REPUBLIC OF ZAMBIA
Ministry of Mines, Energy and Water Development

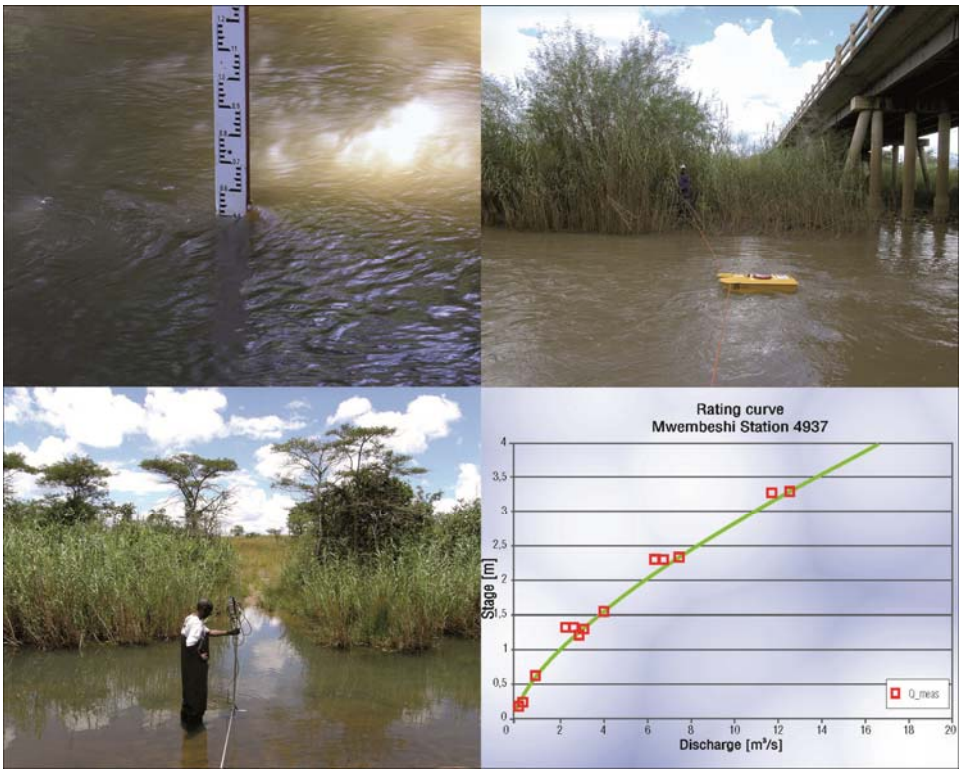
FEDERAL REPUBLIC OF GERMANY
Federal Institute for Geosciences and Natural Resources

Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

TECHNICAL NOTE NO. 7

Discharge Measurements and Rating Curves of the Rivers Chalimbana, Chilongolo, Chongwe, Chunga, Kapwelyomba, Mwembeshi, Ngwerere and Laughing Waters Spring

by Torsten Krekeler & Chisanga Siwale



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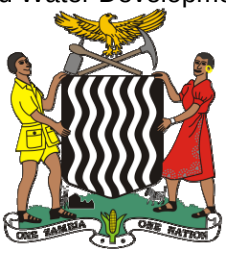

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Abbreviations

A	Area
a	Velocity weighted coefficient
ADC	Acoustic digital current meter
ADCP	Acoustic doppler current meter profiler
ArcGIS	Geographic Information System
asl.	Above sea level
b	Width
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe *Federal Institute for Geosciences and Natural Resources*
C	Expansion or compression loss coefficient
C_h	Overfall coefficient
cm	Centimeters
DWA	Department of Water Affairs
ESE	East-south-east
Fig.	Figure
g	Gravitational acceleration
GPS	Global Positioning System
GReSP	Development of a Groundwater Information and Management Program for the Lusaka Groundwater Systems
h	Water level
h_e	Energy head loss
HEC-RAS	US Army Corps of Engineers - Hydraulic Engineering Centre – River Analysis System
i	Slope
K	Conveyance
km	Kilometers
L	Reach length
l_{ob}	Left overbank
m	Meters
n	Roughness coefficient (Manning's n)
OTT	OTT Hydrometry GmbH (Manufacturer of hydrometric instruments)
pc	Personal computer
P_{wet}	Wetted perimeter
Q	Discharge
r	Radius
r_{hy}	Hydraulic radius
r_{ob}	Right overbank
S_f	Friction slope
v	Velocity
WNW	West-north-west
wo	Upstream waterlevel
wu	Downstream waterlevel
Y	Water depth at cross section
Z	Elevation
φ	Reduction factor

List of Reports compiled by the project in Phase II

Date	Authors	*Title*	Type
Apr. 2009	Museteka L. & Bäumle R.	*Groundwater Chemistry of Springs and Water Supply Wells in Lusaka - Results of the sampling campaigns conducted in 2008*	Report No. 1
Oct. 2009	Bäumle R.& Kang'omba S.	*Development of a Groundwater Information & Management Program for the Lusaka Groundwater System: Desk Study and Proposed Work Program Report*	Report No. 2
March 2010	Hahne K. & Shamboko-Mbale B.	*Karstification, Tectonics and Land Use in the Lusaka region*	Report No. 3
Oct. 2010	Mayerhofer C., Shamboko-Mbale B. & R.C. Mweene	*Survey on Commercial Farming and Major Industries: Land Use, Groundwater Abstraction & Potential Pollution Sources-*	Report No. 4
Aug. 2012	Hennings V.	*Assessment of annual percolation rates in the Lusaka region*	Report No. 5
Dec. 2012	Massmann J.	*Numerical groundwater flow model of the Lusaka region*	Report No. 6
Dec. 2012	Shamboko-Mbale B., Siwale C., Bäumle R. & Krekeler T	*Water Balance Estimates for Sub-catchments of the Chongwe and Mwembeshi Rivers in the Lusaka region*	Report No. 7
Feb. 2008	Bäumle, R. & Nkhoma J.	*Preliminary Assessment of the Hydrogeological Situation around Lusaka South Local Forest Reserve No. 26*	Technical Note No. 1
Nov. 2010	Tena, T. & Nick A.	*Capacity Building and Awareness Raising Strategy for Phase II (2010-2012)*	Technical Note No. 2
Nov. 2010	Nick A., Museteka L. & Kringel R.	*Hydrochemical Sampling of Groundwater in the Lusaka Urban Area (April/May 2010) and Preliminary Findings*	Technical Note No. 3
Feb. 2011	Bäumle R.	*Results of pumping test evaluation and statistical analysis of aquifer hydraulic properties*	Technical Note No. 4
Apr. 2011	Kringel R., Fronius A., Museteka L. & Nick A.	*Assessment of CVOC- and BTEX-contamination level in Lusaka ground-water in 2010 based on developing and testing a method to sample and analyse groundwater containing organic volatile substances after extended storage*	Technical Note No. 5
Aug. 2011	Nick A.	*Compilation of a vulnerability map according to the PI- method – A documentation and manual*	Technical Note No. 6
Dec. 2012	Krekeler T. & Siwale C.	*Discharge measurements and rating curves of the rivers Chalimbana, Chilongolo, Chongwe, Chunga, Kapwelyomba, Mwembeshi, Ngwerere and Laughing Waters Spring*	Technical Note No. 7
Jun. 2012	Bäumle R., Anscombe, J., Siwale C. & Nick A.	*Results of drilling and test pumping at three selected sites in Lusaka, Kafue and Chibombo Districts*	Technical Note No. 8
2012, in prep.	Hennings, V., Willer, J., Sokotela, S., Bwalya, A. & Tena T.	*Regionalization of soil physical parameters in the Lusaka region*	Technical Note No. 9

Summary

Authors: Torsten Krekeler & Cisanga Siwale

Title: Discharge Measurements and Rating Curves of the rivers Chalimbana, Chilongolo, Chongwe, Chunga, Kapwelyomba, Mwembeshi, Ngwerere and Laughing Waters spring

Key words: hydrology, Lusaka, discharge, rating curve

Objective of this report is the measurement of discharge and the development of rating curves of selected rivers in the Lusaka area. The measurements were carried out with modern instruments using the acoustic doppler method. Some rating curves were extrapolated by extension of the stage-area and the stage-velocity relation. At sites where weirs exist discharge was calculated using weir formulas. Furthermore water levels were modelled using the software HEC-RAS. Rating curves of seven rivers and one spring were developed.

Extended Summary

A well designed and operational hydrometric network provides necessary information for management, development, planning and decision making on water resources. The information that is generated from the network can only be useful if the hydrometric installations are in good working order and are adequately calibrated.

The Groundwater Resources Project for Lusaka, whose ultimate goal is to develop a groundwater management strategy, incorporated a component of Hydrometric and Water Quality Monitoring as part of the Groundwater Information System. This monitoring network included existing stations and additional ones which the project established. This report is focused on the surface water monitoring stations within the boundaries of the project area. These were Ngwerere River at Estate Weir, Chalimbana River at Romor Farm, Chunga River at Shandyongo Village, Mwembeshi River at Mumbwa Road Bridge, Chongwe River at Great East Road Bridge, Kapwelyomba at Khalamazi Farm and Muchumbo stream at Laughing Waters spring. The main objective of the exercise was to collect stage, discharge and hydraulic parameters of the stations. Stage and discharge data were collected for two hydrological years (2009/2010 and 2010/2011). During the same period the existing rating equations were also revised. For the two new stations in the Chunga catchment, a new rating equation was developed.

