ASSESSMENT OF THE IMPACT OF GAUGING WEIR LIMITATIONS ON THE ESTIMATION OF FLOOD PEAKS AND ON DESIGN FLOODS

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Submitted in partial fulfilment of the requirements
for the degree of MSc. Engineering

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8/6/2014

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ABSTRACT

Data from flow gauging stations in South Africa are used in the design of hydraulic structures, riparian developments, hydrologic modelling, water resource assessments and management. However, these flow gauging structures are regularly overtopped and the stage-discharge relationships do not always extend to the stages associated with extreme events. This is problematic when using the discharge data for design, planning and management purposes. It is therefore important for the flow gauging network to be able to estimate discharge under all flow conditions.

At flow gauging weirs the relationship between stage and discharge is used estimate discharge from the recorded stage measurements. The stage-discharge relationship is not static and it is important to keep note of the changes to this relationship and to adjust it accordingly.

There are limitations to rating curves which impacts on the estimation of flood peaks as well as design floods. For design and management purposes it is desirable to extend rating curves so better estimations can be attained. It is proposed that by using hydraulic principles as well as available stage-discharge data, and taking into account the associated uncertainties, it is possible to extend the rating curves.

The purpose of the proposed study will be to develop a desktop method to extend rating tables at flow gauging stations across South Africa using historical data. This will be done using accepted discharge equations for both modular and non-modular flow conditions. These equations require both upstream and downstream stage values. For this purpose it is necessary to attain a relationship, for varying weir types, representative of the energy loss which occurs between the upstream and downstream stage measurement points. This relationship can then be applied to flow gauging weirs which do not have a downstream stage measurement point such that a theoretical downstream stage can be estimated.

The model developed through this will enable the estimation of the discharge associated with extreme events which exceed the stage-discharge relationships currently in use. This will contribute towards better hydraulic design, hydraulic modelling and water resource planning.

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1. INTRODUCTION

Discharge data is used extensively in the design of hydraulic structures, riparian developments, modelling, water resource assessments and decision making (Guven and Aytek, 2009). The lack of discharge data related to extreme events may lead to an inadequate design, resulting in economic loss or the possible loss of life (Smithers *et al.*, 2007). When measured discharge data are not available at the site of interest, then regional methods or rainfall-runoff models have to be used for design flood estimation (Smithers *et al.*, 2007). Therefore, accurate and extensive data on discharge is of the utmost importance especially in a dry country such as South Africa (Wessels and Rooseboom, 2009a). In South Africa it is the mandate of the Department of Water Affairs (DWA) to develop and maintain a network which is capable of recording hydrometric data (Wessels and Rooseboom, 2009a).

Discharge can be estimated using either direct or indirect methods. Owing to practical reasons, particularly in South Africa, it is not always possible to measure discharge directly (Wessels and Rooseboom, 2009a). Therefore it is necessary to develop and maintain a gauging network which uses both direct and indirect methods. Flow gauging weirs form a significant part of such a network. Discharge at a flow-gauging weir is determined through the use of a stage-discharge relationship. Typically flow-gauging weirs will experience both modular and non-modular flow, for which there are discharge equations. Modular flow is defined as flow over a weir which is not affected by the downstream water level, whereas non-modular flow is affected by the downstream water level (Wessels and Rooseboom, 2009a). For cost and environmental reasons weirs are not designed to accommodate all flows.

Data measured at a gauging station is used to develop a stage-discharge relationship. This relation is often referred to as a rating curve or table. The relationship is established by measuring discharge, where possible and using a direct method, and stage over a period of time (Chow *et al.*, 1988). However, in South Africa rating curves at flow-gauging weirs are calibrated by recording stage and calculating a discharge using suitable equations (Wessels and Rooseboom, 2009b). To attain an accurate relation it is necessary to conduct measurements of stage over a long period of time. The resulting relationship is unique and makes it possible to determine a discharge if only stage is recorded. In some cases the rating curve is limited to a certain discharge, even though larger events have occurred. This is due to a number of reasons including the practical and safety issues associated with recording extreme events using a direct method and also due to inundation or flooding of flow-gauging weirs (Lang *et al.*, 2010). The results obtained from a discharge data series can be misleading if the errors associated with it are not taken into account (Lang *et al.*, 2010). This and other limitations have been addressed in numerous studies which use various methods to extend rating curves. Examples of such studies were conducted by Leonard *et al.* (2000), Fenton and Keller (2001), Petersen-Overleir (2006b).

Owing to the unstable nature of natural waterways, the stage-discharge relation is likely to change over time (Westerberg *et al.*, 2011). Typically temporal variables include changes in cross sectional shape of the waterway due to erosion, deposition or vegetation growth. Therefore, the stage-discharge relation must be updated when the values attained are no longer deemed acceptable. This may be a costly and time consuming activity. A site where the stage-discharge relation is likely to remain acceptable for a long period of time is desirable.

The objectives of this document are to:

a) Assess the process used to develop a stage-discharge relationship.
b) Assess the various uncertainties associated with rating curves.
c) Provide an overview of methods which have been used to extend rating tables.
d) Present a project proposal for the development of a desktop method to extend rating tables across South Africa.

This study does not encompass the design of gauging structures. Instead the goal of this project is to develop a method, using available data, which can be used to extend rating curves beyond the current ratings. Chapter 2 contains a discussion on the importance of a gauging network in terms of the collection of hydrometric data and the most common weir types used in South Africa. Chapter 3 provides an overview of the development of a stage-discharge relation and the associated uncertainties, both broadly and in a South African context. Chapter 4 contains a discussion of methods used to extend rating tables. It includes a discussion on associated errors related to the extension of a rating table, especially under non-modular flow conditions. Chapter 5 provides a discussion of the literature examined as well as the conclusions drawn from the literature review. Chapter 6 contains a brief project proposal for the development of a desktop method to extend rating curves.

2. DISCHARGE DATA

Discharge data is measured using a flow gauging network which is developed and maintained by the Department of Water Affairs (DWA) in South Africa. The most common means of measuring discharge data is the use of a flow gauging weir. This data is extensively used extensively for the purposes of design, planning and management. Discharge data is used by design engineers and hydrologists in the design of hydraulic structures, hydraulic modelling and decision making with respect to water resources. Without adequate discharge data the design of a hydraulic structure may be inadequate leading to economic loss as well as the potential loss of life (Smithers *et al.*, 2007). Discharge data is an important input into hydraulic modelling used for decision making as well as water resource planning. If there is no measured discharge data available it may be necessary to use rainfall-runoff models to estimate design discharges (Smithers *et al.*, 2007). Regional methods of determining flood

2.1 Flow Gauging Networks

To collect discharge data it is necessary to introduce a structure which can control flow and introduce stability to a channel section. Examples of such structures include flow gauging weirs, which are designed in varying configurations, bridge contractions and dam spillways (Van Bladeren and Burger, 1989). The most common method of determining discharge is to continuously measure stage at a point and convert it to a discharge using a stage-discharge relationship (Petersen-Overleir, 2006a). Uses for discharge data include the design of flood protection, design of hydraulic structures, water resources planning and for modelling purposes (Burnham and Davis, 1990; Fenton and Keller, 2001; Guganesharajah *et al.*, 2006; Petersen-Overleir and Reitan, 2009). It is therefore important to develop operations and a gauging network which are capable of recording discharge data accurately and continuously. If such a network is not in place, efforts to improve flood estimates, flood forecasting, provision of flood warnings and water management planning may be limited (Lumbroso and Gaume, 2012).

In South Africa it is the mandate of the DWA to develop and maintain a gauging network (Wessels and Rooseboom, 2009a). Flow gauging-weirs are a major constituent of a gauging network. The biggest advantage of these structures is that they can be calibrated prior to construction (Wessels and Rooseboom, 2009a). According to Lambie (1978), a gauging station is defined as a site on a river which has been selected, instrumented and used to record raw data such that systematic records of stage and discharge can be derived. It consists of a suitable, stable natural or artificial flow channel cross-section where a continuous record of stage can be recorded and as a result the stage-discharge relation can be determined (Lambie, 1978). This relationship is unique to the gauging station of interest (Perumal *et al.*, 2004).

Once a structure has been calibrated it is desirable, as far as practically possible, to prevent any changes to the discharge characteristics at the station (Wessels and Rooseboom, 2009a). Natural changes due to erosion, sedimentation and vegetation growth can cause changes in the discharge characteristics at a gauging structure (Arcement and Schneider, 1989; Wessels and Rooseboom, 2009a). This makes it necessary to recalibrate a structure in order to develop a new relationship which is applicable to the new discharge characteristics. On average a weir should be recalibrated every five years (Wessels, 2014). However this is not always the case as it may be a costly and time consuming process. In South Africa, it may also be a difficult process due to the lack of funds and personnel to perform recalibration (Canto *et al.*, 2002). Once a stage-discharge relation has been determined for a gauging station it is only necessary to record stage. This can be done using pressure sensors, floats, staff gauges and needle gauges amongst others which are connected to a suitable recording device (Smoot, 1978).

