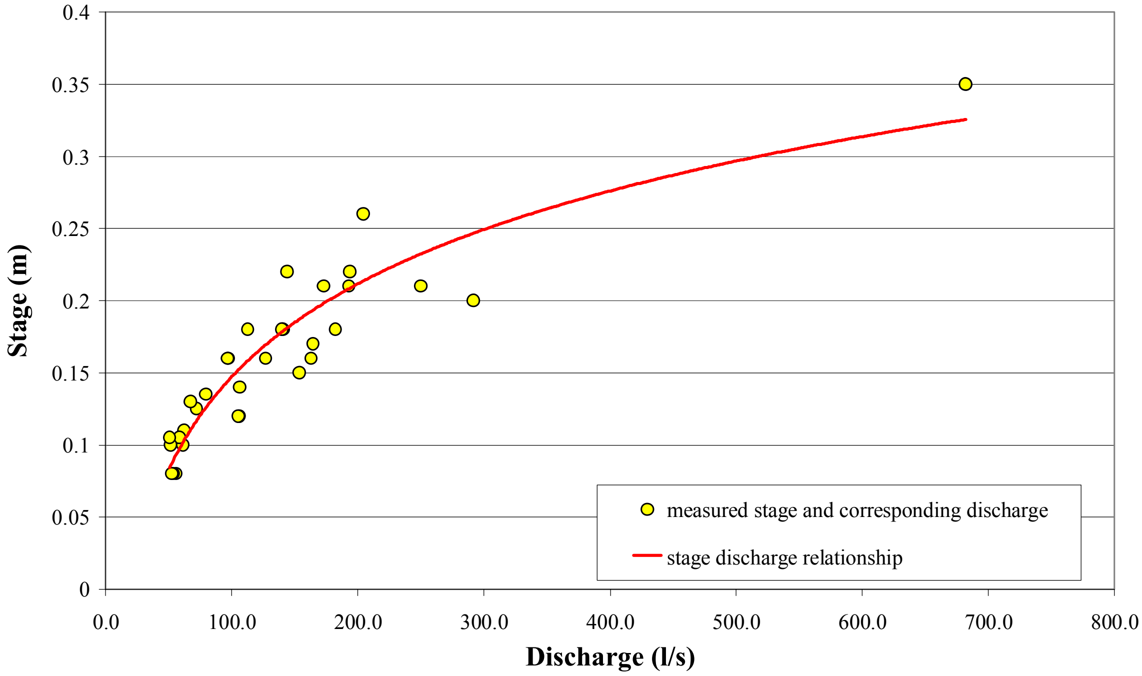


Figure 5.6, an arithmetic plot showing the stage discharge relationship at site 2, the bridge in Grainsgill Beck.

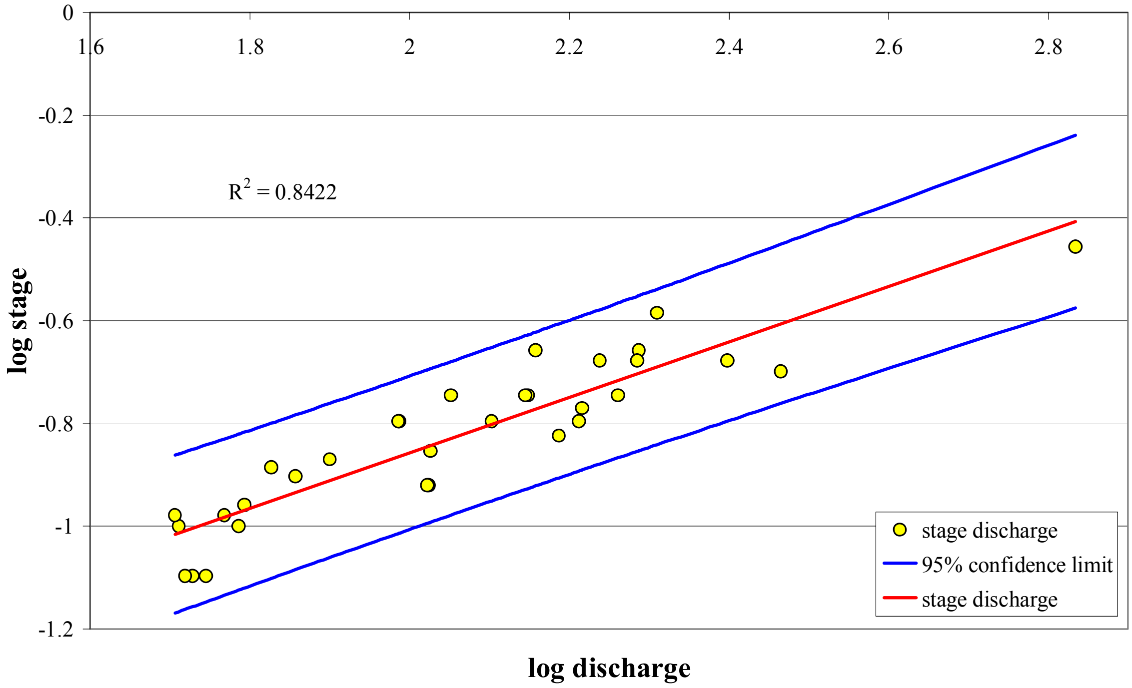


Figure 5.7, a plot showing the log stage discharge relationship at site 2, the bridge in Grainsgill Beck.

It can be seen by looking at the above diagram that the stage and discharge at the bridge in Grainsgill Beck, site 2, does not follow as perfect a relationship as the weir in the Mine Adit. Although the data does follow a log linear relationship there is a greater degree of scatter around the stage discharge relationship, which is highlighted by the low goodness of fit (R^2) value of 0.84. The 95% confidence limits are also much further apart indicating that for a given discharge the range in possible stage, at 95% confidence is much greater.

The 95% confidence for the stage were also calculated, this is plotted on the graph below (figure 5.8), which shows the range in possible discharges, at 95% confidence, for a given stage measurement.

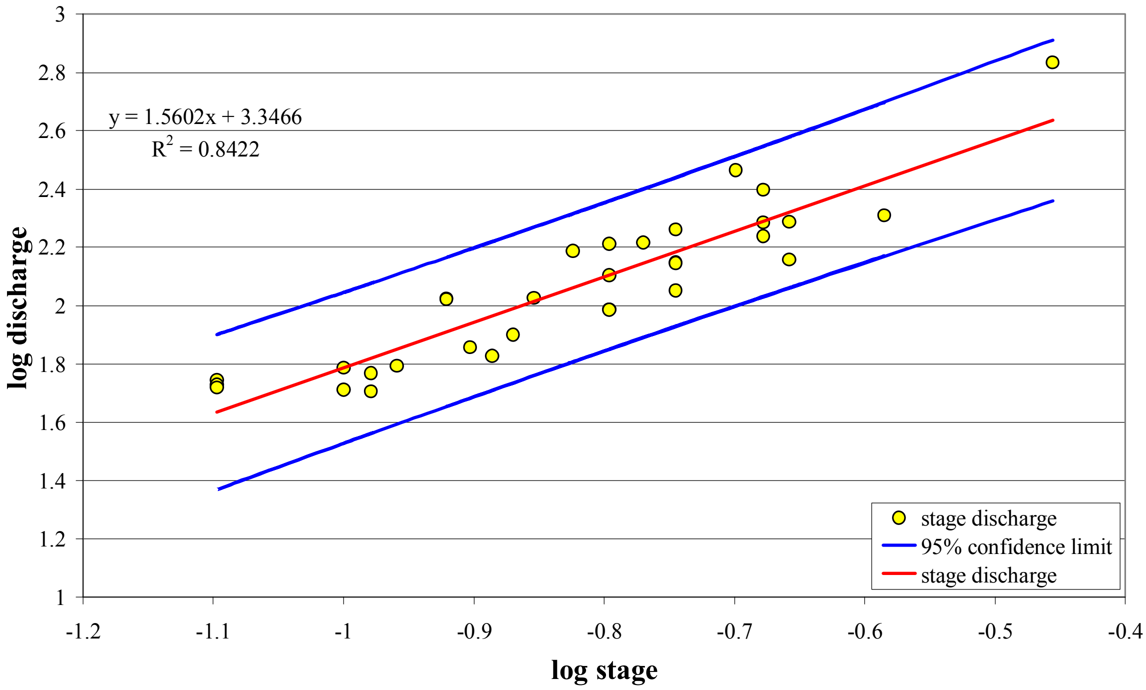


Figure 5.8, a plot showing the log discharge stage relationship at site 2, the bridge in Grainsgill Beck. The equation of the stage discharge relationship is shown as a log linear relationship.

By using the equation of the above log linear stage discharge relationship it is possible to calculate the best estimate of discharge for a given stage measurement; this was done for all the stage measurements made and is shown in figure 5.9 in arithmetic form. Error bars are included on the plot; these represent the 95% confidence in the individual best estimates.