The data collected from these stations was used as an input in the overall water balance analysis of the study. The revised and new rating equations will be used for various hydrological services such as water resources assessment, issuance of water rights, research, catchment yield analysis among others. This report therefore serves as a basis for similar and subsequent works in other subcatchments of the country.

1 River catchments in the investigation area

The Lusaka Plateau is about 70 km long and about 10 km wide and stretches from ESE to WNW. The elevation ranges between 1200 and 1300 m asl. The main catchments are Chongwe and Mwembeshi (Fig. 1). The Chongwe catchment has three subcatchments in the Lusaka area namely Ngwerere, Chalimbana and Kanakantapa. The Mwembeshi river system has two subcatchments in the Lusaka area which are Chunga and Kembe. (Bäumle & Kang'omba, 2009)

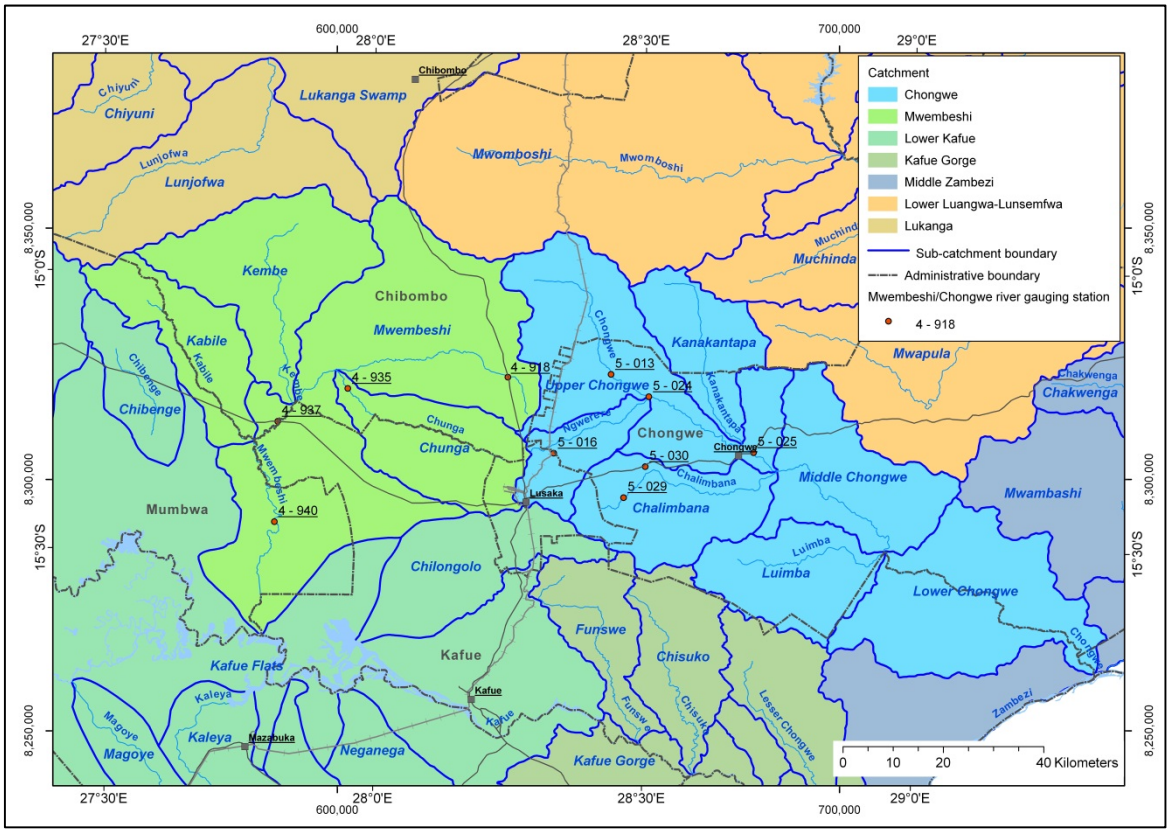

Fig. 1 River catchments in the investigation area (Shamboco-Mbale et.al. 2012)

Existing gauging stations at Mwembeshi (station 4937), Ngwerere (station 5016), Kapwelyomba (station 5030), Chalimbana (station 5029) and Chongwe (station 5025) were investigated under the GReSP project. The gauging station 5030 of Kapwelyomba, a tributary to Chalimbana, is located inside a farm. Following the retrenchment of gauge readers, this station was not operational from 1999.This station was overhauled and set into operation in 2009. Two new gauging stations were established in 2009 at Chunga and Laughing Waters spring. Discharge at Chilongolo was measured several times, but no gauging station was established there because no appropriate location (hydraulic and logistic) could be found.

2 Measurements

2.1 Measurement of stage

Stage is the water level above the deepest point in a cross section of a river.

Stage was measured with gauge plates (Fig. 2) and recorded manually. A gauge reader from the local village was employed to record the water level three times a day: at 6:00h, 12:00h and 18:00h. During extreme events such as floods, when the gauging installations

are submerged, the gauge reader was further instructed to mark the flood mark whose value can later be determined or leveled using the established benchmark.

Fig. 2 Gauging station at Chunga

The gauging stations consist of up to four gauge plates and two benchmarks. They are located at sites that show a clear stage/discharge relation, which are usually straight and stable river sections or sites upstream of weirs.

2.2 Measurement of discharge

Discharge was measured several times at all of the gauging stations. Discharge measurements were carried out with OTT ADC (Acoustic Digital Current meter) as shown in Fig. 3 and OTT QLiner (Acoustic Doppler Current meter Profiler) as shown in Fig. 5.

The OTT ADC measures point velocities in open waterways like classic propeller driven current meters. It is fixed on a rod and operated by wading through the river or from a bridge. Instead of a propeller, flow velocity is measured by an ultrasonic probe. This probe emits an ultrasonic burst consisting of 30 single pings that will be reflected by suspended particles in the water body. An echo returns to the sensor and is processed. This process is repeated several times.

The velocity is measured at about 10 cm in front of the probe. Additionally the instrument consists of a pressure probe to support the user in finding the correct depth for the measurement (OTT ADC leaflet).

Fig. 3 Discharge measurement with OTT ADC

The results of measurements can be displayed on the instrument right after the measurement is completed. Data from the ADC can be downloaded to a pc. The software OTT QReview can be used to download, display and revise data (Fig. 4).

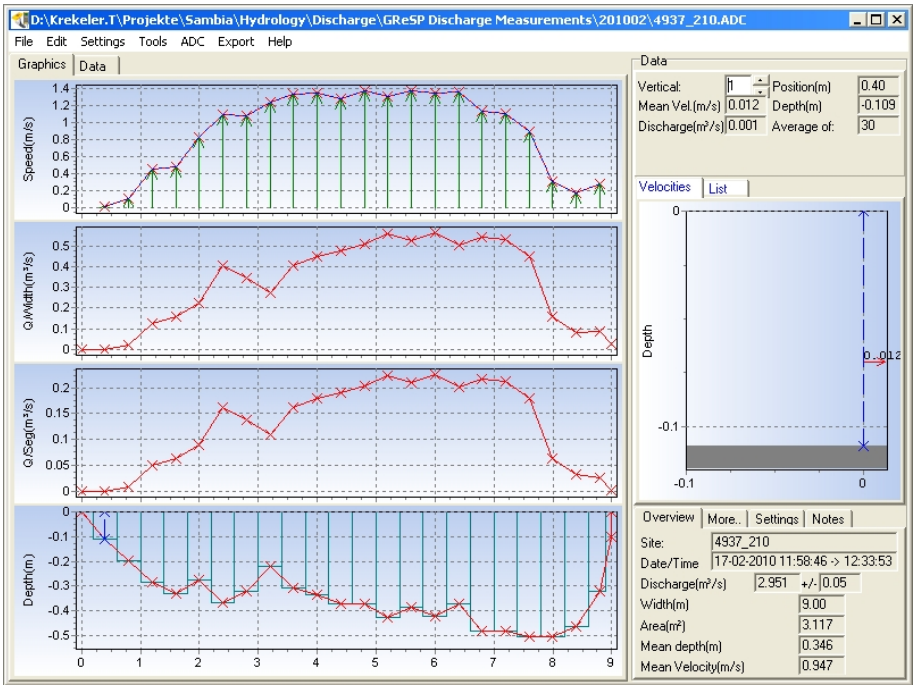

Fig. 4 Result of discharge measurement with ADC

For high water levels where wading is not possible, an ADCP (Acoustic Doppler Currentmeter Profiler, OTT QLiner) was used.

This instrument also uses ultrasonic sound for the discharge measurement. The probe is fixed on a float that bears it about 4 cm below the water surface. The QLiner measures the

water depth and the flow velocity in different depths. Unlike most ADCP the QLiner does not use bottom track or GPS. The instrument was manually fixed in position by a rope and the measurement was carried out stationary after the section-by-section method.

Fig. 5 Discharge measurement with OTT QLiner

A pocket pc was used to control the measurement and to store data via Bluetooth®. The results of measurements can be displayed on this pocket pc after the measurement is completed. Data are stored in the pocket pc and can be transferred to a pc using ActiveSync software. The software OTT QReview can be used to download, display and revise data (Fig. 6).