In a relatively dry country with a variable climate, such as South of Africa, information on river flow is essential. However, measurements in South African rivers are complicated by the high variability in flows and high sediment and debris loads (Wessels and Rooseboom, 2009a). It has been necessary to compensate for this by modifying standard gauging station designs (Wessels and Rooseboom, 2009a). Therefore, weirs are constructed with numerous notches at varying heights, known as compound weirs, allowing for the accurate measurement of both low and high flows (Canto *et al.*, 2002). Sharp crested weirs and long-base weirs, *i.e:* broad-crested weirs, triangular profile weirs and ogee spillways, are the predominant weir types used in South Africa (Wessels and Rooseboom, 2009a). At the end of 2007 discharge was being gauged at 782 different locations in South Africa (Wessels and Rooseboom, 2009a). Of these 782 stations around 55% are constructed with sharp-crested weir components and 35% with Crump-weir crests (Wessels and Rooseboom, 2009a). The remaining 10% of sites consist of dams, broad-crested weirs and velocity-area gauging sites (Wessels and Rooseboom, 2009a). An area of concern for the DWA is the lack of funds and appropriate manpower to both operate and maintain the flow gauging system in South Africa (Lotriet and Rooseboom, 1995).

2.2 Weir Types

According to Wessels and Rooseboom (2009a) the most commonly used flow gauging structures used in South Africa to date include:

a) thin plate or sharp crested weirs,
b) broad crested weirs,
c) crump or v-crump weirs,
d) ogee weirs and
e) Parshall, hydro and sluicing flumes.

These structures provide an advantage in that their known geometry allows them to be pre-calibrated (Wessels and Rooseboom, 2009a). The typical thin plate weir condition has been modified in South Africa to make it better suited to use in rivers (Wessels and Rooseboom, 2009a). As shown in Figure 2-1 a piece of angle iron was introduced to the crest of a sharp crested weir (Wessels and Rooseboom, 2009a).

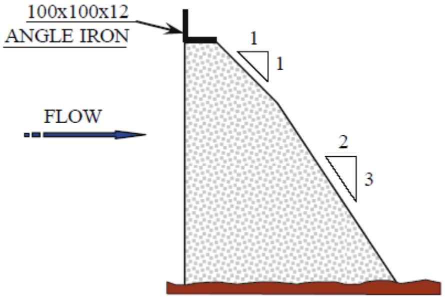

Figure 2-1 Typical cross section of a sharp crested weir (Wessels and Rooseboom, 2009a)

The most popular triangular shaped weir currently used worldwide is the crump weir, two varieties of which are depicted in Figure 2-2. Two main types of crump weirs exist, namely a horizontal (left in Figure 2-2) and v-shape crump weir (right in Figure 2-2). The v-shape crump weirs are generally only used in smaller stream which are known to carry little sediment (Wessels and Rooseboom, 2009a).

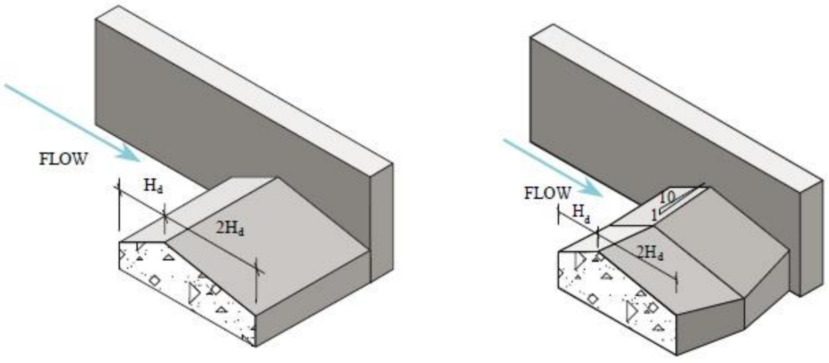

Figure 2-2 Horizontal and v-shape crump weir (Wessels and Rooseboom, 2009a)

In channels where it is desirable to introduce as little energy loss as possible, such as in an irrigation canal, flumes are generally used (Wessels and Rooseboom, 2009a). Typically, in a stream or river, sedimentation occurs upstream of a weir. To try limit sedimentation the DWA developed two flumes to use in conjunction with a flow gauging weir (Wessels and Rooseboom, 2009a). The calibration of such a structure is complex and is discussed by Bruce *et al.* (2002). The hydro flume (left) and sluicing flume (right) are illustrated in Figure 2-3 below.

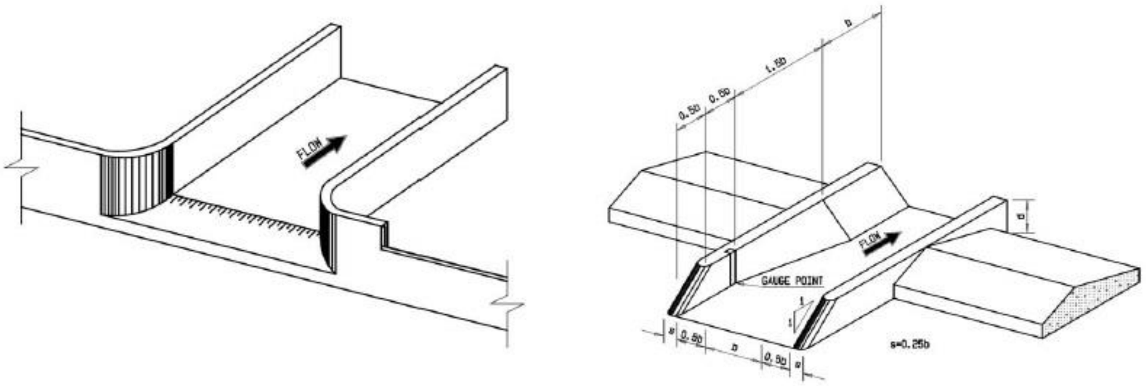

Figure 2-3 Hydro and sluicing flumes (Wessels and Rooseboom, 2009a)

Due to the large variability in flow experienced in South Africa it has been necessary to construct compound weirs, which are capable of gauging discharge accurately over a large range of flow depths (Wessels and Rooseboom, 2009b). A compound weir consists of individual weirs, either crump or sharp crested weirs, with different crest heights spanning the width of a stream or river (Wessels and Rooseboom, 2009b).

3. RATING CURVE DEVELOPMENT

Typically, stage is continuously recorded at a cross-section where the relationship between stage and discharge can be determined (Petersen-Overleir, 2006b). Therefore, weirs are constructed to introduce an artificial control. Where possible, both stage and discharge measurements are recorded at these structures. These recordings are used to determine the relationship between stage and discharge at the weir (Lambie, 1978). The values for discharge and their corresponding stage values, attained during the calibration, are plotted and a curve is fitted to the points. This stage-discharge relationship is often referred to as a rating table or curve. These curves are estimates of the true rating curve (Petersen-Øverleir and Reitan, 2009).

In order to develop an extensive rating curve it is necessary to use both direct and indirect methods of determining a discharge (Wessels and Rooseboom, 2009a). It is frequently not possible to record peak discharges using a direct method and therefore it is necessary to estimate a peak discharge using an indirect method (Barnes and Davidian, 1978; World Meteorological Organization, 2010). Some indirect methods which have been widely used are the slope-area, conveyance-slope method, step-backwater method and flood routing (Barnes and Davidian, 1978). Direct methods commonly used include the use of flow-gauging weirs and velocity-area methods (Wessels and Rooseboom, 2009a). The accuracy of this relation determines the accuracy of the discharge data attained from a gauging site (Petersen-Overleir, 2006b). An essential assumption with regards the stage-discharge relation is that a single discharge value is associated with each stage value (Guerrero *et al.*, 2012). This is complicated by the fact that hysteresis may occur during a flood, leading to different discharge values for the same stage (Fenton and Keller, 2001). Therefore, in an effort to attain an accurate relationship between stage and discharge, the recordings are taken over a long period of time (Chow *et al.*, 1988).

According to Chow *et al.* (1988) there are three areas of uncertainty when assessing a hydraulic and hydrologic system, viz. inherent properties of the system, the parameters used and the hydraulic models used. In their study, Guganesharajah *et al.* (2006) identify a fourth area of uncertainty which they state is related to statistics. Inherent uncertainties are related to the natural processes which occur over time. Processes such as erosion, deposition and vegetation growth fall under this category of uncertainty. For the purposes of this study, inherent uncertainties are discussed in further detail under temporal uncertainties. Parameter uncertainties are linked to the variable nature of parameters used in hydraulic equations (Guganesharajah *et al.*, 2006). Model uncertainty is related to the fact that it is difficult to fully interpret and express a hydrologic system and hydraulic processes using mathematical methods (Guganesharajah *et al.*, 2006). Finally, statistical uncertainties refer to the length of available records and the accuracy of the hydrometric data (Guganesharajah *et al.*, 2006).

3.1 Velocity-area methods

Velocity-area methods can be used to record discharge during an event. The velocity-area method entails the discrete integration of velocity over a channels cross-section (Le Coz *et al.*, 2012). Therefore, it is necessary to measure velocity during an event and also have access to the channels cross section. There are various methods of measuring velocity at a point. Charlton (1978) identified mechanical or rotor current meters. These meters are subjected to calibration processes, which has uncertainties associated with it, as well as repeatability tests (Charlton, 1978). These meters must be re-calibrated and serviced regularly as the accuracy of the meter changes with use. More recently the use of Acoustic Doppler Current Profilers (ADCP) has been used to measure discharge (Callede *et al.*, 2000). The DWA now prefers this method for their direct measurement of discharge (van der Spuy, 2014) It has been found that this method consistently underestimates discharge, therefore requiring a correction to be applied (Callede *et al.*, 2000). The inaccuracies associated with both the mechanical current meters and the ACDP are related to statistical uncertainties.