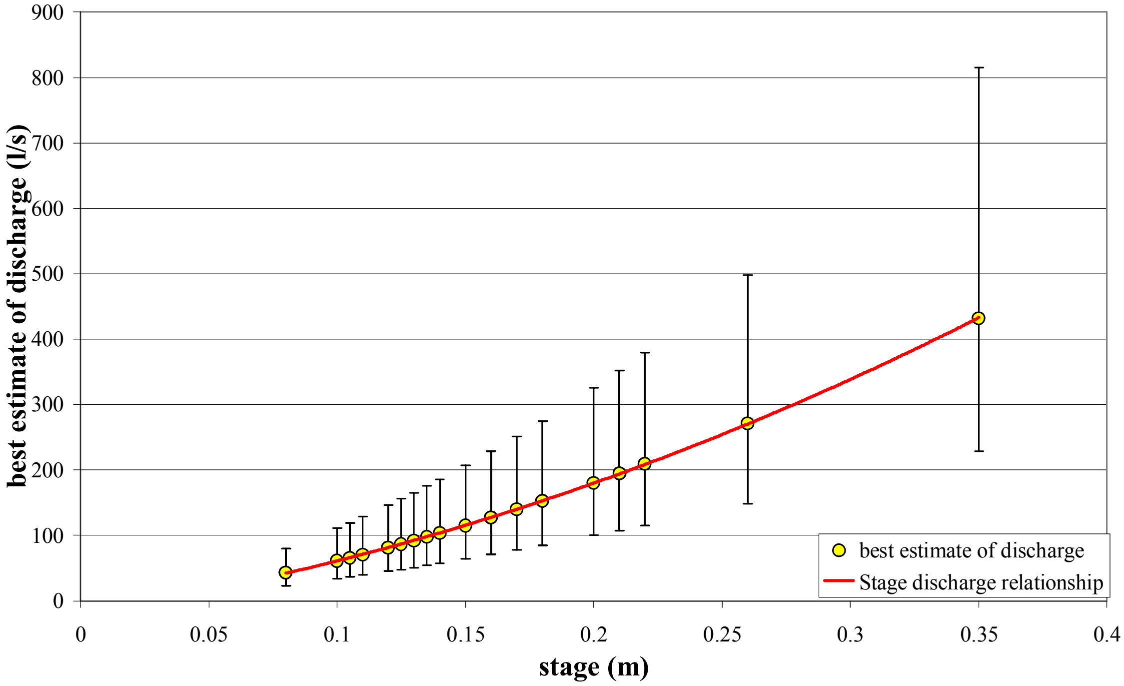


Figure 5.9, the discharge stage relationship for site 2, the bridge in Grainsgill Beck, showing the 95% confidence in discharge for a given stage.

The above graph shows that there are very large possible ranges in the individual best estimate of discharge at site 2, the bridge in Grainsgill Beck at the 95% confidence limit. The 95% confidence in the best estimates is so low that for most best estimates, the range of possible discharges is nearly one and a half times greater than the value predicted by the stage discharge relationship.

The 95% confidence in the individual best estimates of discharges is low; to check if the confidence in the actual stage discharge relationship is acceptable the observed stage and discharge may be plotted in arithmetic form with the 95% confidence limits. This is done by taking the anti log of the values in figure 5.8. This is shown in figure 5.10 and represents the completed stage discharge relationship at site 2, the bridge in Grainsgill Beck.

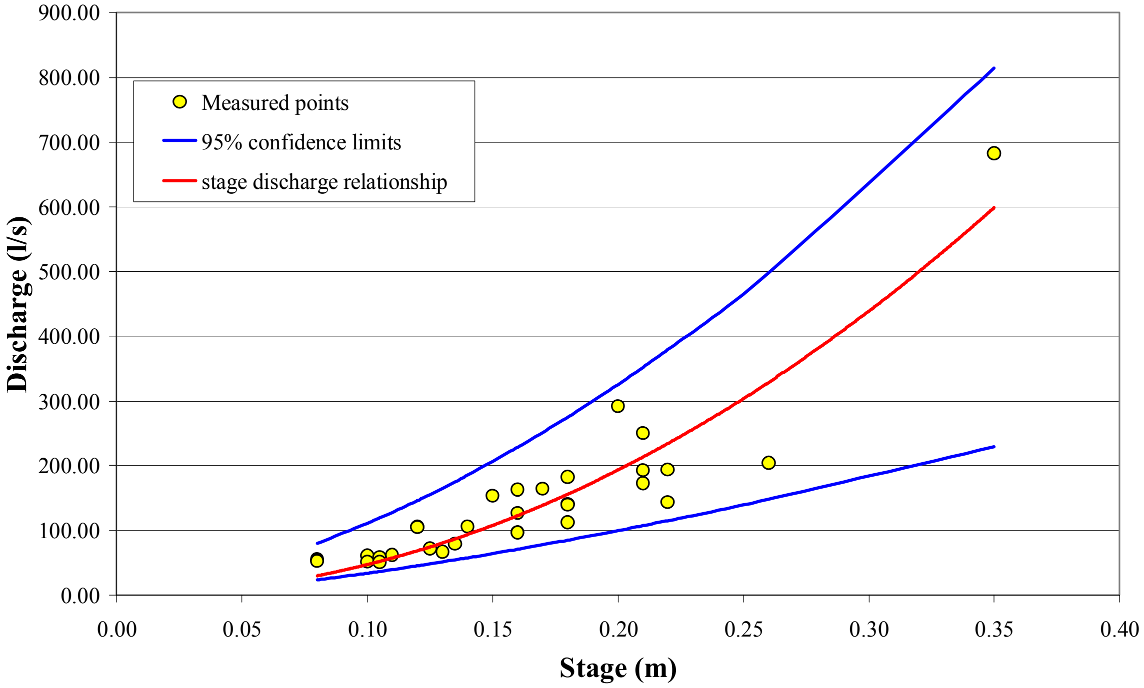


Figure 5.10 an arithmetic plot showing the 95% confidence limits for the stage discharge relationship at the bridge in Grainsgill Beck, site 2.

Using this diagram it is possible to convert a measurement of stage, made at the bridge in Grainsgill Beck, into discharge, the 95% confidence in that discharge may also be quoted. It is apparent by looking at the above plot that as stage increases, the 95% confidence in the discharge becomes very low; the range in possible discharges is actually as large as the predicted discharge from the stage discharge relationship.

To ensure that the above stage discharge relationship for site 2, the bridge in Grainsgill Beck, is not just down to chance the significance of the correlation must be tested.

Calculated r = 0.92 n = 32

Tabulated r with 30 degrees of freedom and α = 0.01 = 0.449

Therefore as the calculated r is much greater than tabulated r there is a significant relationship between stage and discharge at the 1% level.

5.2 Rainfall data for the catchment

Rainfall was collected for a three week period commencing on Friday 11th October 2002 and finishing on Saturday 2nd November 2002; the recorded levels of rainfall are shown in figure 5.11.

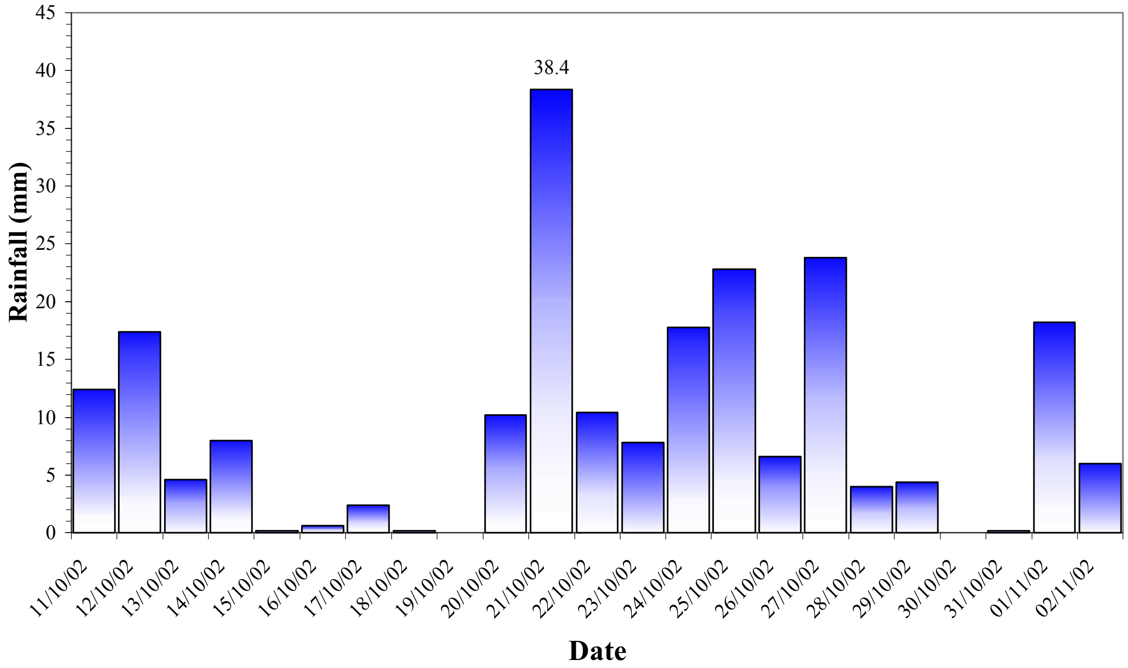


Figure 5.11, a plot showing daily rainfall levels for the Grainsgill Beck catchment during the three week period.