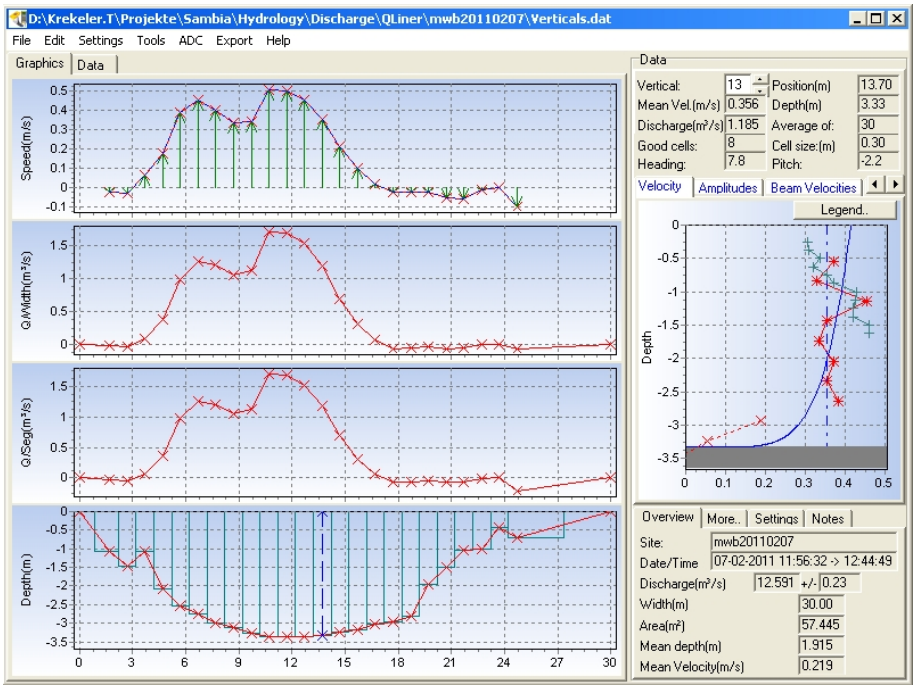

Fig. 6 Result of discharge measurement with QLiner

Several measurements were carried out at different water levels at all stations. The reason was to figure out a clear relation between water level and discharge. As the water level was recorded three times a day, the annual discharge could be calculated from these data, if a clear mathematical stage/discharge relation was determined.

3 Inter- and extrapolation of data

3.1 Water surface profile calculation at natural channels

3.1.1 Manual extrapolation of stage / discharge relations

If stage data were measured that are beyond levels that have corresponding discharge values, it will be necessary to extend the stage/discharge curve.

This can be achieved by developing stage/area and stage/velocity curves. The curves are extended and discharge values beyond the values that are measured were calculated after

$Q = v \cdot A$ (1)

Where: Q = discharge [m³/s]

v = velocity [m/s]

A = area [m²]

The area of the cross section is measured with each discharge measurement. The stage/area curve was extended by levelling cross sections. An example for the development of the stage/area relation for Chunga is given in Fig. 7.

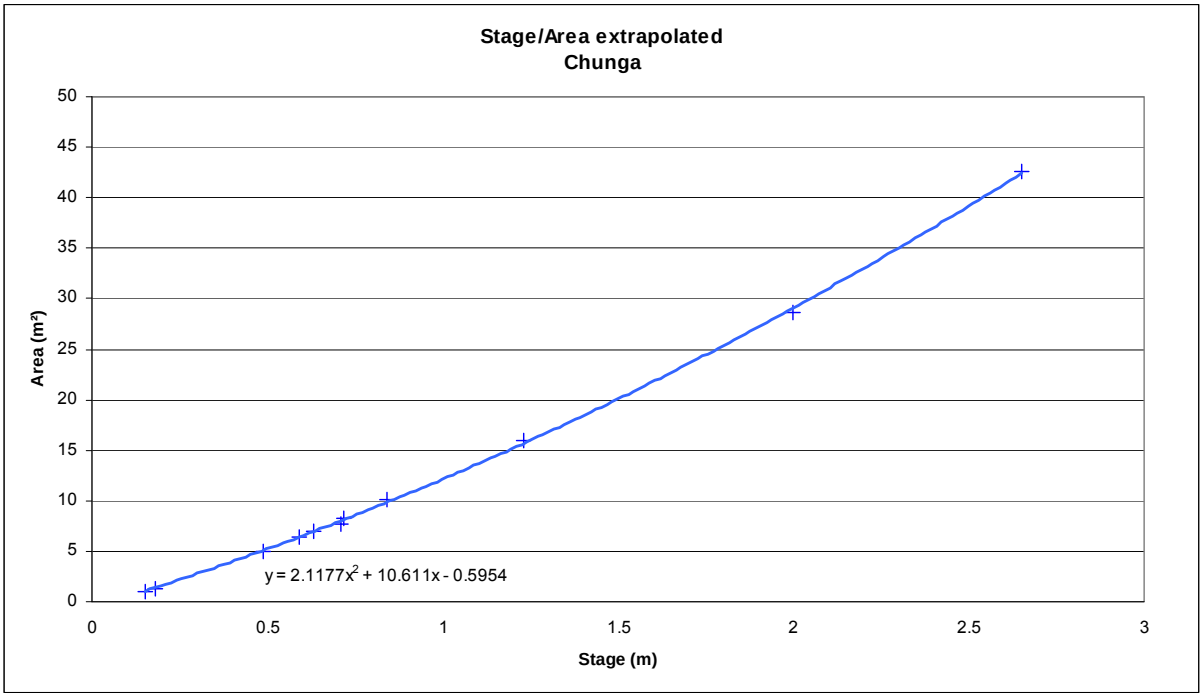

Fig. 7 Stage/area curve for Chunga extended by levelled data

The stage/velocity curve was extrapolated by values calculated using the Manning formula (Maidment 1993).

$$v = \frac{r_{hy}^{2/3} i^{1/2}}{n} \qquad (2)$$

Where: v = velocity [m/s]

r_{hy} = hydraulic radius (A/P_{wet}) [m]

A = area [m²]

P_{wet} = wetted perimeter [m]

i = slope [1]

n = roughness (Manning's n) [1]

An example for the development of the stage/velocity relation with the Manning formula is given in Fig. 8.

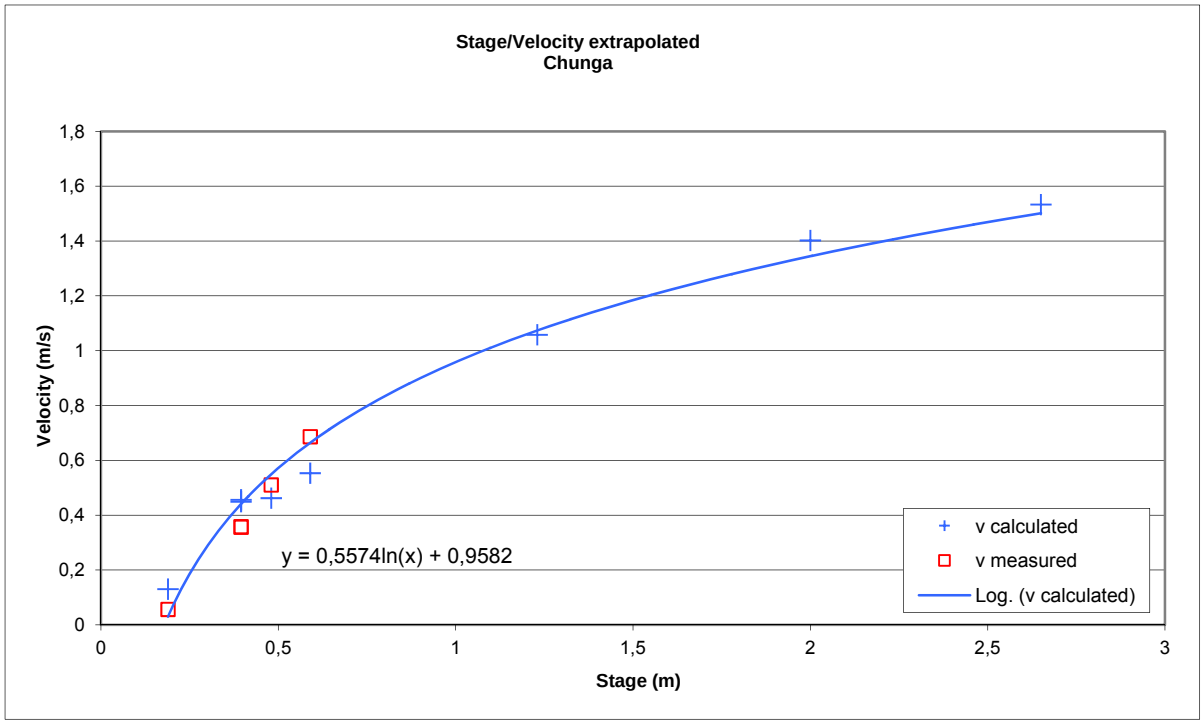

Fig. 8 Extrapolated stage/velocity curve for Chunga

Calculated discharge data for Chunga stream gauge are given in Table 1.

Table 1 Manually calculated discharge values

h [m]	A [m²]	v [m/s]	Q [m³/s]
1.23	15.93	1.058	16.848
2.00	28.63	1.402	40.130
2.65	42.59	1.533	65.309

The next steps in the development of rating curves are described in chapter 4.