There are a number of difficulties associated with direct measurements. In their study Perumal *et al.* (2004) mention that it may be dangerous due to the velocities associated with the high flows. According to Perumal *et al.* (2004) it is difficult to record flood peaks which occur during the evening. In South Africa direct methods are not extensively used, Wessels and Rooseboom (2009a) list the following practical reasons:

a) logistical difficulties in that gauging sites are spatially dispersed and that the hydrological responses of catchments in South Africa are generally short,
b) a number of velocity-area sites need to be rated at the same time as events which cause high runoff to occur over extended areas,
c) access to sites, as a result of high intensity events, may be dangerous,
d) a lack of appropriately trained personnel to take the required readings, and

e) roughness and cross-section parameters vary during an extreme event.

The documentation of the 1987 floods in KwaZulu-Natal by Van Bladeren and Burger (1989) illustrates the above mentioned difficulties. Table 3-1 contains a summary of the number of measurements of flood peaks estimated for the 1987 floods using various methods. The table also shows the number of events, with a return period (T) of greater than 50 years, which were recorded using the different methods.

Table 3-1 Measurement methods used to estimate discharges during the KwaZulu-Natal 1987 floods (Van Bladeren and Burger, 1989)

Method of flow measurement	**Number of measurements**	**Number of flood peaks with T > 50 years**
Slope-Area	43	14
Weirs	44	5
Reservoir spillways	18	5
Bridge contractions	1	1

3.2 Weir Measurements

This section serves to discuss weir flow gauging and the requirements for accurate gauging, particularly for South African conditions. Measurements attained using a weir are considered a direct form of measurement as they provide a reading during an event. Choosing a site suitable for a weir can be a difficult process. In their study Wessels and Rooseboom (2009a) outline the criteria related to the three main components of a flow measuring station. This includes the approach channel, the downstream channel as well as the gauging structure itself. If the design criteria pertaining to each component are followed correctly, the hydrometric data attained from a gauging structure should be acceptable.

Modular flow conditions prevail when discharge over a gauging structure is not affected by the downstream water level (Wessels and Rooseboom, 2009a). Flow-gauging weirs are well designed to cope with these flows as they still act as a total control of the flow. To gauge accurately, it is necessary to ensure that atmospheric pressure occurs underneath the nappe, as is shown in Figure 3-1 which illustrates the ideal flow for gauging of discharge over a sharp crested weir.

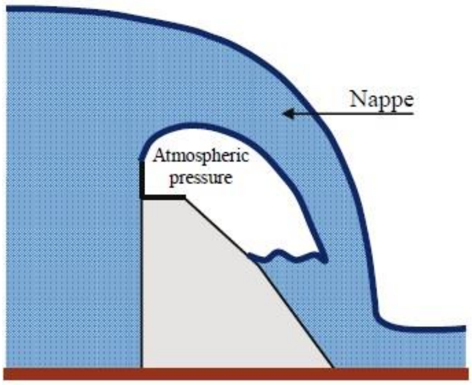

Figure 3-1 Flow over a sharp crested weir (Wessels and Rooseboom, 2009b)

An underestimation of the discharge will occur if sufficient ventilation is not supplied (Wessels and Rooseboom, 2009a). At certain flow-gauging weirs in South Africa it is possible to gauge both upstream and downstream stage. The location and requirements for the upstream measurement section for sharp-crested weirs and crump weirs differ. To ensure that the approach velocities are acceptable Wessels and Rooseboom (2009a) provide guidelines for the minimal upstream pool depth for crump and sharp crested weirs as well as flumes.

For crump weirs Wessels and Rooseboom (2009a) recommend that the upstream measuring section be placed twice the total design head (in meters) upstream of the weirs crest. The location of the downstream measurement section is the same for both crump and sharp-crested weirs. To locate the downstream measurement section Wessels and Rooseboom (2009a) recommend that the following equation is used:

$$\text{Distance downstream} = 10\,(Z + H_d) \tag{3.1}$$

where

$Z =$ mean crest height above the streambed (m).

This is necessary to ensure that the measurements are taken below the hydraulic jump which may occur during non-modular flows. Non-modular flow conditions prevail when the downstream water levels influence the discharge over a weir (Wessels and Rooseboom, 2009a). Figure 3-2 illustrates non-modular flow conditions over a crump weir.

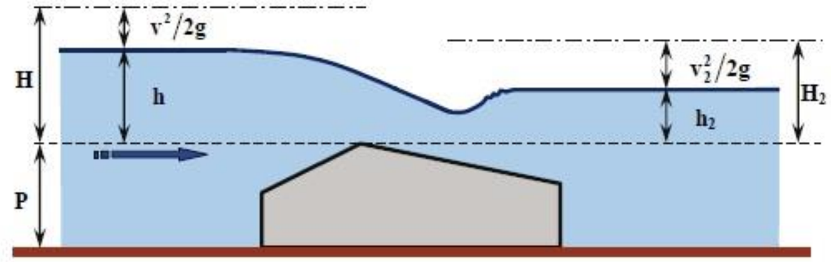

Figure 3-2 Non-modular flow over a crump weir (Wessels and Rooseboom, 2009b)

3.2.1 Weir calibration

Flow-gauging weirs can be pre-calibrated based on the shape and size of the weir being built. It is then necessary to only record stage at the weir. Rating curves at these weirs are then developed using the stage record in conjunction with the following modular and non-modular flow equations.

To determine discharge (Q), for a crump-weir, Ackers *et al.* (1978) developed the following equation:

$$Q \;=\; \mathrm{C_{de}}\, f\, \frac{2}{3} \sqrt{\frac{2}{3}\mathrm{g}}\, b\, \mathrm{H}^{\frac{2}{3}} \tag{3.2}$$

where

C_{de} = coefficient of discharge,

f = drowned flow-reduction factor,

b = width of the weir crest measured perpendicular to flow direction (m), and

H = total energy head upstream of the weir crest (m).

The coefficient of discharge can be calculated as follows:

$$C_{de} \;=\; 1.163\left(1 \;-\; \frac{0.0003}{h}\right)^{3/2} \tag{3.3}$$

where

h = stage relative to the weirs crest (m)

The drowned flow reduction factor relies on the submergence factor which can be calculated by dividing the total downstream energy (H_2) by the total upstream energy head (H). Total energy can be calculated by adding the velocity head to the stage relative to the weirs crest. Depending on the value of the submergence ratio, the flow reduction factor can be calculated as follows:

If $0.75 \geq H_2/H$ then

$$f = 1.00 \tag{3.4}$$

If $0.75 < H_2/H \leq 0.93$ then

$$f = 1.035[0.817 - \left(\frac{H_2}{H}\right)^4]^{0.0647} \tag{3.5}$$

If $0.93 < H_2/H \leq 0.985$ then

$$f = 8.686 - 8.403\left(\frac{H_2}{H}\right) \tag{3.6}$$

To calculate the discharge under non-modular flow conditions for sharp crested and thin plate weirs, Wessels and Rooseboom (2009b) recommend the use of an equation developed by the DWA. This technique requires that a comparable modular flow condition, with the same discharge, is created for the non-modular conditions (Wessels and Rooseboom, 2009b). It is then possible to use the modular flow equation to determine a discharge value, the procedure is set out by Wessels and Rooseboom (2009b) is detailed below. The process starts by considering modular flow conditions which are illustrated in Figure 3-3.

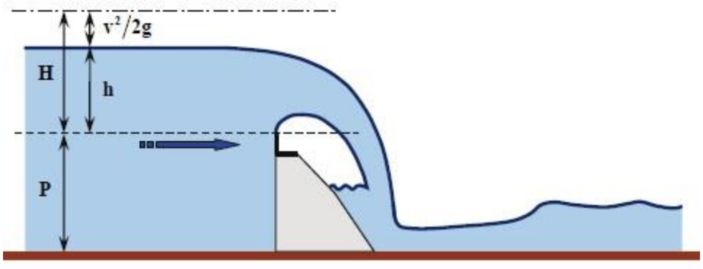

Figure 3-3 Modular flow over a sharp crested weir (Wessels and Rooseboom, 2009b)

The equations to calculate the discharge for thin-plate weirs are as follows:

$$Q = 1.777\ b\ C_p(H\ +\ 0.001)^{3/2} \tag{3.7}$$

where

$C_p =$ a coefficient.