The above graph shows that in the three week period rainfall peaked at 38.4mm on the 21st October whilst there were two days when rainfall fell to 0mm. The mean rainfall throughout the entire sampling time was 9.5mm.

5.3 Discharge data for the catchment

5.3.1 Discharge at site 1, the Mine Adit

Stage was measured daily for the same three week period. These stage measurements were then converted to discharges using the stage discharge relationship from section 5.1.1. The discharge from the Mine Adit can be seen in figure 5.12.

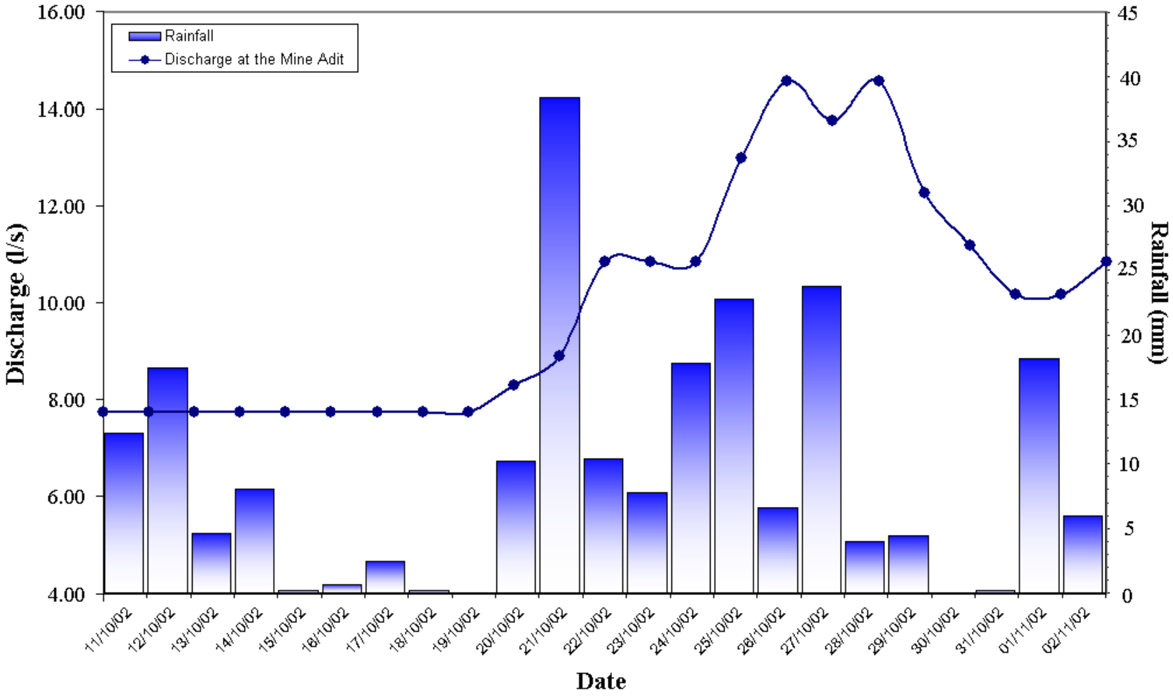


Figure 5.12, a plot showing the discharge from site 1, the Mine Adit over the three week period. Rainfall is also plotted.

The above graph shows how the discharge at site 1, the Mine Adit, responded to rainfall over the three week monitoring period. Discharges at the site can be seen to remain constant for the first nine days of monitoring, at around 7.7 l/s, until on the 20th of October when discharges begin to rise. The discharge peaked twice in the three week period at a value of 14.5 l/s, firstly on the 26th October and then on the 28th October.

5.3.2 Discharge at site 2, the bridge in Grainsgill Beck

Stage was measured on four days spread throughout the above three week period. The stage discharge relationship defined in section 5.1.2 was used to convert these stage measurements to discharges. The discharges at the bridge in Grainsgill Beck can be seen in figure 5.13; the discharges from the Mine Adit have also been displayed on this plot to illustrate the difference in scales of the two discharges.

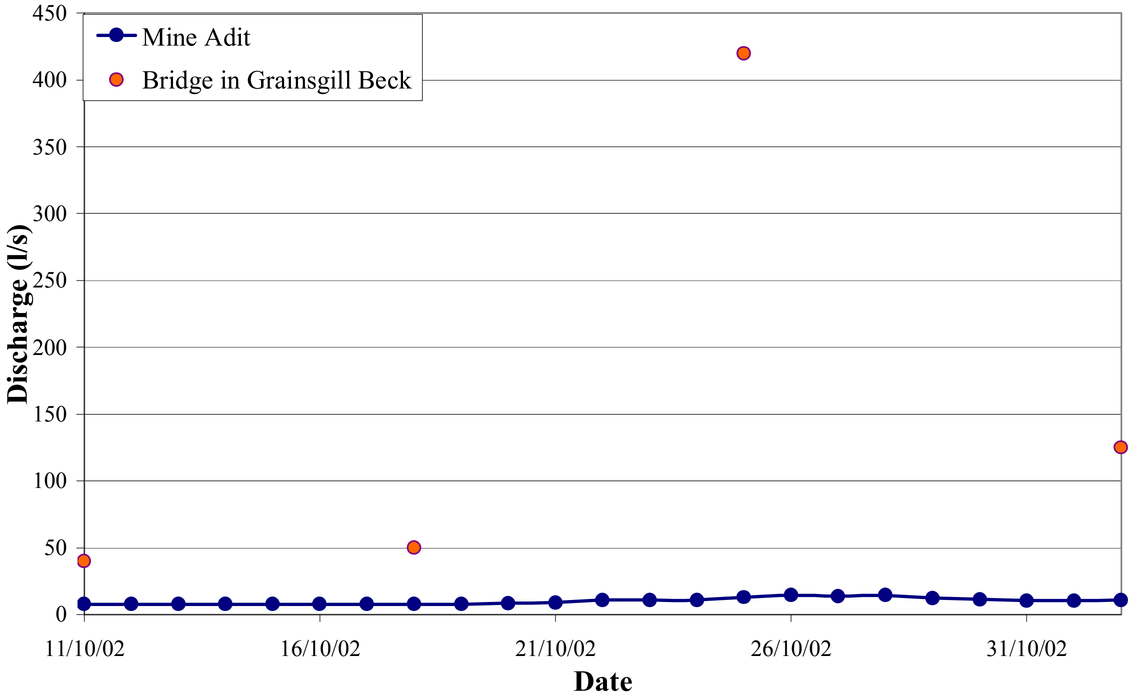


Figure 5.13, a plot showing the discharge from the site 2, the Bridge in Grainsgill Beck and site 1, the Mine Adit.

The maximum discharge recorded at site 2 the bridge in Grainsgill Beck was 420 l/s, this measurement was made on the 25th October. High discharges calculated at this site using the stage discharge relationship described in section 5.1.2 are subject to large uncertainties; this is due to there being very little stage and discharge data in the upper stage ranges to calibrate the relationship. Therefore this figure of maximum discharge must be treated with some caution. From the observed stage reading of 0.3 metres at 95% confidence limits the range of possible discharges is 180-640 l/s.

6.0 Discussion

The results collected in the above chapter must now be discussed and explained so that the aims of this project may be fulfilled. Firstly to develop the stage discharge relationship at site 1, the Mine Adit, a small weir had to be constructed. The construction and operation of this weir will be discussed. Secondly the stage discharge relationships that have been established at the Mine Adit and the bridge in Grainsgill Beck will be examined. Finally the rainfall and discharge data collected from the sites within the catchment will be discussed. Using the rainfall data collected as well as the discharge data from site 1, the Mine Adit, some rainfall runoff modelling will be carried out.

6.1 The construction and operation of the weir

Prior to the stage discharge relationship in the Mine Adit being established a weir had to be constructed in the channel. The aim of this weir was simply to force the flow to switch from subcritical to supercritical thus enabling the conditions under which stage discharge relationships apply to be created, as described in section 2.