3.1.2 Stage / discharge calculation with HEC-RAS

In addition to the manual extrapolation of stage/discharge relations, a numerical model was used. The water surface profiles were calculated with the one-dimensional model HEC-RAS (US Army Corps of Engineers - Hydraulic Engineering Centre – River Analysis System). Brunner (2008a) and Brunner (2008b) give detailed information about this software.

The basic computational procedure is based on the one-dimensional energy equation (Brunner, 2008b).

$$Z_2 + Y_2 + \frac{a_2 V_2^{\,2}}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^{\,2}}{2g} + h_e \qquad (3)$$

Where: Z_1, Z_2 = *elevation of the main channel inverts [m]*

Y_1, Y_2 = *depth of water at cross sections [m]*

V_1, V_2 = *average velocities (total discharge / total flow area) [m/s]*

a_1, a_2 = *velocity weighting coefficients [1]*

g = *gravitational acceleration [m/s²]*

h_e = *energy head loss [m]*

The energy head loss (he) between two cross sections comprises friction losses and contraction or expansion losses. The equation for the head losses is as follows:

$$h_e = L\bar{S}_f + C\left|\frac{a_2 V_2^{\,2}}{2g} - \frac{a_1 V_1^{\,2}}{2g}\right| \qquad (4)$$

Where: L = *discharge weighted reach length [m]*

$\bar{S}_f$ = *representative friction slope between two sections (slope of the energy grade line)[1]*

C = *expansion or contraction loss coefficient [1]*

$$L = \frac{L_{lob}\bar{Q}_{lob} + L_{ch}\bar{Q}_{ch} + L_{rob}\bar{Q}_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \qquad (5)$$

Where: L_{lob}, L_{ch}, L_{rob} = *cross section reach length specified for flow in the left overbank, main channel and right overbank, respectively [m]*

$\bar{Q}_{lob}, \bar{Q}_{ch}, \bar{Q}_{rob}$ = *arithmetic average of the flow between sections for the left overbank, main channel and right overbank, respectively [m³/s]*

The Mean Kinetic Energy Head (or Discharge-Weighted Velocity Head) and the velocity coefficient 'a' are calculated after the formula:

$$a\frac{\bar{V}^2}{2g} = \frac{Q_1\frac{V_1^{\,2}}{2g} + Q_2\frac{V_2^{\,2}}{2g}}{Q_1 + Q_2} \qquad (6)$$

3.1.3 Entering data into the model

The schematics showing the course of the rivers are geo-referenced (Fig. 9): making use of Google Earth® the river courses were digitised and by using the ArcGIS application HEC-GeoRAS the datasets were transferred to HEC-RAS. When digitising the schematics it is important to digitise in flow-direction.

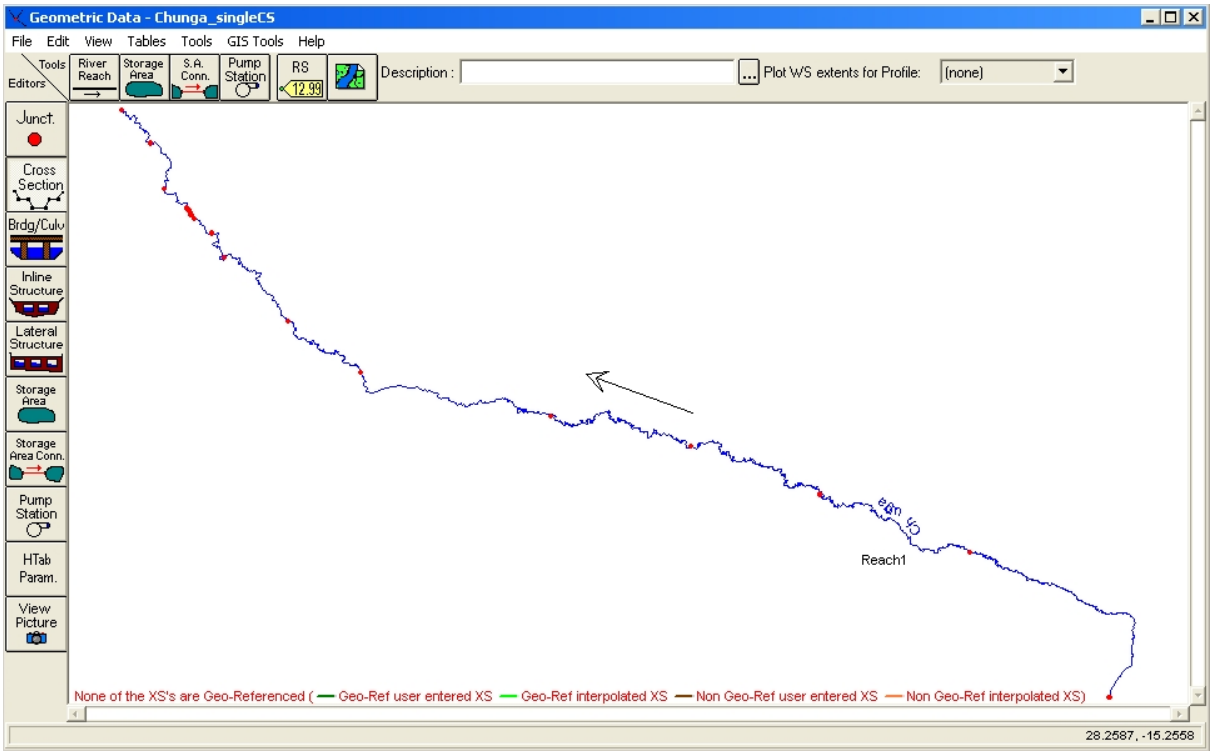

Fig. 9 Schematic of Chunga imported to HEC-RAS

The slopes of the entire rivers were estimated by the determination of benchmarks with Differential GPS. The cross sections at the gauging stations were levelled with reference to benchmarks. The cross-section data were entered into the model by copying station and level data into the target table (Fig. 10) and the location of the cross-section within the reach was defined by the river station and the distance to the next cross-section downstream (downstream reach length).

In natural rivers where no weirs or other structures control the level/discharge relation, about four cross-sections were measured: one at the gauging station, one upstream and two downstream. The exact locations were chosen depending on the shape of the valley.

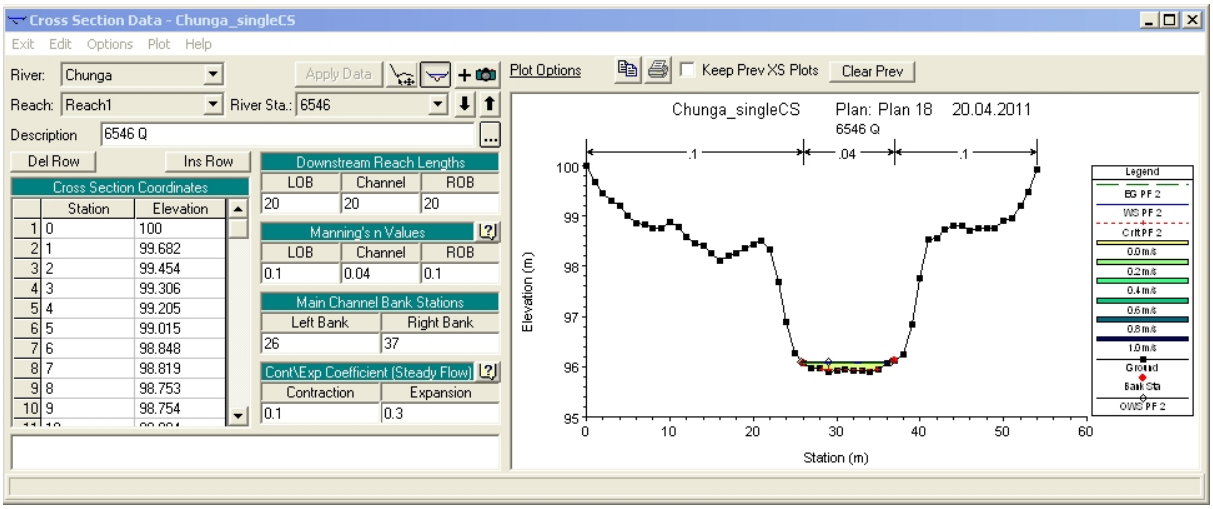

Fig. 10 Cross-section of Chunga gauging station imported to HEC-RAS

To enhance the geometric conditions for the calculation, more cross-sections were interpolated by making use of a HEC-RAS tool. The distance between two cross-sections was specified to be 50 m.

The model calculates water surface profiles for discharge volumes that are predetermined by the user. Water level data from the cross-sections that are located at the gauging stations and the corresponding discharge data are used to determine the rating curve (chapter 4).

3.2 Water surface calculation at weirs

Two of the gauging stations are equipped with weirs. These are Ngwerere River at Estate Weir, and Kapwelyomba River at Khalamazi Farm. Both weirs are broad-crested weirs that consist of two controls.

It is important to distinguish between the flow over a weir a clear overfall and a diving or submerged overfall. A clear overfall can alter into a submerged overfall if the water level rises (Fig. 11).