The coefficient C_p was introduced by DWA to take into account a large range of total upstream energy heads (H) and pool depth (P) ratios. Depending on the H/P ratio the coefficient can be calculate as follows (Wessels and Rooseboom, 2009b):

If $H/P \leq 3.4$

$$C_p = 1.000 + 0.11\left(\frac{H}{H+P}\right)^{1.24} \tag{3.8}$$

If $3.4 < H/P \leq 200$

$$C_p = 1.145\left(\frac{P}{H+P}\right)^{0.04} \tag{3.9}$$

If $H/P > 200$

$$C_p = 0.926 \tag{3.10}$$

The DWA equations to calculate the discharge for sharp-crested weirs are as follows (Wessels and Rooseboom, 2009b):

$$Q = 1.61\ b\ C_p(H + 0.001)^{1.416} \tag{3.11}$$

If $H \leq 0.310$ m and $H/P \leq 3.40$

The coefficient, C_p, for the above mentioned conditions can be calculated using Equation 4.12 (Wessels and Rooseboom, 2009b):

$$C_p = 1.00\ +\ \left(\frac{0.35H}{H+P}\right)^{1.24} \tag{3.12}$$

Otherwise if $H > 0.310$ m the discharge can be calculated as follows:

$$Q = 1.777bC_p(H + 0.001)^{3/2} \tag{3.13}$$

The coefficient, C_p, in this case can be calculated using Equations 4.8, 4.9 and 4.10 depending on the *H/P* ratio. To calculate discharge under non-modular flow conditions, it is necessary to calculate an equivalent modular upstream head as suggested by Wessels and Rooseboom (2009b). Figure 3-4 illustrates non-modular flow over a sharp-crested weir.

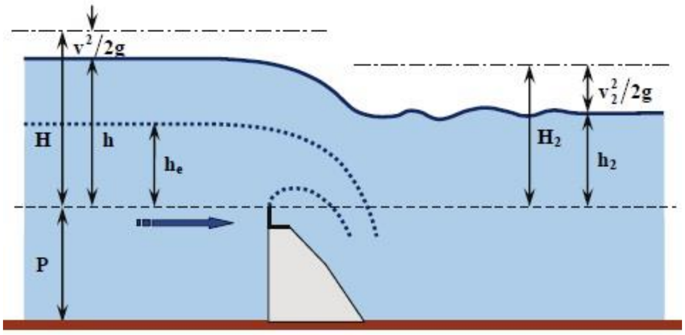

Figure 3-4 Non-modular flow over a sharp crested weir (Wessels and Rooseboom, 2009b)

$$\mathrm{h_e} = \frac{\mathrm{h}\sqrt{1-\left(\frac{\mathrm{h_2}}{\mathrm{h}}\right)^2}}{\alpha} \tag{3.14}$$

where

h_e = equivalent modular upstream head (m),

h =gauged upstream head in non-modular conditions,

h_2 =downstream gauged head relative to the crest of the weir (m), and

h_2/h =submergence ratio.

The coefficient α can be calculated as follows:

$$\alpha = \frac{-b+\sqrt{b^2-4c}}{2} \tag{3.15}$$

where

$$b = -0.3407 - 0.3062\left(\frac{h_2}{h}\right) \tag{3.16}$$

and

$$c = 0.6288\left(\frac{h_2}{h}\right)^2 + 0.1016\left(\frac{h_2}{h}\right) - 0.6096 \tag{3.17}$$

Equations have also been developed to determine the discharge through flumes as well as compound weirs. Bruce *et al.* (2002) set out the complicated process of calibrating a sluicing flume used in combination with either a sharp-crested or crump weir.

3.3 Temporal Uncertainties

The stage-discharge relation is constantly changing due to the unstable nature of a river bed (Westerberg *et al.*, 2011). Temporal uncertainty explains the change, over time, in the shape of the channels cross section as a result of natural processes (Fenton and Keller, 2001; Jalbert *et al.*, 2011; Westerberg *et al.*, 2011; Guerrero *et al.*, 2012). These changes make estimating Manning's roughness coefficients difficult (Lang *et al.*, 2010). The introduction of a weir may cause changes in the flow path of the river, especially after extreme events. Naturally this creates a change in the stage-discharge relation. If the relation is not updated after these changes occur, inaccurate discharge values will be attained.

It is necessary and common practice to keep track of the changes and to develop a new stage-discharge relation when necessary. Temporal stability is desirable as it can reduce the degree to which a structure may need to be recalibrated after an extreme event (Lambie, 1978). Figure 3-5 illustrates the stage-discharge relationship for gauging Station A2H014 using raw data obtained from Nhlapo (2014). It can be seen that the rating table was re-calibrated at various times in the flow record. Even after the re-calibrations, it is still apparent that the weir is limited to a given stage value. What is noteworthy is that stage data is still recorded. In this case it would have been necessary to update the stage-discharge relation to attain higher discharge values. In such instances it is important that a rating table is only applied to the period of time for which the rating table was developed. Alternatively, it is possible to make use of Manning's equation and other additional data to track the cross section changes over time (Leonard *et al.*, 2000). Another accepted practice is to shift the stage-discharge relation. This should be done when the departure, of a discharge measurement, from a defined section of a rating curve is more than 5% (Rantz, 1982).

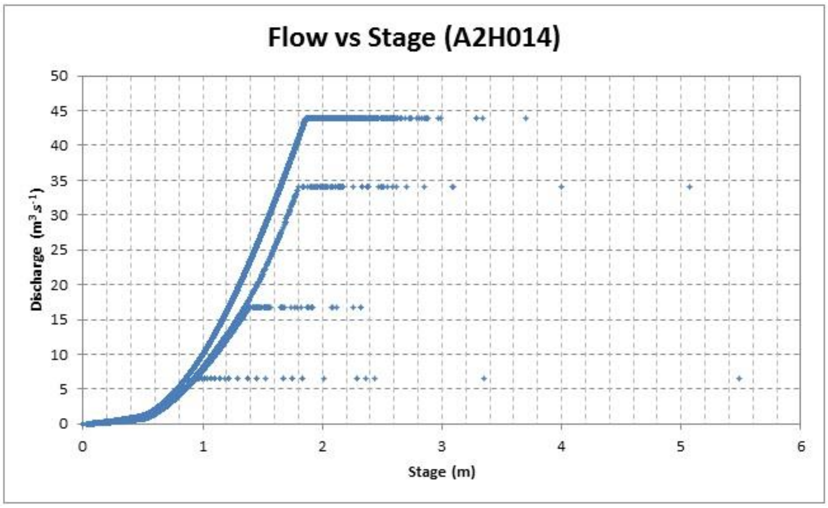

Figure 3-5 Discharge vs Stage using raw data for Station A2H014 (Nhlapo, 2014)

3.4 Hysteresis in Rating Curves

The effect of hysteresis in rating curves is particularly prominent during a flood event (Fenton and Keller, 2001). The result of such an unsteady event is a stage-discharge plot which appears as a loop (Petersen-Overleir, 2006a). This explains why the slope of the water surface differs during an event, when compared to the slope of a constant stage (Fenton and Keller, 2001). The result is that two discharge values are related to a single stage value as can be seen in Figure 3-6. Figure 3-6 illustrates how the slope of the rising arm is greater than that of the slope of a rating curve attained under steady conditions (Fenton and Keller, 2001). The result is that the discharge is overestimated Similarly for the falling arm, the discharge is underestimated (Fenton and Keller, 2001). The slope varies based on whether the stage is increasing or decreasing (Fenton and Keller, 2001).

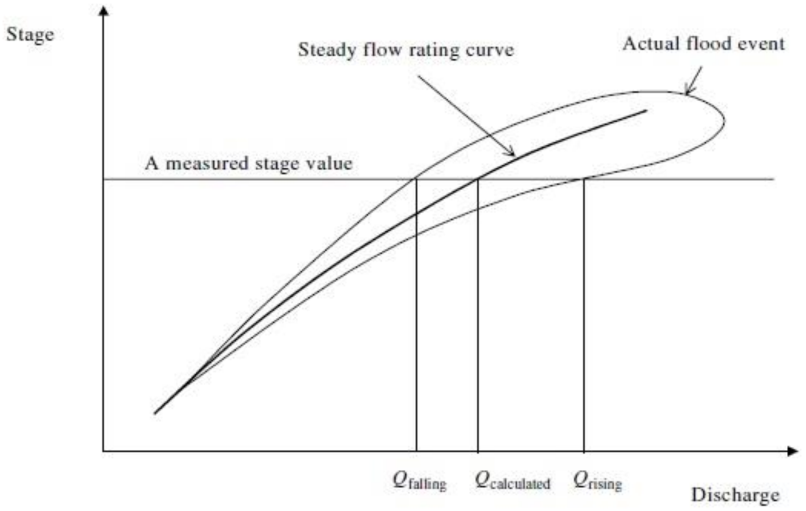

Figure 3-6 Typical hysteresis as a result of a flood wave (Fenton and Keller, 2001)

4. EXTENDING RATING CURVES

When primary data from a flow-gauging weir is plotted, a threshold discharge can be observed as is illustrated in Figure 4-1 (Smithers *et al.*, 2007). Smithers *et al.* (2007) assumed that this threshold is the result of the rating table at the weir being overtopped. This limitation results an underestimation of flow volumes as well as impacting on the Annual Maximum Series (AMS) (Smithers *et al.*, 2007). Therefore it is desirable to extend rating curves beyond their current ratings. An extensive and accurate stage-discharge relation is important for the production of quality discharge data. An unsuitable rating curve will make any gauging site worthless (Petersen-Overleir, 2006b). In general, stage a flow-gauging weir is not recorded in the most extreme events. During extreme events a gauging structure may be damaged or the rating table for the site may be exceeded. To complete the data sets it is necessary to extend the rating curve.