The construction of the weir was successful; once water was allowed to flow over the weir any small leaks in the concrete walls were spotted and blocked using plumbers tape and axel grease. Even under lower flow conditions water flowed over the notch and sprang clear of the face of the weir allowing the nappe to fully develop.

Although the completed weir runs well and produces accurate and precise discharge measurements there are some small changes to the design and construction that could help yield an even greater level of accuracy.

Firstly by making the notch angle smaller the weir would become more sensitive to changes in discharge. When the weir was originally designed the notch angle was set at 53˚8' and for the purpose of this study that proved sufficient, however if a greater level of sensitivity were required a narrower notch e.g. 28˚4' (BS 3680, 1981) could be used.

Secondly the diversionary dam constructed was not completely water tight, and so a small but significant amount of water continually flowed through the construction site. This made concreting very difficult and may have prevented a completely water tight seal between the weir and the rock floor from being achieved. In hindsight the diversionary dam should have been constructed further upstream, a pump could then have been used to remove the water from the upstream pond. This would have ensured that the construction site remained dry, easing working conditions and reducing the amount of water leakage in the final structure.

One final improvement to the weir in the Mine Adit could have been to treat the concrete with a water proof sealant such as tar; this would have the effect of increasing the life time of the structure as well as preventing seepage out of the confining walls.

6.2 Discussion of the stage discharge relationships

In order for discharge data to be collected from the Mine Adit and the bridge in Grainsgill Beck it was decided that long term stage discharge relationships would be set up.

6.2.1 Site 1 the Mine Adit

Fourteen stage and corresponding discharge measurements were made at the weir in the Mine Adit; these measurements were made over a range of stages and discharges, the smallest of which had a stage of 3 centimetres and a discharge of 0.14 litres per second, whilst the largest had a stage of 23 centimetres and a discharge of 17.69 litres per second. This range does not cover the maximum stage of the weir, which is 45 centimetres; it does however cover the range of flows that were experienced as part of this project.

These fourteen measurements were used to construct the stage discharge relationship, which is detailed in section 5.1.1. From figure 5.3 it is apparent that stage and discharge over the weir in the Mine Adit follow a very strict log linear relationship. The 95% confidence in this relationship was tested and is shown in figure 5.5, for a given stage at 95% confidence the range in possible discharges is very small. This range can be determined from the graph. To test that this relationship was not simply down to the random correlation of these two sets of data a significance test was carried out. This significance test showed that at the 1% level there is no chance that the stage and discharge relationship observed at the weir in the Mine Adit was down to a random correlation.

Using the stage discharge relationship developed in section 5.1.1 it is possible to calculate discharge from any given value of stage in the range 0-23 centimetres. The linear nature of the relationship along with the high level of confidence in the data also allows the extrapolation of this stage discharge relationship for any stage measurement up to 45 centimetres. At this point the angle of the notch changes and therefore the relationship must change. To calculate a discharge in the Mine Adit using the stage discharge relationship the following procedure must be followed:

1. The stage must be measured using the ruler positioned on the wall of the weir; this is accurate to 0.5 centimetres e.g. 15.5 cm.
2. Take the log of this value i.e. log 15.5 = 1.1903
3. Substitute it into the following equation:

$$\text{log discharge} = 2.3863 \times \text{log stage} - 2.0165$$

e.g.

$$\text{log discharge} = 2.3863 \times 1.1903 - 2.0165$$

$$\text{log discharge} = 0.8239$$

therefore,

$$\text{discharge} = 6.67 \text{ litres per second.}$$

As previously stated it is possible to calculate discharge for stages up to 45 centimetres using this relationship; however it can be seen from figure 5.5 that as stage increases the level of confidence in the discharge decreases. This is due to the limited amount of calibration data in the upper stage range. As stage increases beyond the measured range, the confidence limits may continue to diverge; the calculated discharge will therefore be subject to very low confidence limits. To increase the confidence in discharges calculated at greater stages it would be necessary to collect more calibration data in this range.

6.2.2 Site 2 the bridge in Grainsgill Beck

Unlike site 1, where a purpose built structure was used to provide the necessary conditions to create a stage discharge relationship, site 2 utilised an existing structure to play a similar role. The bridge in Grainsgill Beck confined the flow and therefore produced the necessary conditions, detailed in section 2, to create a stage discharge relationship.

At site 1 all the calibration measurements required to construct the stage discharge relationship were collected over a period of several weeks whereas at site 2 the stage and discharge data was collated from previous studies carried out within the catchment. This information was then augmented with some new stage and discharge measurements carried out for this project.

In total 32 stage and corresponding discharge measurements were collected by Buist (1998), Conning (2002) and Lancaster University field courses (1998, 1999 and 2000). All of these measurements were made using the same method of dilution gauging described in section 4.2.1. The smallest stage was recorded by Lancaster University (1998) as 0.08 metres and had a corresponding discharge of 52.4 litres per second. The largest stage was recorded by Buist (1998) as 0.35 metres with a discharge of 681.9 litres per second; However Buist found that this high discharge lead to increased humic substances and suspended load, which increased the coloration of the water and caused problems with the pump. For this reason this high discharge value has been treated with caution.

The range of calibration data points used to create the stage discharge relationship does not cover the maximum capacity of the bridge in Grainsgill Beck, although it does cover the range of stages observed as part of this study.

Using these 32 measurements a stage discharge relationship was constructed for the bridge in Grainsgill Beck, this is shown in section 5.1.2. It can be seen from figure 5.8 that this stage discharge relationship follows a strict log linear relationship, however unlike the relationship developed for the weir in the Mine Adit there is much greater scatter of the calibration data around the stage discharge relationship.

This scatter means that the 95% confidence limits are further apart, giving greater uncertainties in the stage discharge relationship. By looking at figure 5.10 it is possible to see that at the upper stages the 95% confidence limits are so far apart that the range in possible discharges makes the stage discharge relationship very unreliable. Once again a significance test was carried out on the data to ensure that the observed correlation was not down to random luck. The significance test showed that at the 1% level there is no chance that the stage and discharge data, for the bridge in Grainsgill Beck, are related by a random correlation.

Using this stage discharge relationship it is possible to determine the discharge for any stage in the range of 0.08 - 0.35 metres although discharges may be extrapolated to 0 metres stage if necessary. Once stages rise above 0.25 metres the confidence in the relationship becomes so low that any discharges calculated must be treated with caution. To calculate a discharge the following procedure should be followed:

1. Measure the stage at the bridge in Grainsgill Beck as detailed in section 4.2.2. This value is accurate to 0.005 metres e.g. 0.155m
2. Take the log of this value i.e. log 0.155 = -0.8096
3. Substitute it into the following equation:

$$\log \text{discharge} = 1.5602 \times \log \text{stage} + 3.3466$$

e.g.

$$\log \text{discharge} = 1.5602 \times -0.8096 + 3.3466$$

$$\log \text{discharge} = 2.0833$$

therefore,

discharge = 121.1 litres per second.

There may be several reasons that could explain why the calibration data, used to create the stage discharge relationship at the bridge in Grainsgill Beck, exhibits a greater degree of scatter. The reasons for this scatter could include:

Firstly the stage and discharge data used in this project was collected from a variety of sources; although it is assumed that the individuals responsible for collecting this data worked to the same high level of accuracy, it may not have always been the case. Measurements in stage may be particularly subject to human error as it is down to the individual to gauge an acceptable water level, taking into account the effect of water ripples.

Secondly, sedimentation around the point of stage measurement may give the impression of a shallower channel. It is therefore critical that all sediment is removed from the area prior to the stage being measured.

Finally it was assumed that the dimensions of the bridge are constant through the range of stage heights. If the width of the bridge varied at different depths a log linear stage discharge relationship would not apply, instead a series of smaller stage discharge relationships would have to be combined.

To increase the confidence in the stage discharge relationship at the bridge in Grainsgill Beck it would be necessary to collect more calibration data, especially in the upper stage ranges, as this is where confidence is lowest. The dimensions of the bridge could also be examined and checked through a range of depths to ensure a constant width. One final step to improve the stage discharge relationship at the bridge in Grainsgill Beck could be to smooth the channel floor and walls so that sedimentation could not occur. In an extreme case, where a very high level of accuracy and precision were required, this could result in the installation of a small flume for flow monitoring.

6.3 Discussion of rainfall

Rainfall was monitored for the three week period commencing on Friday 11th October 2002. During this period rainfall varied substantially between 0mm and 38.4mm with the daily mean for the period being 9.5mm. Environment Agency rainfall data collected at Holm Hill for the period 1968 to 1996 shows that the mean daily precipitation during October is approximately 4.8mm (Environment Agency, 2001). This difference in rainfall may be attributed to the fact that the Grainsgill Beck catchment is an upland site whereas the Holm Hill monitoring station is a lowland site; therefore it is likely that greater rainfall will be recorded at the Grainsgill Beck catchment.