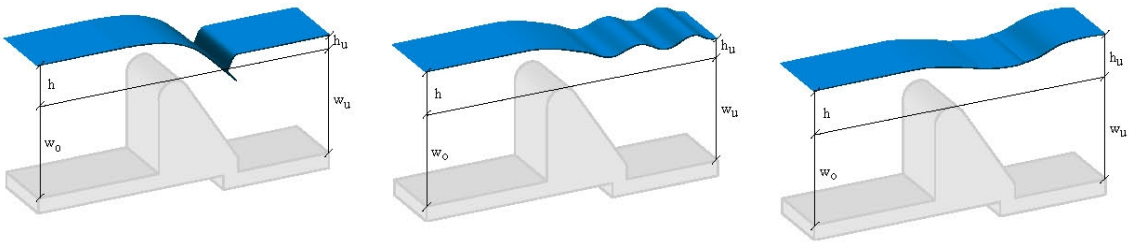

Fig. 11 Clear overfall weir and submerged weir (Peter 2002)

In case of a **clear overfall** the discharge through weirs was calculated for every single control after the Poleni formula

$$Q = C_h \cdot b \cdot h^{\frac{3}{2}} \qquad (7)$$

Where: Q = Discharge [m³/s]

b = width of the weir [m]

h = upstream water level above weir bottom [m]

C_h = overfall coefficient [$m^{1/2}/s$]

with $$C_h = a_1 + \frac{a_2}{\left[1+\left(\frac{x-a_3}{a_4}\right)^2\right]} + \frac{a_5}{\left[1+\left(\frac{y-a_6}{a_7}\right)^2\right]} + \frac{a_8}{\left[1+\left(\frac{x-a_3}{a_4}\right)^2\right]} \cdot \left[1+\left(\frac{y-a_6}{a_7}\right)^2\right] \quad (8)$$

Where: $x = \frac{w_0}{h}$ $y = \frac{r}{w_0}$ (see Fig. 12)

Table 2 Parameters for clear overfall weir calculation

a_1	1.68916268
a_2	2.06702945
a_3	-0.57061547
a_4	0.30562981
a_5	-0.96301454
a_6	-0.10942429
a_7	0.06203078
a_8	4.25768196

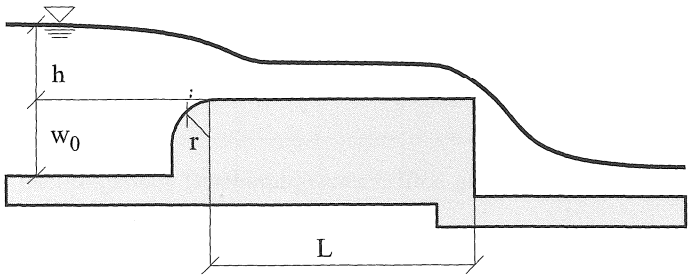

Fig. 12 Weir profile (Peter 2005)

The flow over a **submerged weir** was calculated using the formula

$$Q = C_h \cdot \varphi \cdot b \cdot h^{\frac{3}{2}} \quad (9)$$

Where: Q = Discharge [m³/s]

C_h = overfall coefficient [$m^{1/2}/s$]

φ = reduction factor [1]

b = width of the weir [m]

with $$C_h = 1.70905 - 0.1668 \cdot \left(\frac{h_u}{h_u + w_u}\right) + 0.6384 \cdot \left(\frac{h_u}{h_u + w_u}\right)^2 \quad (10)$$

Where: h_u = downstream water level [m]

w_u = downstream weir height [m]

Boundaries: $$0.15 < \frac{h_u}{h_u + w_u} < 0.75$$

and

$$\varphi = a_1 \cdot x_1^{\,3} + a_2 \cdot x_1^{\,3} \cdot x_2^{\,3} + a_3 \cdot x_1^{\,3} \cdot x_2^{\,2} + a_4 \cdot x_1^{\,3} \cdot x_2 + a_5 \cdot x_1^{\,2} + a_6 \cdot x_1^{\,2} x_2^{\,3} + a_7 \cdot x_1^{\,2} \cdot x_2^{\,2} + a_8 \cdot x_1^{\,2} \cdot x_2 + a_9 \cdot x_1 + a_{10} \cdot x_1 \cdot x_2^{\,3} + a_{11} \cdot x_1 \cdot x_2^{\,2} + a_{12} \cdot x_1 \cdot x_2 + a_{13} \cdot x_2 + a_{14} \cdot x_2^{\,2} + a_{15} \cdot x_2^{\,3}$$

$$x_1 = \frac{h_u}{(h_u + w_u)} \qquad x_2 = \frac{h_u}{h}$$

Table 3 Parameters for submerged weir calculation

Parameters for 0.4 < φ < 0.85		and for 0.85 < φ < 1	
a_1	-7708.23	a_1	1201.04
a_2	8782.23	a_2	-1445.32
a_3	-25177.72	a_3	4076.89
a_4	24104.38	a_4	-3837.45
a_5	8535.80	a_5	-2281.50
a_6	-9483.13	a_6	2888.11
a_7	27416.97	a_7	-8022.19
a_8	-26469.92	a_8	7420.42
a_9	-1747.64	a_9	1085.89
a_{10}	1687.74	a_{10}	-1334.30
a_{11}	-5127.06	a_{11}	3762.62
a_{12}	5186.61	a_{12}	-3513.02
a_{13}	52.48	a_{13}	-58.42
a_{14}	-101.85	a_{14}	143.78
a_{15}	49.72	a_{15}	-86.59

Like the procedure for natural channels described in chapter 3.1, stage was calculated for different discharge volumes until the discharge corresponding to the highest expected water levels were determined. Using MS Excel, rating curves are determined from the computed level and discharge data (chapter 4).

4 Rating curves

The relation between water level and discharge can be outlined with rating curves. It is generally important that the measurements cover a high range of stages and discharges.

Rating curves usually comply with the formula $Q = C \cdot (h + a)^N$ (11)

Where: Q = Discharge [m³/s]

C = Calibration parameter [1]

h = Water level [m]

a = Water level at which discharge is zero [m]

N = Calibration parameter [1]

Possibly a change in the flow regime at a certain water level might occur. The reason can be a change in the cross-section geometry, change in plant cover and therefore in roughness or a flood of the banks. In this case the rating curve is split into two parts.

4.1 Chunga

Discharge at Chunga was measured eleven times between December 2009 and February 2011. For five measurements stage data are available. Older discharge data cannot be used for the establishment of a rating curve since the gauging station was established in 2009 by GReSP.

For the development of the rating curve at Chunga gauging station with HEC-RAS three measured cross sections were used:

1. the gauging station
2. the ford, 20 m downstream
3. a third profile 50 m downstream of the ford

This part of Chunga shows generally a uniform morphology. Upstream are some dams along the main river channel. The confluence with Mwembeshi is about 6.5 km downstream of the gauging station. During dry season the discharge of Mwembeshi is much smaller than the Chunga discharge. The reason is a constant discharge from the Chunga wastewater treatment plant into Chunga.

HEC-RAS provides a tool to work out rating curves from modelled data (Fig. 13).

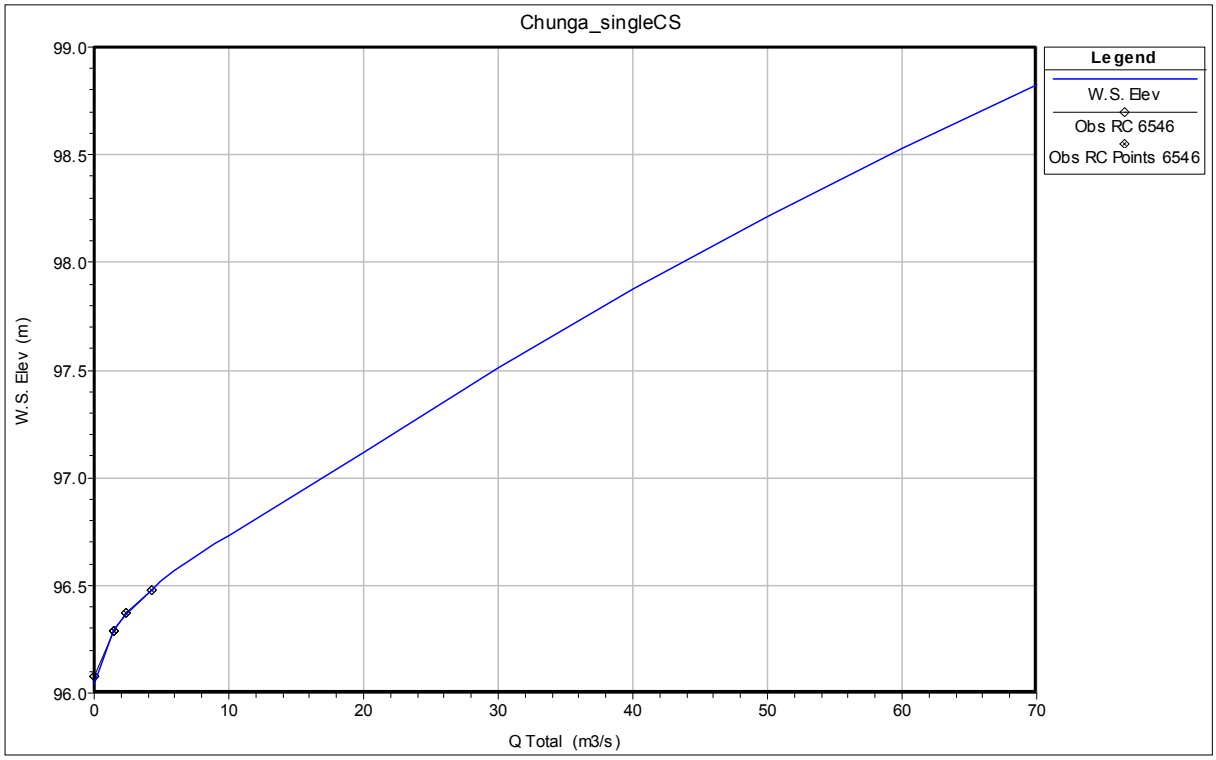

Fig. 13 Chunga rating curve generated with HEC-RAS

Stage – discharge data gained from HEC-RAS (Q modelled), manually extrapolated data as described in chapter 3.1.1 (Q calculated) and measured data (Q measured) were finally combined into one diagram (Fig. 14 for Chunga) and were evaluated.