Although it is recommended that extrapolation be avoided where possible it is sometimes necessary (Petersen-Overleir, 2006b). However, estimating discharge well beyond the highest gauged stage value is not common practice due to the errors which may be introduced (Lang *et al.*, 2010). In such a situation the use of indirect methods which use the physical characteristics of the channel and gauging structure is recommended (Petersen-Overleir, 2006b). As mentioned by Guganesharajah *et al.* (2006), uncertainties are a part of hydrometrical observations. It is therefore necessary to acknowledge the uncertainties associated with stage-discharge relationships and the extrapolation thereof. The uncertainty related to the stage-discharge relation has been extensively documented in the literature (Petersen-Overleir and Reitan, 2009; Lang *et al.*, 2010; Di Baldassarre and Claps, 2011; Westerberg *et al.*, 2011; Sikorska *et al.*, 2013).

Two main categories of methods to extend rating curves have been identified in the literature. Firstly, graphical methods such as the power-law rating curve and the log-log extrapolation method have been widely used. These methods aim to fit a curve to calibration data collected at a weir. Secondly, hydraulic models have been used this includes methods such as the slope conveyance and slope-area method. These methods use equations, such as the Manning equation, in an effort to account for the various hydraulic processes and changes which occur over a river reach. In South Africa

4.1 Need for Extending Rating Curves

In their study Smithers *et al.* (2007) analysed a number of flow-gauging weirs in the Thukela catchment and used weir V1H031 to illustrate the effects of not being able to record the peak discharge of an event. Figure 4-1 illustrates the threshold discharge for this particular station. It can be seen that the discharge reaches, but never exceeds a particular value. The fact that stage data was recorded during these events, as illustrated in Figure 3-5 in the previous section, suggests that it is unlikely that the entire gauging structure may have been overtopped during these events (Smithers *et al.*, 2007).

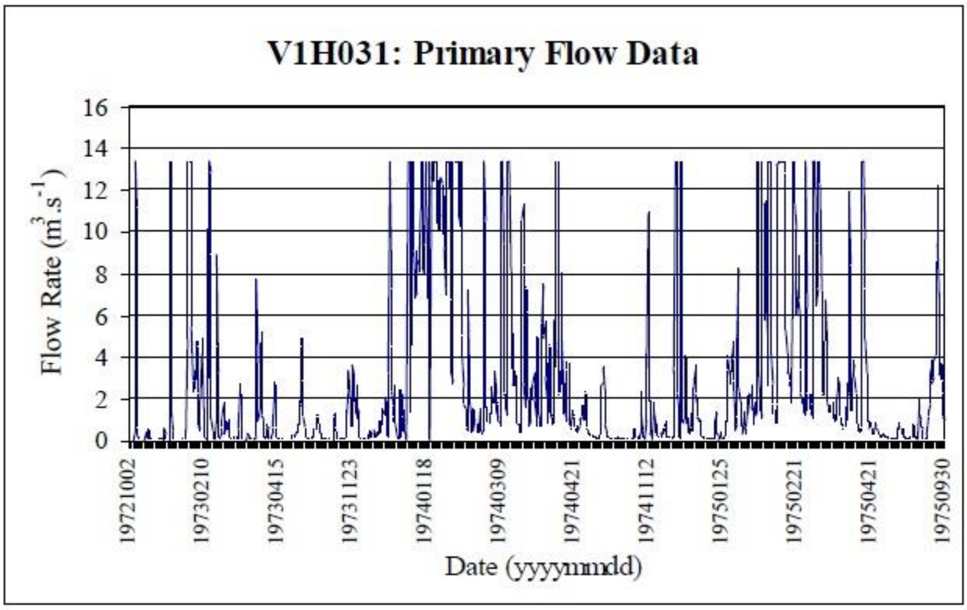

Figure 4-1 Discharge threshold as a result of a limited rating table (Smithers *et al.*, 2007)

The rating table for this particular flow-gauging weir was extended. Following this an accumulated streamflow was determined using both the extended rating curve as well as the original rating curve. Figure 4-2 illustrates shows the difference in the accumulated streamflow lines, the blue line represents the primary data attained using the extended rating curve and the red line represents the primary data attained using the original rating curve. This illustrates how volumes are underestimated with the use of limited rating curves. Smithers *et al.* (2007) also extracted an AMS using primary data attained using the extended rating curve as is illustrated in Figure 4-3. The AMS is extensively used in the estimation of design floods. It is clear that the AMS is underestimated when using the limited rating curve, which may result in inadequate design (Smithers *et al.*, 2007).

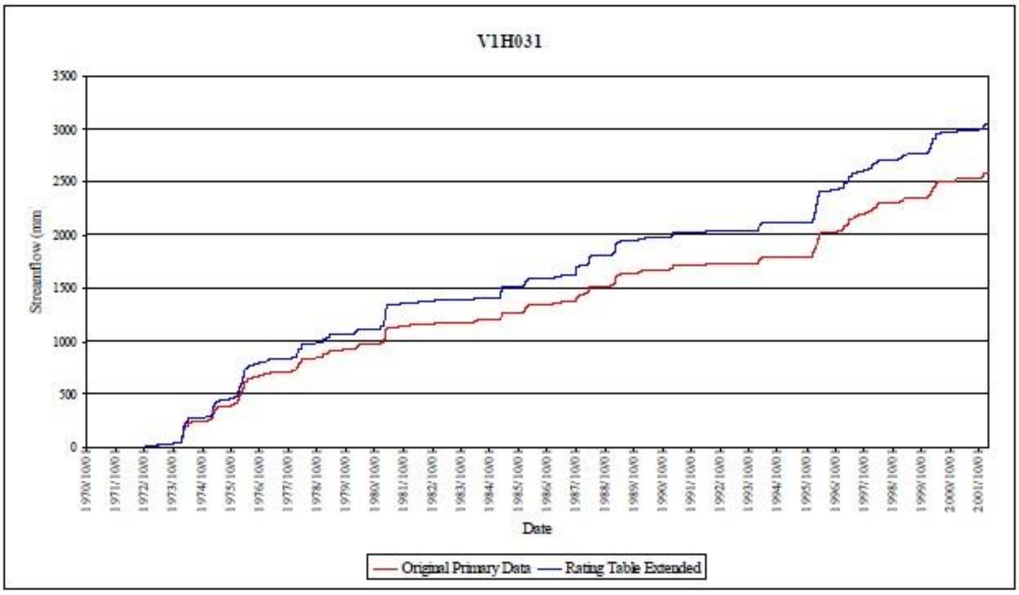

Figure 4-2 Accumulated streamflow using original primary data and primary data using an extended rating curve (Smithers *et al.*, 2007)

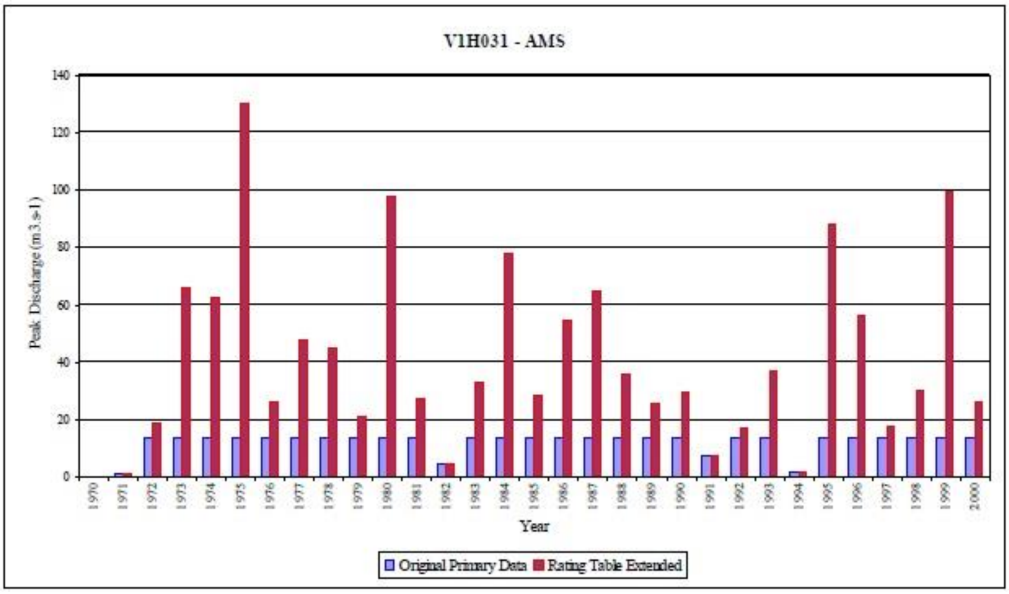

Figure 4-3 AMS extracted from original primary data and primary data attained using the extended rating curve

4.2 Methods Used to Extend Rating Curves

The most common stage-discharge relation, according to the literature, expresses discharge as a function of stage using a power law rating curve (Lambie, 1978; Petersen-Overleir, 2004; Di Baldassarre and Claps, 2011). According to Lambie (1978) the discharge equation can be expressed as follows:

$$Q = C(h + a)^{\beta} \tag{4.1}$$

where

Q = discharge ($m^3 .s^{-1}$),

h = stage (m),

C = coefficient,

β = coefficient, and

a = difference in height between the zero level of the gauge and the true level of zero discharge.