The area of the catchment is known to be 3.36km^2 and so by multiplying this value by the measured daily rainfall value it is possible to calculate the total volume of water received each day in the catchment. This was done and the results are shown in figure 6.1.

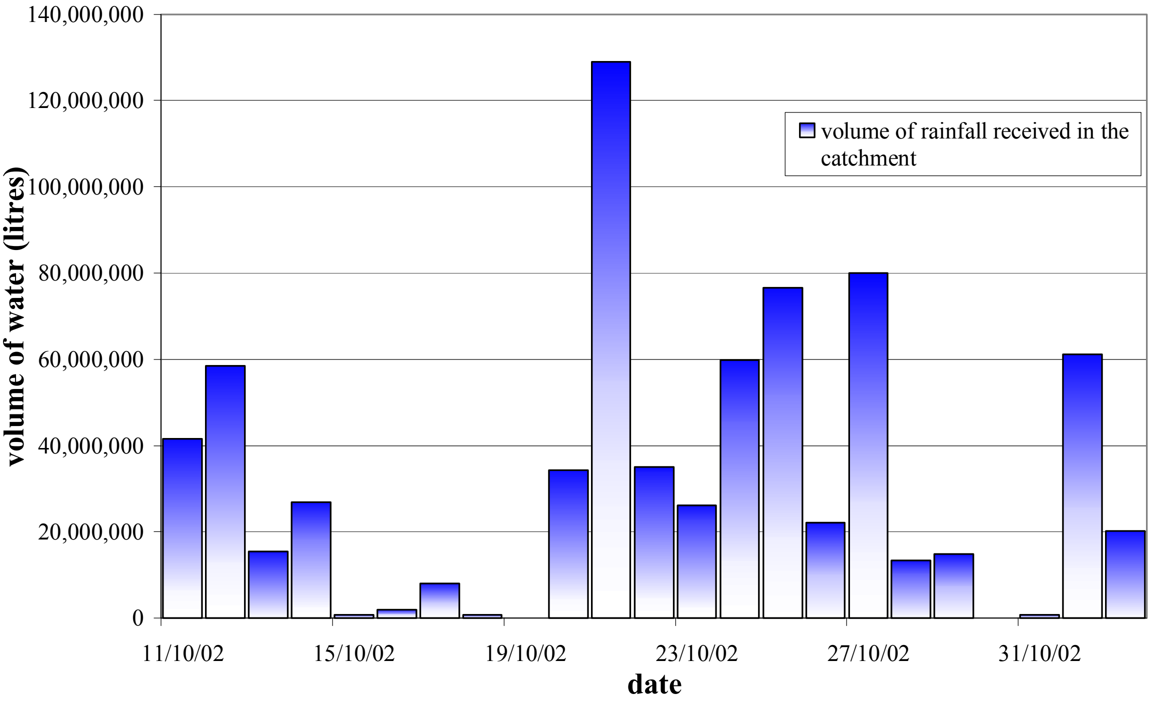


Figure 6.1 shows the volume of water received in the entire catchment each day during the three week period.

The maximum volume of water received in the Grainsgill Beck catchment, during the three week period, was 129,024,000 litres. Throughout this period the total water received in the catchment was 727,104,000 litres, which gives a daily mean of approximately 31.6 mega litres.

6.4 Discussion of the discharge data site 1, the Mine Adit

6.4.1 Discussion of discharge data

Monitoring of discharges at site 1 was carried out for the three week period; the data collected is displayed above in section 5.3.1. By looking at this data it is possible to see that for the first nine days of monitoring discharges remained constant at 7.7 l/s, as rainfall increased the discharge from the Mine Adit also increased, the response appears to be instantaneous. The rainfall then decreased and in response the discharge at the Mine Adit fell. Finally the discharge increased until it twice peaked at 14.5 l/s, firstly on the 26th October and then on the 28th October; rainfall follows a similar pattern.

By studying figure 5.12 above, which shows the discharges from the Mine Adit over the three week period, it is possible to see a similar trend between the recorded rainfall levels at the catchment and the discharges from the Mine Adit. Originally it was believed that discharges from the Mine Adit would reflect the pattern of rainfall but would be heavily damped due to the slow movement of water through the subsurface and into the stream; however it is clear that this is not the case. There are two possible reasons that will be discussed here for this rapid response of discharges in the Mine Adit to fluctuations in rainfall.

Firstly, once the Mine Adit surfaces it flows overland for approximately 50 metres. Initially it flows over reasonably flat ground before the gradient increases; whilst on this flat land there is a relatively large area of ground, which drains towards the Mine Adit, and so could act as a source for the stream. If this area were large enough the effect of new rainfall could be superimposed on top of the steady level of water being discharged from underground, thus providing the sharp peaks.

If this were the sole reason for the fluctuations in discharges from the Mine Adit days when no rain fell would always produce a similar discharge. This discharge would remain fairly constant through time, due to the underground source of the Mine Adit being insulated and damped from the fluctuations in rainfall. It can be seen from figure 5.5 that on the two days when no rainfall was observed the discharges in the Mine Adit did not drop to the same level and so it is unlikely that this is the only explanation for discharges varying so greatly in the Mine Adit.

The second reason that might explain why the Mine Adit displays such a swift response to rainfall could be the rapid release of “old”, stored water from the subsurface into the stream. If the response of the Mine Adit to rainfall is caused by the release of “old” water, contained within the soils and rocks, there must be some mechanism allowing subsurface water to travel quickly into the stream. One such mechanism could involve the propagation of a pressure wave through the subsurface, i.e. as “new” water arrives at the surface and percolates into the capillary fringe “old” water must be displaced further down slope in order to make space in the soil (Hornberger *et al.*, 1998). It is plausible that the displacement of “old” water is occurring along all the tunnels and mining shafts that lead into the Mine Adit; if this were the case the volume of water being displaced could be huge and may therefore account for the sharp fluctuations in discharge from the Mine Adit.

To test whether “old” water accounts for the increased flow in the Mine Adit during rainfall events it may be possible to measure the chemical composition of the water at regular intervals throughout a storm. Prior to the storm occurring, the water in the Mine Adit would have a certain chemical signature, which would differ from rainfall entering the catchment. The identification of a natural tracer within the two separate water sources means that the portion of “old” and “new” water being discharged from the stream may be calculated at any time throughout the storm.

Although it is difficult to ascertain the origin of water within the Mine Adit, and therefore determine whether overland or subsurface flow is the dominant processes affecting the response of the stream to rainfall, it does appear that there is a relationship between rainfall and discharge from the Mine Adit. To check whether this relationship actually existed and to see if it would be possible to model the response of the Mine Adit to rainfall, some rainfall runoff modelling was carried out using the TFM package, which is described in appendix D.

6.4.2 Rainfall runoff modelling using the TFM package

Using the rainfall data collected for the Grainsgill Beck catchment and the discharge data collected for site 1, the Mine Adit, some rainfall runoff modelling was carried out. The aim of this modelling exercise was to prove that there is a relationship between rainfall and discharge at the Mine Adit. The rainfall and discharge data were input into the TFM package and the program was run, this produced a graph showing the rainfall and discharge at each time step and is shown in figure 6.2.

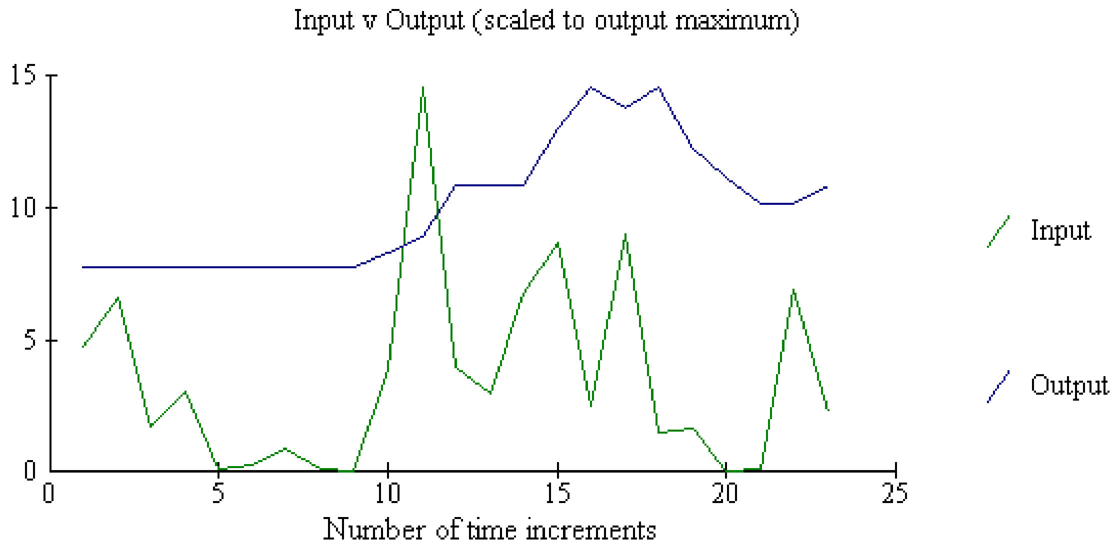
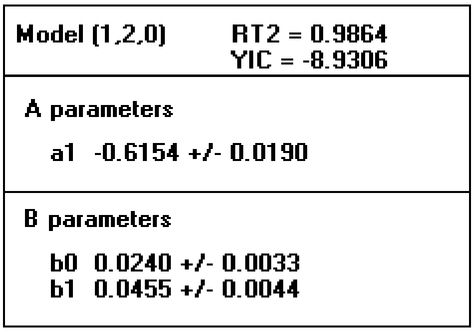


Figure 6.2 shows the rainfall input and discharge output of the Mine Adit calculated using the TFM package.