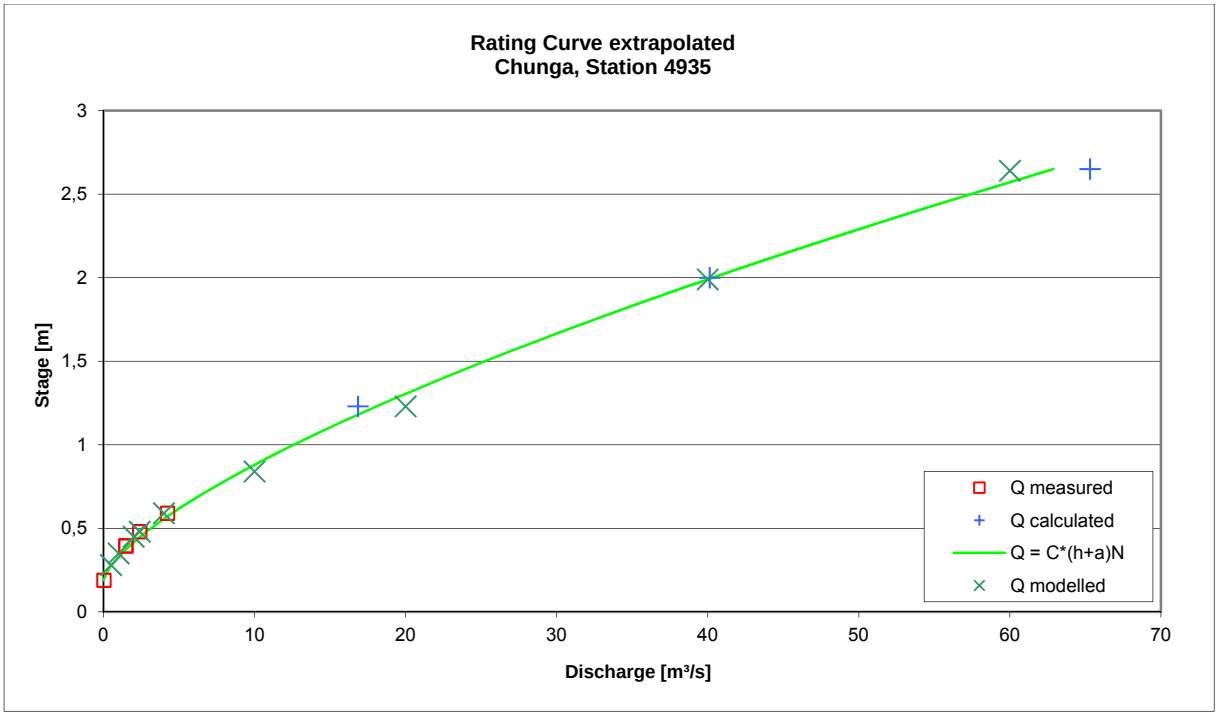

Fig. 14 Q/h relation – measured, manually extrapolated and modelled data

Discharge at Chunga can be calculated after the formula

$$Q[m^3/s] = 17.06 \cdot (h[m] - 0.19)^{1.448} \qquad (12)$$

4.2 Chongwe

Station 5025 is located at Great East Road bridge. The river Chongwe is the biggest river in the project area. As this gauging station was established by DWA and had been operated for many years, there are historic data available from this site (Fig. 15).

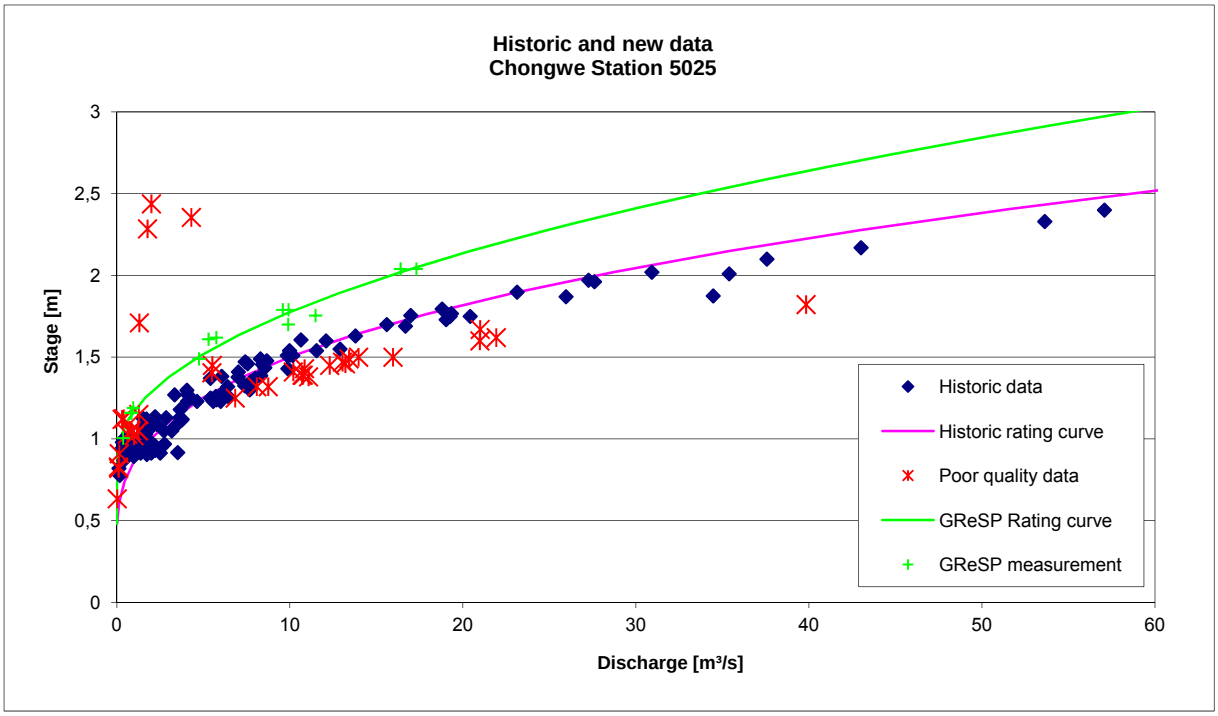

Fig. 15 Chongwe: Q/h relation – historic and new data

Newly measured data (displayed in light green) are highly different from the historic data.

The newly gained fourteen datasets of stage and corresponding discharge (Fig. 16) were received by measurements with the OTT ADC and with the OTT QLiner. They generally fit very well; hence all available data from GReSP measurements were used for the calibration of this gauging station.

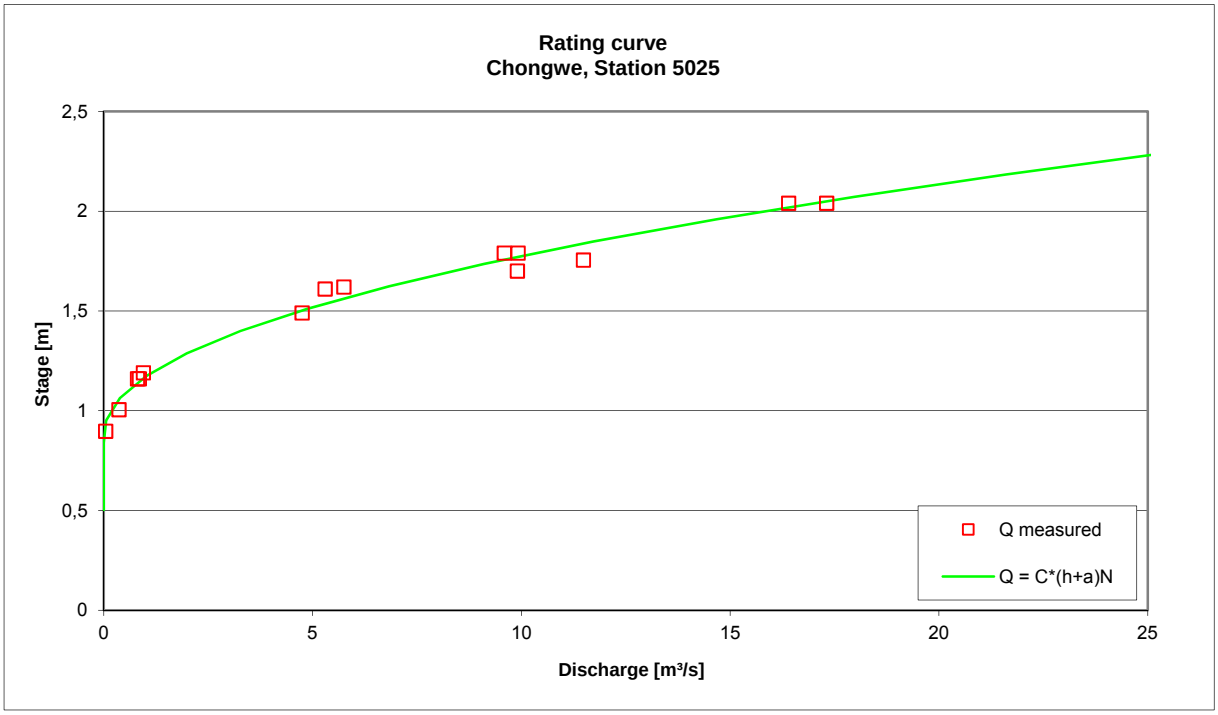

Fig. 16 Rating curve for Chongwe from measured data (Station 5025)