This model is widely used due to the simplicity of its application (Petersen-Overleir, 2006b). This power relationship can be used to extrapolate a rating curve by using a statistical approach to estimating the coefficients in equation 4.1 (Venetis, 1970). A statistical approach is used in an attempt to eradicate subjectivity and to decrease the inaccuracies associated with this method (Petersen-Overleir, 2006b). It has been common practice in Norway, since to 1970's, to use the method of non-linear least squares to fit the power-law curve to the data obtained. Other methods suggested by Kuczera (1996) include the slope-conveyance method, log-log extrapolation as well as fitting a curve to stage and indirect discharge measurements. The log-log extension requires that the rating curve be plotted using a log scale on both axis, this results in curve being represented as a number of straight lines (van Rensburg, 2005). The extension of the rating curve is then done by extending the last segment of these straight lines (van Rensburg, 2005).

The above mentioned methods do not take into account the hydraulic changes which occur throughout an event. To take into account the changes which do occur Lang *et al.* (2010) used a hydraulic modelling approach to extrapolate rating curves. The changes which may occur, according to Lang *et al.* (2010), are listed as follows:

a) the shape of the channel changes as the water level rises,
b) backwater effects, overbank flow and hydraulic jumps may occur as the water level changes,
c) the channels roughness changes with a change in flow depth,

d) overtopping of gauging weirs may occur,
e) secondary flows may cause energy losses,
f) flow upstream of the control may bypass the control as flow depth changes,
g) hysteresis may affect the rating, and
h) temporal changes may occur during an extreme event.

Hydraulic models can account for all the above considerations, except for the temporal changes. The fact that a hydraulic model takes into account the cross section at a point of interest is of the utmost importance (Stretch, 2014). However, it is important to note that there are uncertainties related to the various surveying methods used to attain the cross sections needed for this approach as described by Burnham and Davis (1990). The difficulty with temporal changes is the lack of information describing them (Lang *et al.*, 2010). For their study Lang *et al.* (2010) developed an envelope of curves using a hydraulic model as is illustrated in Figure 4-4. The envelope is developed by taking two extreme cases which involve the addition or subtraction of flow depth. In this case it was assumed that the measurement of stage at a gauging station can be incorrect by a depth of 5 cm (Lang *et al.*, 2010). This envelope is used to take into account the uncertainties related to the roughness coefficient, which are used in the model, and gauging measurements (Lang *et al.*, 2010). This envelope was developed by Lang *et al.* (2010) using a one dimensional hydraulic model to extend rating curves. This model was chosen as it is capable of solving hydraulic equations under unsteady equations using the Saint Venant equations (Lang *et al.*, 2010). This model was calibrated using gauged values of stage (Lang *et al.*, 2010).

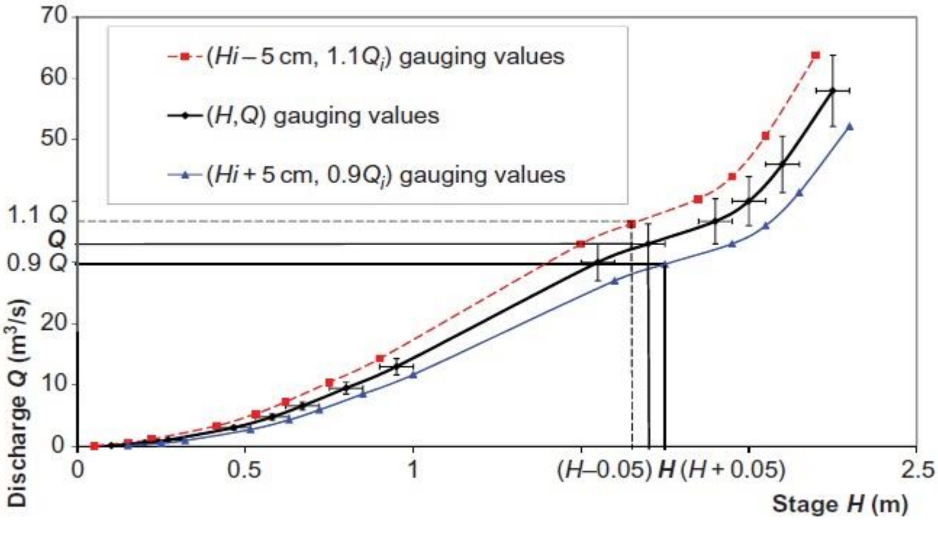

Figure 4-4 Rating curve envelope (Lang et al., 2010)

In order to develop a discharge model suitable for application at sites which demonstrate similar characteristics to those at gauging stations below a reservoir, Petersen-Overleir (2006b) utilised data captured at gauging stations located directly below reservoirs. These sites are suitable as they are not subject to significant temporal changes, unsteady flows and hysteresis (Petersen-Overleir, 2006b).

It is also possible to extend a rating curve using the slope-area method, which is also considered a hydraulic model. This method provides an estimation of discharge after an event has occurred. Therefore, a graphical approach may still have to be used to extend the curve to the discharge attained using the slope-area method. The slope-area method uses a uniform-flow equation which takes into account the channels characteristics, water-surface profiles and a roughness coefficient (World Meteorological Organization, 2010). The World Meteorological Organization (WMO) provide a simplified description, however in their study Dalrymple and Benson (1967) explain the hydraulic principles and calculation procedures used in more detail. It is known that the passage of a hydrograph involves steady flow. This method requires a post event visit to observe high water marks which define the water-surface elevations and slopes (Henderson, 1966; Barnes and Davidian, 1978). It is possible to use any of the Chezy equations using this method. However, the most commonly used equation is the Manning equation, which was developed for uniform flows, can be applied (World Meteorological Organization, 2010). This method was extensively used in South Africa as is illustrated in Table 3-1. However, the DWA now prefers to use a flood routing approach to extending rating curves on an event based basis as it is deemed more reliable than using the slope-area method (van der Spuy, 2014). Various methods such as the Muskingum, which requires some variables to be calibrated, and Saint-Venant equations can be used to route a flood down an open channel (Moussa and Bocquillon, 1996; Tewolde and Smithers, 2006). Generally releases from a dam are controlled such that they are within safe limits, meaning that flow-gauging weirs located near dams have a controlled flow (Kumar *et al.*, 2011). This provides an input hydrograph for the flood routing.

4.3 Errors Due to Rating Curve Extension

Generally any discharge value attained is the result of some form of estimate. This includes rating curves which are an approximation of the true rating curve at a gauging station (Petersen-Øverleir and Reitan, 2009). Therefore, discharge measurements are prone to uncertainties. In the same way extending a rating curve introduces further uncertainties.

Petersen-Øverleir and Reitan (2009) state that the uncertainties associated with rating curves are often overlooked because little effort has been put into trying to understand the effect of using inaccurate data for modeling purposes. The uncertainties are related to all data, variables and parameters used in the extension of a rating curve lead to errors. Errors in the derivation of parameters used in methods, such as the power law rating curve model, can lead to significant errors in discharge estimation (Kuczera, 1996). When using a hydraulic model it is necessary to take into account the changes to factors such as the Manning's roughness coefficient which can be very difficult to estimate (Leonard *et al.*, 2000). Typical errors which may arise are outlined by Kuczera (1996) using the illustration shown in Figure 4-5. From Figure 4-5 it is apparent that the error may grow larger the further the rating curve is extended. Therefore, extending rating curves must be done cautiously and not beyond 20% of the stage limit of the current DWA rating curves (Görgens, 2014).

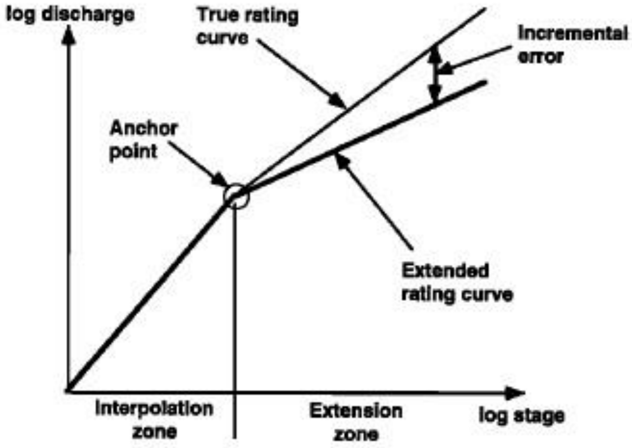

Figure 4-5 Error in extended rating curve (Kuczera, 1996)

5. DISCUSSION AND CONCLUSION

This document contains a review of the importance of discharge data, how stage-discharge relations are derived, how they can be extended and the uncertainties associated with rating curves. It was found that there are two main categories of methods which are used to extend rating curves, namely graphical approaches and a hydraulic modelling approach.

The weirs which have been adapted to South African conditions are capable of measuring flows at low and high flows. However, it has been found that weirs are not capable of measuring some of the most extreme events as evidenced by Van Bladeren and Burger (1989). This may be due to equipment damage or simply because it has not been possible to rate the weir to such a high values. Indirect methods are particularly useful in this case as they can be used to determine the discharge after the flood has occurred. By combining the estimated discharges attained using both direct and indirect methods it is possible to develop an extensive rating curve.

However, it is still necessary to extend rating curves to include all measured stages which frequently exceed their current ratings. It is evident that the AMS as well as the estimated volumes of water may be underestimated as a result of the rating curve limitations. Figure 3-5 clearly shows that there is stage data which can be used to extend the rating curves. The use of hydraulic modelling to extend rating curves can help compensate for some of the uncertainties associated with rising water levels. The calibration of a hydraulic model can be done as a desktop exercise as it is possible to calibrate using existing rating curve data. This approach is universally applicable as the inputs, channel cross section and roughness coefficients, can be attained from the site of interest.