The TFM program utilises a lumped transfer function approach to produce a linear model of the response of a stream to rainfall input. As explained in appendix D there are two types of nonlinear transformation that may be made to the input data; these transformations are required in order to produce an effective rainfall, which may be more linearly related to the output than the original input (Beven, 2001). By making repeated runs of the model it was found that the optimum results were obtained by using the bilinear power transformation, the value being 0.55.

Once the input data was sufficiently transformed the model was identified in order to find the optimum model structure, i.e. the number of a and b parameters and the number of time delays. The model structures are ranked in order of the Young Information Criteria, the more negative the YIC the better the estimations of the parameters. The chosen structure has one a parameter, two b parameters and no time delays. The estimated values of these parameters are shown below in table 6.1.



```
Model (1,2,0)       RT2 = 0.9864
                    YIC = -8.9306

 A parameters

   a1  -0.6154 +/- 0.0190

 B parameters

   b0  0.0240 +/- 0.0033
   b1  0.0455 +/- 0.0044
```

Table 6.1 shows the estimated values of the a and b parameters. The YIC and RT^2 values are also shown.

The YIC value is shown above and is -8.9306; this is a low value and therefore implies that the a and b parameters quoted are well estimated.

The transfer function was then plotted to check for any negative values or oscillatory behaviour. The transfer function, which is shown in figure 6.3, should rise sharply to a peak and then fall exponentially back to zero. It can be seen by examining figure 6.3 that the transfer function used here has an acceptable shape with no negative values.

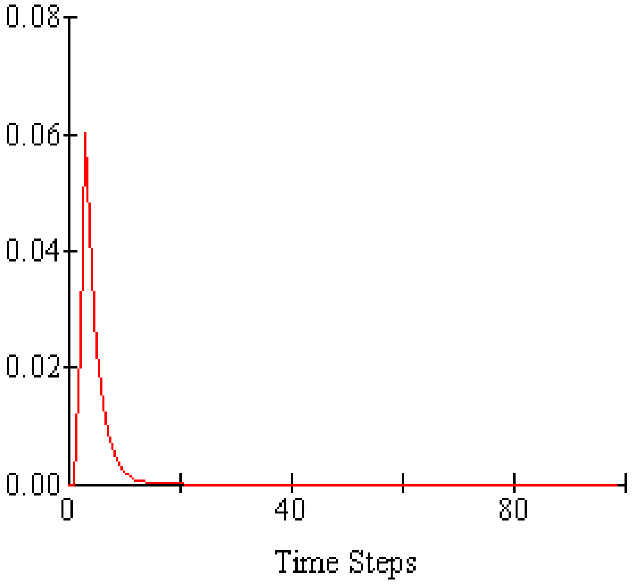


Figure 6.3 shows the transfer function of the model used.

Finally, the actual response of the Mine Adit to rainfall can be compared to the modelled response. The two responses are not exactly the same, otherwise the RT^2 value would be 1, they are however very similar. Both the modelled response and the actual response to rainfall can be seen in figure 6.4.

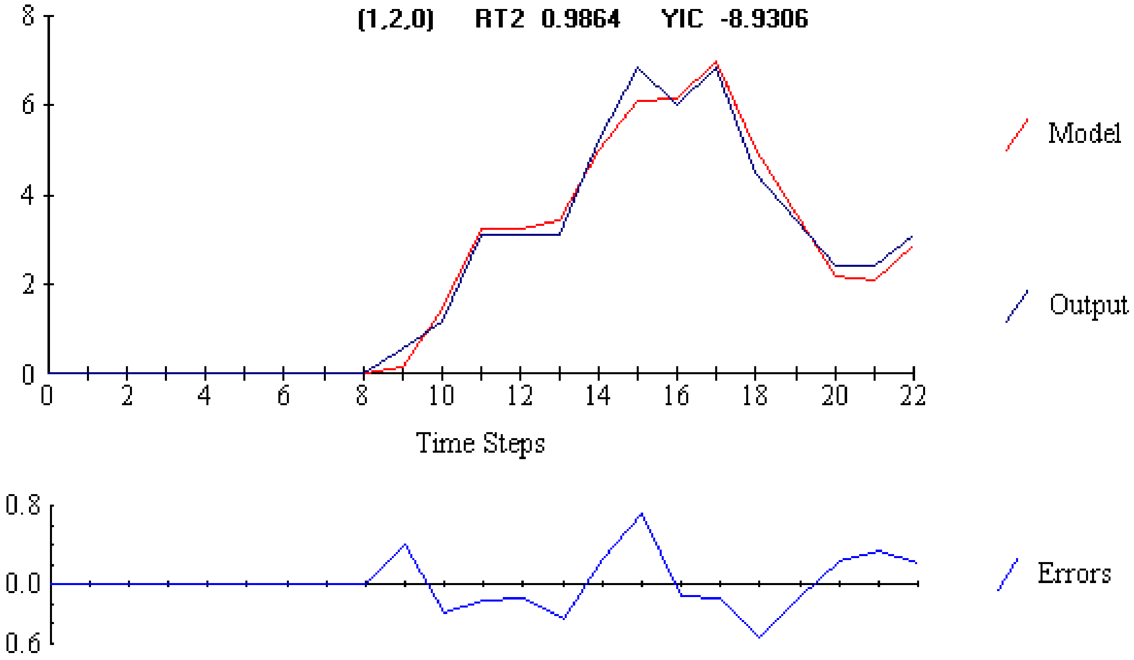


Figure 6.4 shows the modelled and actual response in the Mine Adit to increases rainfall, a plot of the observed error series is also included.

The modelled response and the actual response to rainfall are very similar; this can be seen by the close proximity of the two data series in the above figure. The largest error is approximately 0.8 units, which occurs at the first peak in discharge on the fifteenth time step.

The propinquity of both the actual and modelled response of the Mine Adit to rainfall implies that there is a direct relationship between rainfall into the Grainsgill Beck catchment and discharge out of the Mine Adit. If the modelled response produced larger errors, so that the two responses were very different, it would be unlikely that there was a direct relationship between rainfall in the Grainsgill Beck catchment and discharge out of the Mine Adit.

Using the TFM package it has been shown that it is possible to model the Mine Adits response to rainfall; in order to obtain greater levels of accuracy with the results of this model it would be necessary to validate the model, to do this more rainfall and discharge data must be collected.

6.5 Discussion of the discharge data site 2, the bridge in Grainsgill Beck

Discharges were collected at the bridge in Grainsgill Beck on four days during the same three week period. These discharges were then plotted on a graph with the discharges from the Mine Adit; this can be seen in figure 5.12. The data collected suggests that the discharges at the bridge in Grainsgill Beck rise to a peak of 420 l/s on the 25th October and then fall off again; this high value of discharge is subject to some very low uncertainties.

As explain above in section 6.2.2, the low confidence limits in the stage discharge relationship for the bridge in Grainsgill Beck, at the upper discharge range, means that the high discharge value recorded on the 25th October must be treated with caution. Using the stage discharge relationship developed in section 5.1.2 it is possible to calculate the range of discharges that are possible at the 95% confidence limits. This range was calculated as 180-640 litres per second, which is very large.

The small amount of discharge data for the bridge in Grainsgill Beck makes it difficult to make any conclusions about the response of the stream to fluctuations in rainfall. In order to make more distinct decisions as to the processes affecting the response of Grainsgill Beck and the Grainsgill Beck catchment to variations in rainfall levels more data would be required at more regular time intervals.

7.0 Conclusions

Following this study into the stream flow processes in the Grainsgill Beck catchment some useful conclusions may be made as to the affect that mining in the region has had on these processes. It is clear that mining in the catchment has and is having a major role on the hydrology of the area; the underground exploration has lead to the formation of the Mine Adit, which has been the focus of this study. The following points summarise the results and conclusions of this study:

1. A small weir was successfully constructed in the Mine Adit, site 1, in order to provide the necessary conditions under which a stage discharge relationships would operate. This long term stage discharge relationship, which yields very accurate and precise results, enabled a continuous record of discharges to be collected from the Mine Adit.