The rating equation for Chongwe is:

$$Q[m^3/s] = 12.54 \cdot (h[m] - 0.88)^{2.051} \qquad (13)$$

4.3 Ngwerere

The historic data and data acquired from GReSP project from Ngwerere are displayed in Fig. 17. In the historic water level recording extreme changes can be observed during the following years and dates: 1971, 1978, 1981, 1986, 19.04.1989, 1.10.1989, 1.10.1991, 1.06.1998, 1.10.1998, 1.01.2000, 26.01.2000 and 1.01.2008.

Most probably the observed abrupt changes are due to the weir construction or modification in the river cross section.

In general the stage/discharge relation of the GReSP measurements is quite clear (Fig. 17) and the measured values fit with weir discharge calculations (Fig. 18).

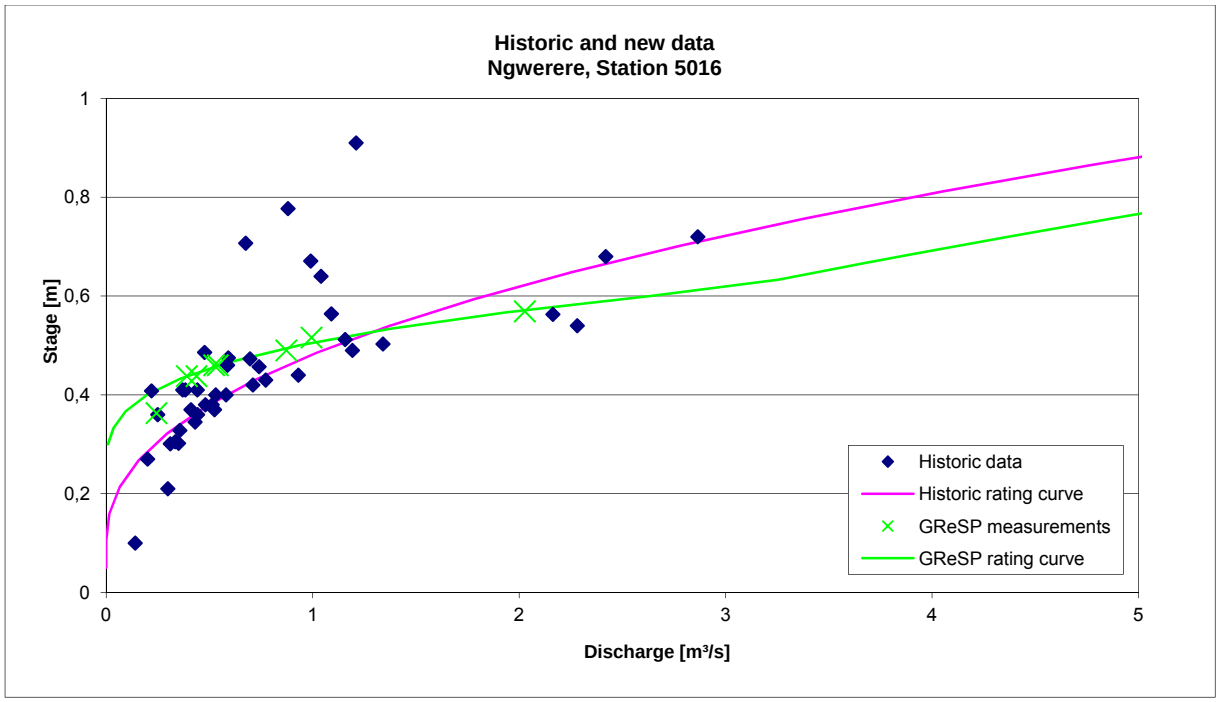

Fig. 17 Historic and new data from Ngwerere (Station 5016)

Discharge at Ngwerere was measured eight times by the GReSP project between June 2009 and February 2011. To calibrate this station, more values are necessary. As there is a weir downstream of the Ngwerere station, the calculation of the stage/discharge relation was carried out by making use for the weir formula presented in chapter 3.2.

The results are calibrated using the measured values.

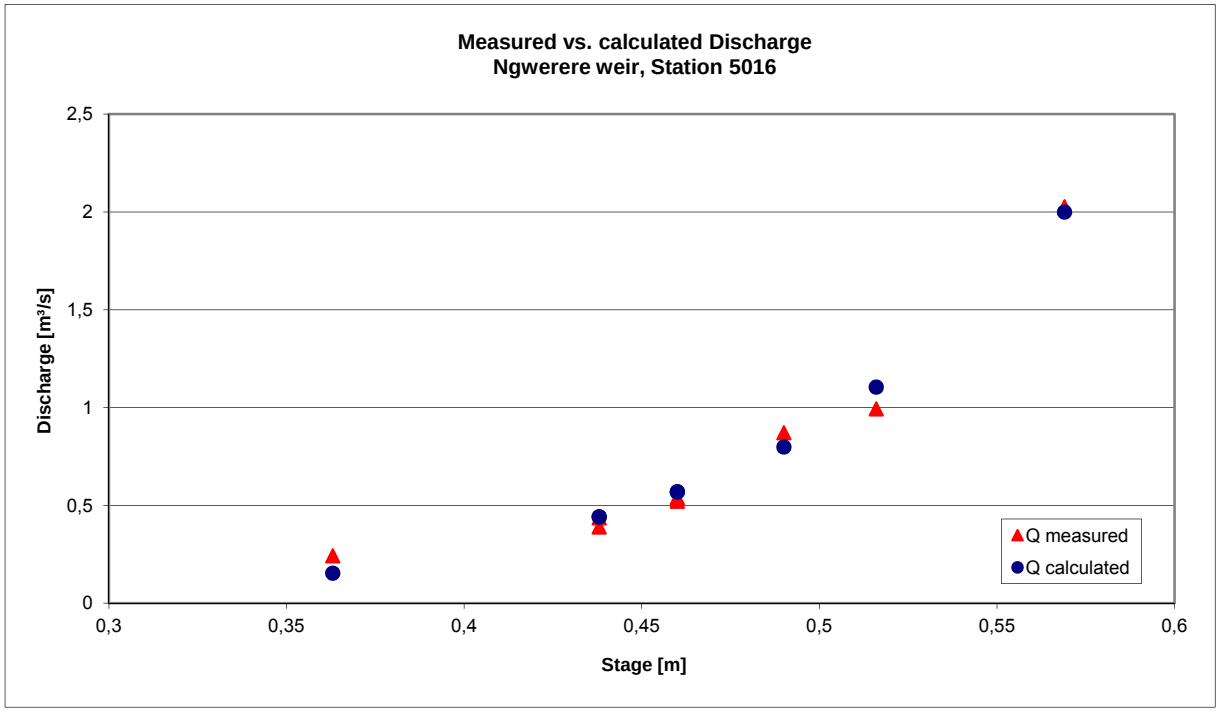

Fig. 18 Q/h relation - measured and calculated data at Ngwerere weir

A weir that consists of two controls with different widths and different heights usually generates two different flow patterns: if water levels are low only the lower control is

responsible for the stage/discharge relation, while at higher water levels water flows through both controls, which generates a completely different stage/discharge relation.

Ngwerere has a quite high discharge during the dry season, because the upstream located Gardens wastewater treatment plant permanently releases water into the stream. Due to high discharge, usually both controls of the weir are flowing.

The flow through the weir was modelled with HEC-RAS. The rating curve generated with HEC-RAS is displayed in Fig. 19.