The use of flood routing to calibrate a gauging weir requires accurate estimates of upstream (e.g. overflow/releases from a dam) or downstream flow, and information required to accurately calibrate the equations used to route a flood. This method is however suited to South Africa as is evidenced by the fact that the DWA now uses this method to calibrate/extend their rating curves, but can only be used where an accurate estimate of upstream and downstream flow is available. The more commonly used methods of extending rating curves such as the graphical methods are suited to a desktop study and could be used in conjunction with other approaches to extrapolate rating curves.

Another option to extend rating curves is the use of the non-modular calibration equations developed for the flow-gauging weirs used in South Africa. This approach is suited to a desk top study as all the data required to perform the calculations is available from the DWA. It would be necessary to use existing rating curves to calibrate the model. This process would require that the existing rating curves be replicated. The stage values beyond the discharge threshold of the current rating can then be used to extend the rating curve, within reason.

This document has met the objectives set. It contains a review of the methods used to extend rating curves, internationally and in South Africa. The uncertainty related to hydrometric data measurement and the concomitant uncertainty associated with rating curves have been identified and discussed. Where available in literature, the methods which have been used internationally and in South Africa to extend rating curves were identified and discussed.

6. PROJECT PROPOSAL

The following sections details the project proposal for the development of a desk top method to extrapolate rating curves in South Africa. A research question is proposed, followed by the aims and objectives of the project. The methodology which will be used to develop the method follows. A list of all the required resources, health, safety, environmental and ethical issues pertaining to the project are provided. Finally, the activities and milestones required to complete the project are listed.

6.1 Research Question

What is the frequency and impact on flood volumes and peak discharges of recorded river stage levels exceeding DWA rating tables and how can discharges be reasonably estimated for these river stages?

6.2 Aim and Objectives

The aim of this project is to assess the frequency and impact of limitations of the rating tables for flow gauging structures in South Africa and to develop and assess a desk top method to extend the rating tables beyond their current ratings for all gauging stations across South Africa.

The specific objectives of this project are to:

a) Review literature on flow gauging, particularly under non-modular conditions.
b) Quantify the extent to which rating curves are exceeded in South Africa.
c) Assess the stage to which flow-gauging weirs in South Africa have been rated.
d) Assess the limitations of rating curves in South Africa.
e) Assess the limitations of available techniques to measure peak flows.
f) Assess methods currently used to extend rating tables.
g) Assess the impact of missing data on peak discharge and runoff volume estimation.
h) Develop and assess the performance of a desktop method to extend rating the tables beyond the current ratings.

6.3 Proposed Methodology

Initially an extensive review of both local and international literature will be conducted. This will serve to provide a synthesis of methods used to extend rating curves and the limitations of the various approaches. Flow duration curves which are attainable from the DWA will be used to determine the amount of time, expressed as a percentage, which the rating curves are exceeded in South Africa. Gauging stations which have stage measurements for both upstream and downstream of the gauging station will be identified and relationships for the energy loss from upstream to downstream will be derived. A list of the identified stations is provided in Appendix A. The relationship will then be applied to gauging stations which are not equipped to record downstream stages. This will enable the application of non-modular flow equations to determine a discharge for stages which exceed the current rating tables.

Alternatively, similar to the approach used by Lang *et al.* (2010) a one-dimensional model can be used. A suitable model such as Hydrologic Engineering Centre's River Analysis System (HEC-RAS) will provide a means of calculating a stage. HEC-RAS uses the Manning's equation to calculate energy losses (US Army Corps of Engineers, 2012). The model can be calibrated using existing rating curves which are available from the DWA. This model requires a discharge as an input, therefore it may be necessary to use an iterative approach to determining the discharge associated with the stage recorded by the DWA.

The research plan entails the following:

a) Conducting an extensive literature review.
b) Quantifying the extent of rating curve exceedance.
c) Development of energy loss relationships:
    - Evaluate stations with both upstream and downstream stage measurements and
    - Apply relationship to stations with no downstream measurement, to attain a theoretical downstream stage value.
d) Development of rating curves based on non-modular flow equations and the energy loss relationships attained.
e) Assess the impact extending a rating curve has on the AMS and accumulated flow over time.

The goal of this project is to produce a desktop method to extend rating curves. It is expected that there will be inaccuracies associated with the use of these rating curves. However, this method will provide the DWA, researchers and practitioners with a means to extend rating curves on a needs basis.

6.4 Required Resources

The project study can be conducted at the University of KwaZulu-Natal, Pietermaritzburg. A list of the resources required to conduct the study is provided in Table 6-1.

Table 6-1 Required resources

No.	Resource	Source	Application
1	Desktop computer	UKZN	Literature review and method development
2	Software	UKZN	Data analysis and model development
3	Mean daily flow	DWA	Rating curve exceedance quantification
4	Primary data	DWA	Development of rating curves
5	Funding	NRF	Research and living expenses

6.5 Health, Safety, Environmental and Ethical Issues

Considering that this project is a desktop study and does not entail fieldwork, there are no safety, environmental and ethical issues to be addressed. If the outcome of this project is to be applied in the workplace, there are still no issues to be addressed. This is due to the fact that method can be applied using only a desktop computer.

6.6 Project Plan

To complete the project it is necessary to comply with deadlines and to set certain goals. Table 6-2 lists the start and end dates of the tasks required to complete this study.

Table 6-2 Project plan

Task	Start Date	End Date
Draft Project Proposal	1 February 2014	31 March 2014
Submission of complete literature review and project proposal	1 April 2014	2 May 2014
Corrected lit review and proposal and method	5 May 2014	30 June 2014

Method development	1 July 2014	30 September 2014
Method assessment	1 October 2014	28 November 2014
Application of method	1 December 2014	31 March 2015
Writing and submission of thesis	1 April 2015	30 June 2015

7. REFERENCES

Ackers, P, White, WR, Perkins, JA and Harrison, AJM. 1978. *Weirs and Flumes for Flow Measurement*. John Wiley & Sons, Chichester, Great Britain.

Barnes, HH, Jr. and Davidian, J. 1978. Indirect Methods. In: ed. Herschy, RW, *Hydrometry: Principles and Practices*. John Wiley & Sons, Chichester, Great Britain.

Bruce, H, Rossouw, J and Rooseboom, A. 2002. *The Rating of Sluicing Flumes in Combination with Sharp-Crested and Crump Weirs Under Modular and Non-Modular Flow Conditions* 980/2/00. Water Research Commission, Pretoria, South Africa.

Burnham, MW and Davis, DW. 1990. Effects of Data Errors on Computed Steady-Flow Profiles. *Journal of Hydraulic Engineering-Asce* 116 (7): 914-929.

Callede, J, Kosuth, P, Guyot, JL and Guimaraes, VS. 2000. Discharge determination by Acoustic Doppler Current Profilers (ADCP): a moving bottom error correction method and its application on the River Amazon at Obidos. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 45 (6): 911-924.

Canto, RR, Rossouw, J and Rooseboom, A. 2002. *The Rating of Compond Sharp-Crested Weirs Under Modular and Non-Modular Flow Conditions*. Water Research Comission, Pretoria, South Africa.

Charlton, FG. 1978. Current Meters. In: ed. Herschy, RW, *Hydrometry: Principles and Practices*. John Wiley & Sons, Chichester, Great Britain.

Chow, VT, Maidment, DR and Mays, LW. 1988. *Applied Hydrology*. McGraw-Hill, New York, USA.

Dalrymple, T and Benson, MA. 1967. *Measurement of Peak Discharge by the Slope-Area Method*. US Government Printing Office, Denver, USA.

Di Baldassarre, G and Claps, P. 2011. A Hydraulic Study on the Applicability of Flood Rating Curves. *Hydrology Research* 42 (1): 10-19.

Fenton, JD and Keller, RJ. 2001. *The Calculation of Streamflow From Measurements of Stage*. 01/6. Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia.

Görgens, A. 2014. Personal communication, Cape Town, South Africa, Guerrero, J-L, Westerberg, IK, Halldin, S, Xu, C-Y and Lundin, L-C. 2012. Temporal Variability in Stage–Discharge Relationships. *Journal of Hydrology* 446–447 (0): 90-102.

Guganesharajah, K, Lyons, DJ, Parsons, SB and Lloyd, BJ. 2006. Influence of Uncertainties in the Estimation Rrocedure of Floodwater Level. *Journal of Hydraulic Engineering-ASCE* 132 (10): 1052-1060.

Guven, A and Aytek, A. 2009. New Approach for Stage-Discharge Relationship: Gene-Expression Programming. *Journal of Hydrologic Engineering* 14 (8): 812-820.

Henderson, FM. 1966. *Open Channel Flow*. Macmillan, New York, USA.

Jalbert, J, Mathevet, T and Favre, AC. 2011. Temporal Uncertainty Estimation of Discharges from Rating Curves Using a Variographic Analysis. *Journal of Hydrology* 397 (1-2): 83-92.

Kuczera, G. 1996. Correlated Rating Curve Error in Flood Frequency Inference. *Water Resources Research* 32 (7): 2119-2127.