2. A stage discharge relationship was successfully developed at site 2, the bridge in Grainsgill Beck. Once again this allowed the collection of discharge data. Whilst stages remain low the accuracy of the calculated discharges were high, however once the stage increases beyond 0.25 metres the confidence in the calculated discharge becomes so low that values must be treated with caution.

3. The event characteristics of the Mine Adit show that this is a very flashy stream. It was found that fluctuations in precipitation levels lead to a very rapid and an almost instantaneous response in discharge from the Mine Adit.

4. Rainfall runoff modelling of the response of the Mine Adit, using the TFM package, showed that it is possible to model changes in discharges from the Mine Adit; it also showed how neat the relationship is between rainfall into the catchment and discharge from the Mine Adit.
5. It is likely that during a rainfall event “old” water is displaced in the extensive underground mine workings by “new” rainfall water

arriving at the surface. This process may then account for the flashy response of the Mine Adit.

6. Discharges at site 2, the bridge in Grainsgill Beck were found to increase with precipitation but seem to peak several days after the start of the rainfall event. This delayed response may be due to the natural lag time of the catchment. However a lack of data makes it difficult to conclude any further as to the response of Grainsgill Beck.

Following this project there are several other areas of work, which may be developed to help further understand the processes operating in the Grainsgill Beck catchment. Such studies could include:

1. The seasonal variation of discharges at site 1, the Mine Adit. This would also provide more data for the runoff modelling package.

2. A study into the chemical fluxes in the Mine Adit and rain water during a rainfall event. By completing this study it may be possible to make a more definite conclusion as to the origin of the increased water in the Mine Adit; be it “new” or “old” water.

3. The expansion of the stage discharge relationship at the bridge in Grainsgill Beck. This would require several stage and discharge measurements to be made under high flow conditions.

4. Using the stage discharge relationships developed as part of this study collect several data sets for both sites. This would involve more frequent measurements to be made at site 2, the bridge in Grainsgill Beck.

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Acknowledgments

My thanks go to all the people who have helped me throughout both the practical and report writing sections of this project;

Firstly, a big thank you belongs to Dr Andrew Binley for his guidance and help with all aspects of the work. Jonny Conning, Helen Dix and Pete Barnes also deserve my thanks for help with the many trips up to the Grainsgill Beck catchment. Also for the use of the hydrology labs during the testing of the weir thanks must go to Charles Blakely. Without Dalemain Estates approval the construction of the weir would not have been allowed and so thank you for that.

Finally I must thank my girlfriend, friends and family who all pitched in and helped carry around half a ton of concrete up a hill side in the Lake District, cheers guys.

Appendix A -

Expected stages for a V-notch weir with an angle equal to 53˚8’.

Selecting the correct notch angle of a V-notch weir is important as to narrow an angle will result in the weir becoming submerged whilst to wide an angle will make the weir indifferent to changes in discharge. The notch angle chosen for the weir in the Mine Adit was set at 53˚8’. Discharges have been calculated for this notch angle through a range of stage heights and are displayed in the British standard BS 3680: Part 4A (1981) in table 2; an extract of this table is shown below in table A.1, the values have been converted into litres per second as these were the units used in this project. The number of significant figures given for discharge does not imply a corresponding accuracy in the knowledge of the value given.

Stage (cm)	Discharge (l/s)
5	0.406
6	0.637
7	0.932
8	1.296
9	1.734
10	2.249
11	2.847
12	3.592
13	4.302
14	5.166
15	6.130
16	7.192
17	8.358
18	9.629
19	11.010
20	12.506
21	14.115
22	15.844
23	17.695
24	19.668
25	21.772
26	24.005
27	26.363
28	28.863
29	31.499
30	34.268
31	37.177
32	40.241
33	43.451
34	46.810
35	50.313
36	53.967
37	57.780
38	61.747

Table A.1 shows discharges for a V- notch weir, with notch angle 53˚8’, through a range of stages.

Appendix B -

Scale plans of the weir design

Instead of trying to follow the specifications for a thin plate weir, detailed in the British Standards (BS 3680, 1981), it was decided that greater accuracy would be achieved by constructing a weir that could be calibrated separately using field measurements. The plans for this weir are shown below.

Firstly the thin plate weir itself; this was constructed using 3mm think stainless steel, the dimensions are shown on the diagram below figure B.1

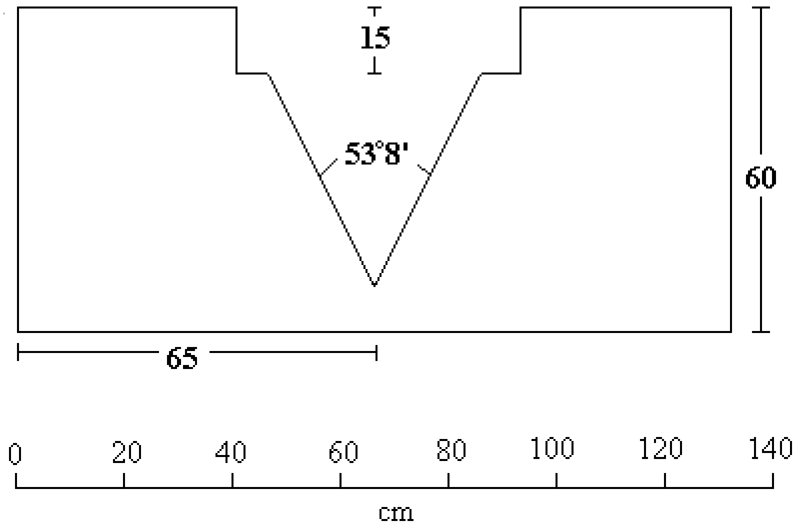

Figure B.1 shows the plan of the thin plate compound weir. All measurements are in centimetres.

The edge of the notch had to be bevelled on the down stream side to an angle of 45°; this was to ensure that the point where critical flow occurred did not travel either up or downstream as the discharge varied. If the crest of the weir plate is too wide the point of critical flow will migrate up and downstream depending upon the magnitude of the discharge. If the crest of the weir is bevelled to a knife edge the nappe will not fully develop and some water will run down the face of the weir.

The thin plate weir was held in place using two concrete walls; the walls also confine the flow, channelling the water over the weir. These walls needed to be strong enough to withstand the force of the water but not so large as to be unsightly to passers bye. For this reason it was estimated that walls 30 centimetres thick would contain the water and would not be a visual eye sore. The diagram (figure B.2) below shows the two concrete confining walls as well as the concrete skirt, which was laid around the base of the weir. The role of this skirt was to create a water tight seal with the ground; it also provides rigidity to the structure as a whole.

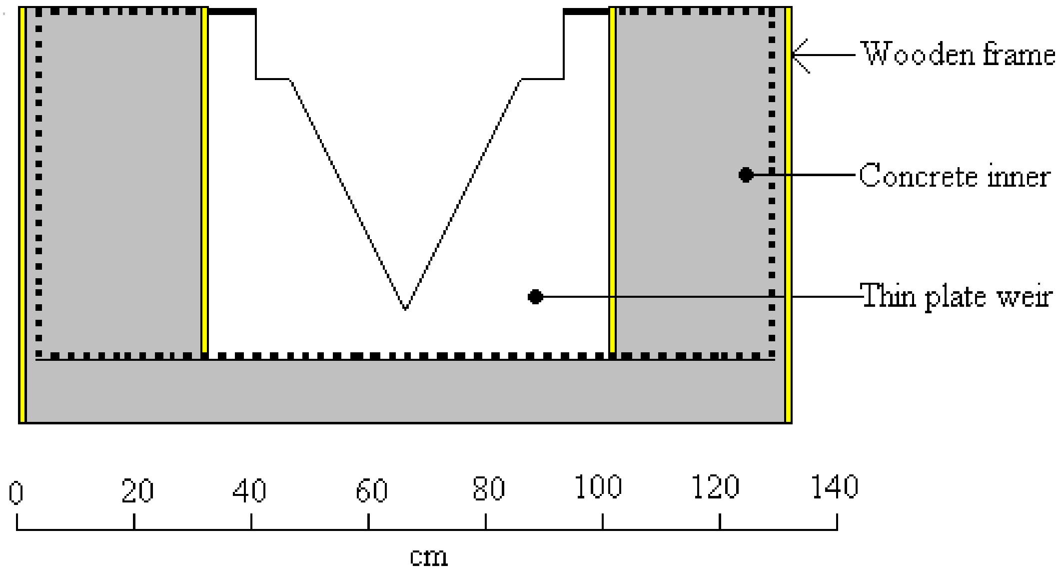

Figure B.2 is a diagram showing a view of the front of the weir, the concrete walls and skirt can be seen to secure the thin plate in place. The wooden frame was removed when the concrete is set.