Kumar, DN, Baliarsingh, F and Raju, KS. 2011. Extended Muskingum Method for Flood Routing. *Journal of Hydro-environment Research* 5 (2): 127-135.

Lambie, JC. 1978. Measurement of Flow - Velocity-area Methods. In: ed. Herschy, RW, *Hydrometry: Principles and Practices*. John Wiley & Sons Chichester, Great Britain.

Lang, M, Pobanz, K, Renard, B, Renouf, E and Sauquet, E. 2010. Extrapolation of Rating Curves by Hydraulic Modelling, with Application to Flood Frequency Analysis. *Hydrological Sciences Journal* 55 (6): 883-898.

Le Coz, J, Camenen, B, Peyrard, X and Dramais, G. 2012. Uncertainty in open-channel discharges measured with the velocity-area method. *Flow Measurement and Instrumentation* 26 18-29.

Leonard, J, Mietton, M, Najib, H and Gourbesville, P. 2000. Rating Curve Modelling with Manning's Equation to Manage Instability and Improve Extrapolation. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 45 (5): 739-750.

Lotriet, HH and Rooseboom, A. 1995. *River Discharge Measurement in South African Rivers: The Development of Improved Measuring Techniques*. Pretoria, South Africa.

Lumbroso, D and Gaume, E. 2012. Reducing the Uncertainty in Indirect Estimates of Extreme Flash Flood Discharges. *Journal of Hydrology* 414–415 (0): 16-30.

Moussa, R and Bocquillon, C. 1996. Criteria for the Choice of Flood-Routing Methods in Natural Channels. *Journal of Hydrology* 186 (1–4): 1-30.

Nhlapo, E. 2014. Personal communication, Department of Water Affairs, Pretoria, South Africa, 17/02/2014.

Perumal, M, Shrestha, KB and Chaube, UC. 2004. Reproduction of Hysteresis in Rating Curves. *Journal of Hydraulic Engineering-ASCE* 130 (9): 870-878.

Petersen-Overleir, A. 2004. Accounting for Heteroscedasticity in Rating Curve Estimates. *Journal of Hydrology* 292 (1-4): 173-181.

Petersen-Overleir, A. 2006a. Modelling Stage-Discharge Relationships Affected by Hysteresis Using the Jones Formula and Nonlinear Regression. *Hydrological Sciences Journal* 51 (3): 365-388.

Petersen-Overleir, A. 2006b. A Robust Stage-Discharge Rating Curve Model Based on Critical Flow from a Reservoir. *Nordic Hydrology* 37 (3): 217-233.

Petersen-Overleir, A and Reitan, T. 2009. Accounting for Rating Curve Imprecision in Flood Frequency Analysis Using Likelihood-Based Methods. *Journal of Hydrology* 366 (1-4): 89-100.

Petersen-Øverleir, A and Reitan, T. 2009. Accounting for Rating Curve Imprecision in Flood Frequency Analysis Using Likelihood-Based Methods. *Journal of Hydrology* 366 (1–4): 89-100.

Rantz, SE. 1982. *Measurement and Computation of Streamflow: Computation of Discharge*. United States Geologoical Services, Washington, USA.

Sikorska, AE, Scheidegger, A, Banasik, K and Rieckermann, J. 2013. Considering Rating Curve Uncertainty in Water Level Predictions. *Hydrology and Earth System Sciences* 17 (11): 4415-4427.

Smithers, JC, Chetty, KT, Frezghi, MS, Knoesen, DM and Tewolde, MH. 2007. *Development and Assessment of a Continuous Simulation Modelling System for Design Flood Estimation*. 1318/1/07. Water Research Comission, Pietermariztburg, South Africa.

Smoot, GF. 1978. Flow Measuring Instruments. In: ed. Herschy, RW, *Hydrometry: Principles and Practices*. John Wiley & Sons, Chichester, Great Britain.

Stretch, D. 2014. Personal communication, Durban, South Africa, 30/07/2014.

Tewolde, MH and Smithers, JC. 2006. *Flood Routing in Ungauged Catchments Using Muskingum Methods*. 0378-4738.

US Army Corps of Engineers. 2012. *HEC-RAS River Analysis System - User's Manual*. California, United States of America.

Van Bladeren, D and Burger, C. 1989. *Documentation of the September 1987 Natal Floods*. 0621126217. The Department of Water Affairs, Pretoria, South Africa.

van der Spuy, D. 2014. Personal communication, Pretoria, South Africa, 02/07/2014.

van Rensburg, J. 2005. *First Interim Report on Improved flood Hydrograph Generation Techniques*. Progress report on WRC Project Number : K5/1420 ("Updated guidelines and design flood hydrograph techniques for dam safety"), Ninham Sahnd Consulting Services, Cape Town, South Africa.

Venetis, C. 1970. A Note on the Estimation of the Parameters in Logarithmic Stage-Discharge Relationships with Estimates of their Error. *International Association of Scientific Hydrology. Bulletin* 15 (2): 105-111.

Wessels, P. 2014. Personal communication, Department of Water Affairs, Pretoria, South Africa, 5/8/2014.

Wessels, P and Rooseboom, A. 2009a. Flow-Gauging Structures in South African Rivers Part 1: An Overview. *Water SA* 35 (1): 1-9.

Wessels, P and Rooseboom, A. 2009b. Flow-gauging structures in South African rivers Part 2: Calibration. *Water SA* 35 (1): 11-19.

Westerberg, I, Guerrero, JL, Seibert, J, Beven, KJ and Halldin, S. 2011. Stage-Discharge Uncertainty Derived with a Non-Stationary Rating Curve in the Choluteca River, Honduras. *Hydrological Processes* 25 (4): 603-613.

World Meteorological Organization. 2010. *Manual on Stream Gauging - Fieldwork*. Geneva, Switzerland.

8. APPENDICES

8.1 Appendix A

Table 8-1 Stations with upstream and downstream stage measurements (Nhlapo, 2014)

A2H006	A6H023	C1H004	E2H003	H2H006	R1H014	V2H014
A2H013	A6H024	C1H005	E2H007	H2H008	R1H015	V3H007
A2H014	A6H027	C1H006	E2H010	H3H005	R2H001	V3H009
A2H019	A6H029	C1H012	E3H001	H3H011	R2H006	V3H010
A2H021	A6H035	C1H019	F5H001	H3H015	R2H008	V3H027
A2H023	A9H003	C2H001	G1H003	H4H016	R2H010	V6H004
A2H027	A9H012	C2H007	G1H008	H4H017	R2H015	V6H006
A2H029	A9H025	C2H061	G1H009	H4H018	R2H027	V7H020
A2H030	B1H002	C2H085	G1H013	H5H004	R3H001	W1H009
A2H032	B1H004	C2H139	G1H014	H6H009	R3H003	W1H028
A2H034	B1H017	C2H177	G1H019	H7H005	S3H006	W2H005
A2H036	B1H018	C3H003	G1H020	H7H006	S5H002	W2H006
A2H038	B1H019	C4H010	G1H021	H7H013	S6H001	W2H030
A2H044	B2H004	C4H017	G1H034	J1H016	S6H005	W3H008
A2H045	B2H007	C5H003	G1H039	K8H005	S7H004	W3H015
A2H047	B2H008	C5H007	G1H040	K8H006	T2H008	W3H022
A2H048	B2H014	C5H035	G1H041	K9H003	T3H004	W4H006
A2H049	B3H025	C5H039	G1H043	L6H001	T3H006	W4H013
A2H050	B4H003	C5H048	G1H062	L7H006	T3H008	W5H024
A2H055	B4H007	C5H056	G1H077	L8H001	T3H009	X1H014
A2H061	B4H010	C7H003	G1H078	L8H005	T3H019	X2H008
A2H083	B4H016	C7H019	G1H080	M1H004	T5H005	X2H010
A2H099	B4H017	C8H001	G2H005	M1H012	T5H012	X2H012
A2H104	B4H024	C8H005	G2H012	N2H007	T7H001	X2H014
A2H106	B4H025	C8H026	G2H020	N4H005	U2H005	X2H015
A4H002	B6H005	C8H027	G2H040	P1H003	U2H006	X2H022
A4H004	B6H011	C8H032	G2H042	P3H001	U2H007	X2H024
A4H005	B7H002	C8H036	G2H044	P4H001	U2H013	X2H031
A4H007	B7H004	C8H037	G4H005	Q1H013	U2H014	X2H036
A4H008	B7H014	C9H009	G4H006	Q3H004	U2H022	X2H047
A4H010	B7H015	D1H009	G4H007	Q3H005	U2H048	X2H068
A4H014	B7H019	D1H011	G4H014	Q4H013	U4H002	X2H070
A5H004	B8H008	D1H032	G5H008	Q7H005	U7H008	X3H003
A5H006	B8H009	D1H033	H1H003	Q8H008	V1H001	X3H008
A6H011	B8H010	D2H012	H1H006	Q8H010	V1H026	X3H020
A6H012	B8H011	D2H033	H1H007	Q9H002	V1H038	X3H023
A6H018	B8H014	D3H008	H1H013	Q9H012	V1H058	X4H004
A6H019	B8H034	D3H015	H1H018	Q9H017	V2H004	Z1H006
A6H020	B8H046	D8H003	H1H033	Q9H019	V2H005	
A6H021	B8H064	E1H006	H2H004	Q9H030	V2H006	