The final weir can be seen in figure B.3, the length of the concrete walls was approximately 1.5 metres. If the concrete walls were not long enough there was a risk that subcritical flow would not occur, once again the visual impact also had to be considered.

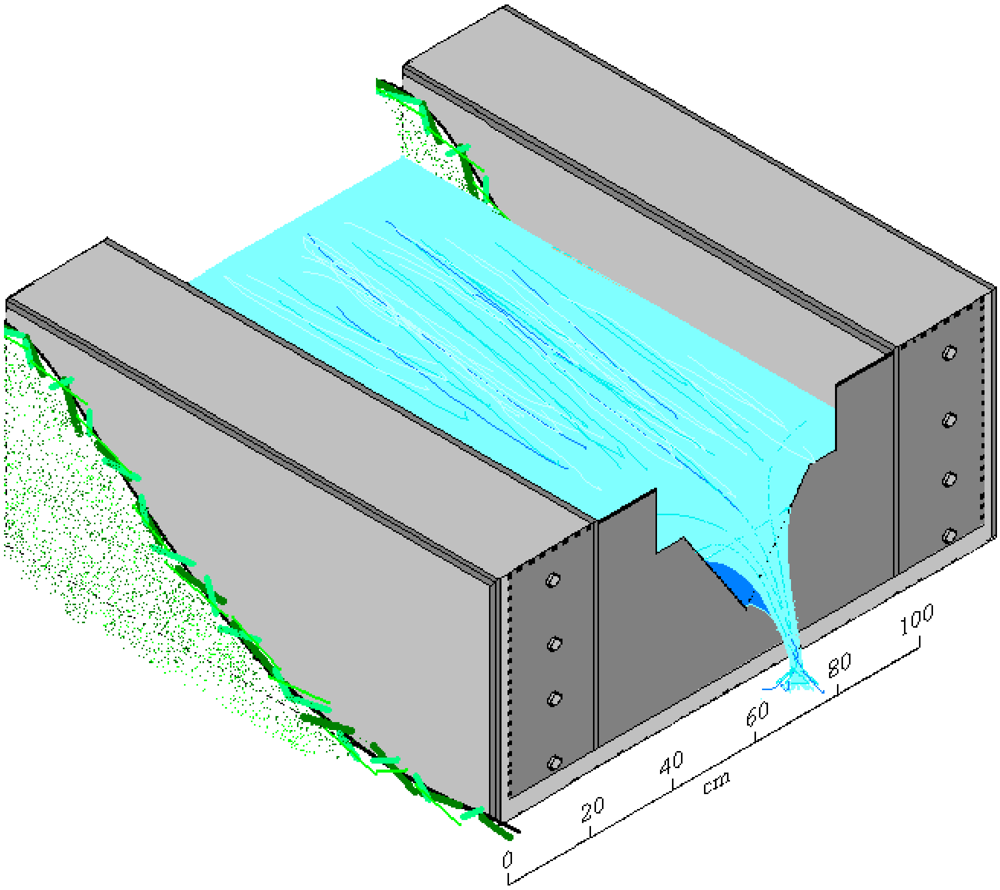

Figure B.3 a diagram showing the appearance of the final weir design, the length of the concrete walls can be measured from the scale bar.

Appendix C -

Calibration data for the stage discharge relationships at sites 1 and 2

To create the stage discharge relationships at the weir in the Mine Adit and the bridge in Grainsgill Beck accurate measurements of stage and the corresponding discharge had to be made. It is recommended that at least 12 measurements are made within the desired range of stage and discharge (BS ISO 1100-2, 1998). For site 1, the weir in the Mine Adit, all of these calibration measurements were made during the course of this project, these are shown below in table C.1.

Stage (cm)	Volume (l)	Time (sec)	Discharge (l sec-1)	Mean Discharge (l sec-1)
3	0.75	6	0.13	**0.14**
	0.80	6	0.13	
	0.75	5	0.15	
	0.70	5	0.14	
	0.77	5	0.15	
6.5	3.85	5	0.77	**0.78**
	3.90	5	0.78	
	3.90	5	0.78	
	3.85	5	0.77	
10	4.90	2	2.45	**2.24**
	6.45	3	2.15	
	6.30	3	2.10	
	6.65	3	2.22	
	4.60	2	2.30	
12	18.50	5	3.70	**3.78**
	19.00	5	3.80	
	20.00	5	4.00	
	18.00	5	3.60	
13	21.60	5	4.32	**4.30**
	21.80	5	4.36	
	21.10	5	4.22	
15.5	32.50	5	6.50	**6.65**
	33.50	5	6.70	
	33.75	5	6.75	
16	36.10	5	7.22	**7.29**
	38.00	5	7.60	
	35.20	5	7.04	
16	21.90	3	7.30	**7.19**
	21.63	3	7.21	
	21.19	3	7.06	
16.5	38.00	5	7.60	**7.37**
	36.00	5	7.20	
	36.50	5	7.30	
17	33.20	4	8.30	**8.35**
	33.90	4	8.49	
	33.00	4	8.26	
18	27.60	3	9.20	**9.63**
	29.25	3	9.75	

	29.82	3	9.94	
19	34.00	3	11.33	**11.56**
	36.00	3	12.00	
	34.00	3	11.33	
20.5	38.00	3	12.67	**12.58**
	37.20	3	12.40	
	38.00	3	12.67	
23	34.70	2	17.35	**17.69**
	35.60	2	17.83	
	35.80	2	17.90	

Table C.1 shows the calibration data collected for the stage discharge relationship at site1, the weir in the Mine Adit

The calibration data used to create the stage discharge relationship at site 2, the bridge in Grainsgill Beck, was collected by Buist (1998), Conning (2002) and Lancaster University field courses (1998, 1999 and 2000). This can be seen in table C.2

DATA POINT	Stage (m)	Discharge (l/s)
1	0.35	681.9
2	0.2	291.5
3	0.21	250.0
4	0.26	204.3
5	0.22	193.5
6	0.21	192.9
7	0.18	182.2
8	0.21	172.8
9	0.17	164.3
10	0.16	162.8
11	0.15	153.7
12	0.22	143.9
13	0.18	140.7
14	0.18	139.6
15	0.16	126.7
16	0.18	112.6
17	0.14	106.2
18	0.12	105.8
19	0.12	105.1
20	0.16	97.1
21	0.16	96.8
22	0.135	79.4
23	0.125	71.9
24	0.13	67.2
25	0.11	62.1
26	0.1	61.1
27	0.105	58.6
28	0.08	55.6

29	0.08	53.5
30	0.08	52.4
31	0.1	51.4
32	0.105	50.8

Table C.2 shows the calibration data used to construct the stage discharge relationship for site 2, the bridge in Grainsgill Beck.

Appendix D -

The TFM rainfall runoff modelling package

Using the discharge data collected for site 1, the weir in the Mine Adit, and the rainfall data collected for the catchment, it was possible to do some rainfall runoff modelling using the TFM or transfer function model package. This program is described by Beven (2001), what follows is a brief description of the program.

The TFM program is used for the analysis of rainfall and discharge data based on transfer function model concepts which are described in Beven (2001). Two data files are loaded, the input and output, which must be of equal time intervals. The input data file must then be transformed by one of two non linear methods; the purpose of this transformation is to create an effective rainfall series, which may be more linearly related to the output than the original rainfall input. Thee two nonlinear transformations are:

1. *Bilinear Power Model* The Bilinear Power Model uses the current discharge as an index of antecedent moisture status of the catchment and transforms the input according to:

   $$U(t) = R(t)\ Q(t)\text{^}n$$

   where n is the power coefficient. When $n = 0$, then the rainfall $R(t)$ alone is used as the effective rainfall variable. When $n = 1$, the effective rainfall is equal to $R(t)Q(t)$ and the model is a simple bilinear model. n normally lies between these two extremes, Beven (2001).

2. *Storage Model* The Storage model input transform updates a soil moisture index S at each time step.

   The effective rainfall is calculated from:

   $$U(t) = S(t)R(t)$$

   S is updated according to:

   $$S(t) = S(t-1) + \{R(t) - S(t-1)\}/Ts$$

   where Ts is a time constant, Beven (2001).

Once the input data has been suitably transformed the most suitable model structure may be chosen. The model may have a number of a parameters, a number of b parameters and a number of time delays. The various combinations of models are evaluated by the program, the model structures are then ranked according to their Young Information Criteria value or YIC. The YIC combines a goodness of fit between the modelled and observed data as well as how well the model parameters are estimated. The RT^2 is also quoted; this describes how well the modelled and observed data series fit together. The model structure with the most negative YIC should be used, this is usually simple, typically with one a and b parameters only.

Once the desired model structure has been chosen the estimate option is used to plot the model, plot the transfer function or to validate the model. Validating the model allows the model to be tested against a new data set.