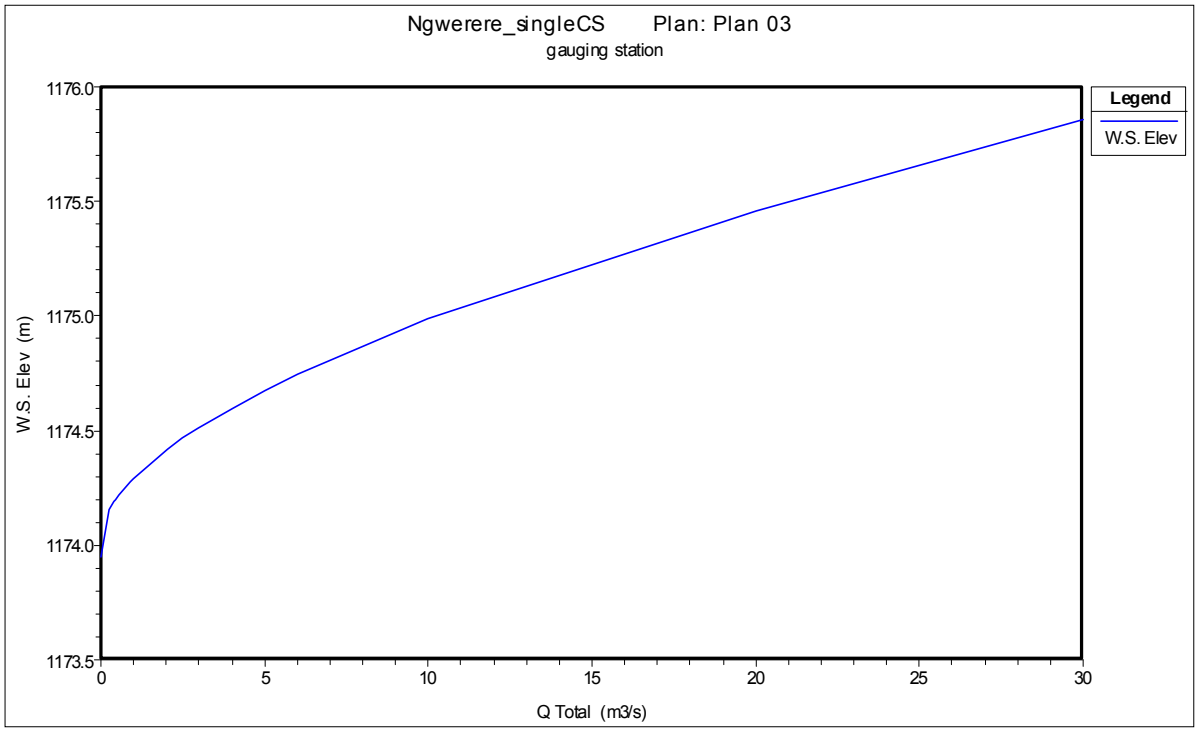

Fig. 19 Rating Curve for Ngwerere, Station 5016 generated with HEC-RAS

At high water levels it is likely, that the flow over the weir turns into a submerged overfall (ch. 3.2). The stage where this flow change occurs is unknown. In this case a rating curve for a clear overfall and a curve for a submerged overfall was calculated. The flow change was assumed at the intersection of both curves (Fig. 20).

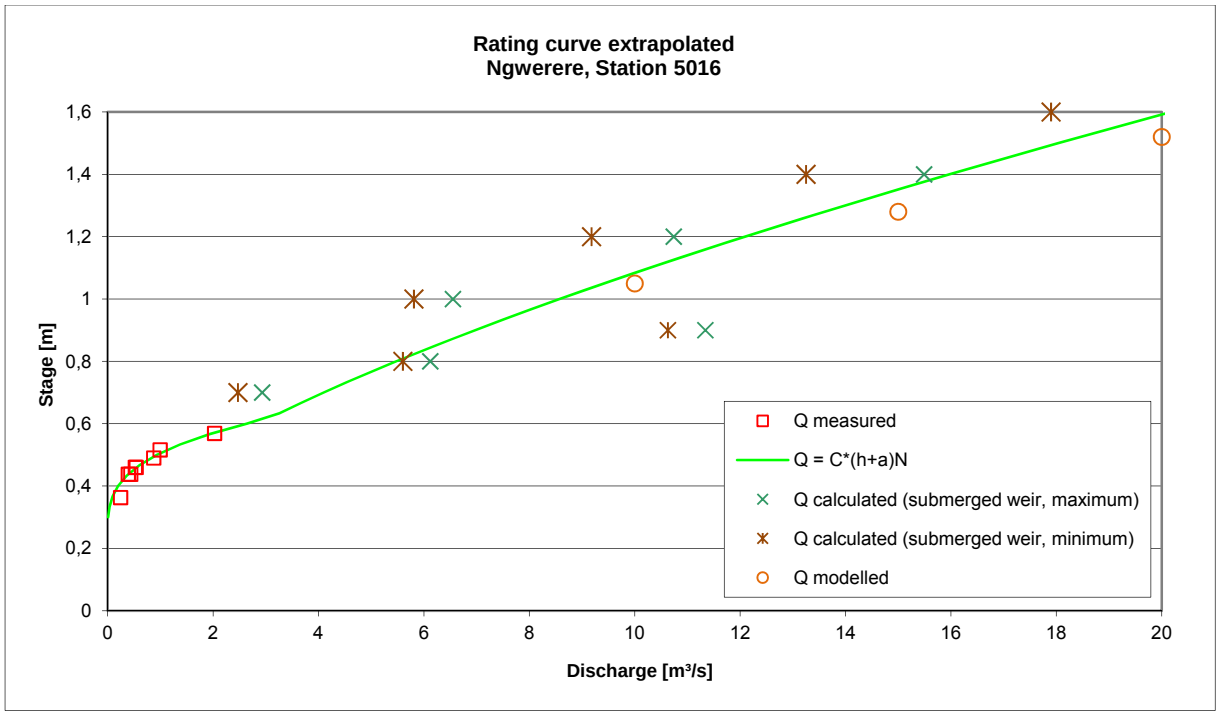

Fig. 20 Rating Curve for Ngwerere, Station 5016

The scatter of the calculated points shows the inaccuracy of this curve. More measurements at high water levels would be very useful.

Preliminary rating equation for Ngwerere at water levels below 65 cm:

$$Q[m^3/s] = 69.04 \cdot (h[m] - 0.24)^{3.196} \qquad (14)$$

For water levels above 65 cm the preliminary equation is as follows:

$$Q[m^3/s] = 12.84 \cdot (h[m] - 0.24)^{1.471} \qquad (15)$$

4.4 Kapwelyomba

Historic data as well as newly gained data are displayed in Fig. 21.

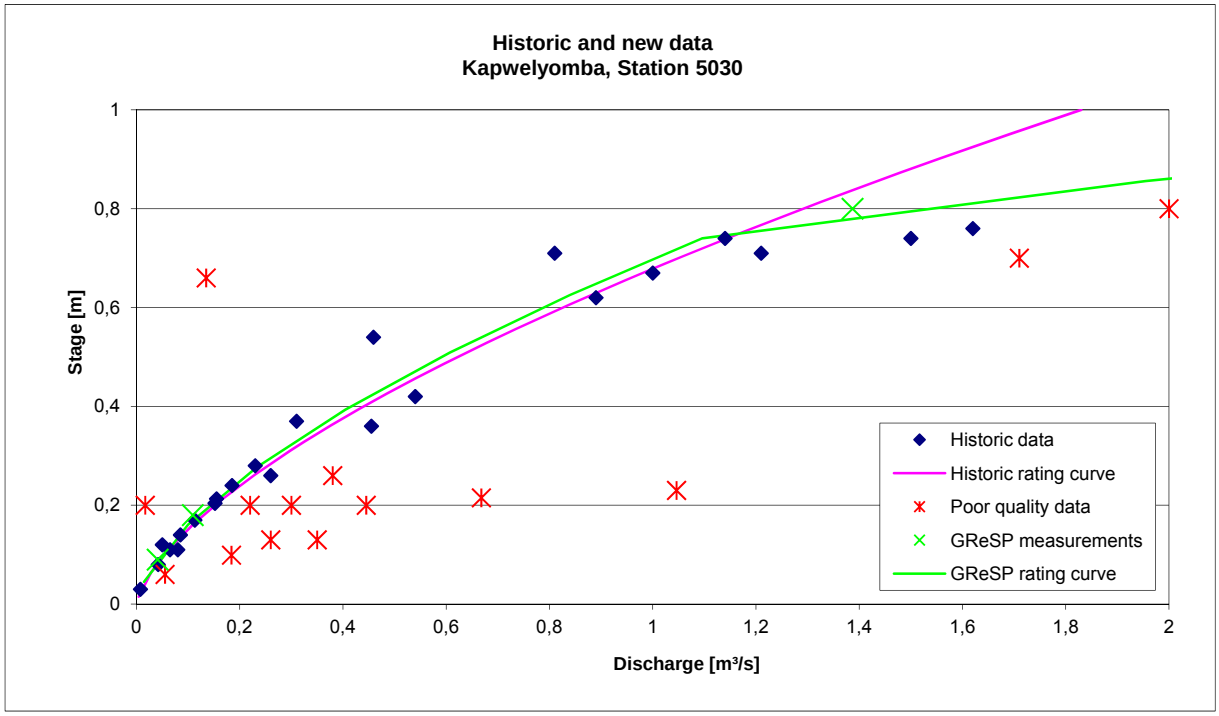

Fig. 21 Historic and new data from Kapwelyomba, Station 5030

Discharge at Kapwelyomba was measured twelve times between June 2009 and February 2011, but as the associated level data were lost (no notes about levels were taken when discharge measurements were carried out as levels were recorded by a gauge reader, but the gauge reader lost the book with level data). Only three datasets with discharge values and associated water levels are available. As there is a weir at the Kapwelyomba station, the calculation of the level/discharge relation was carried out by using a weir formula.

Fig. 22 Weir Kapwelyomba, rainy season and dry season

The discharge through the weir was calculated after the Poleni formula (ch. 3.2). The results of measured and calculated data are compared in Fig. 23.

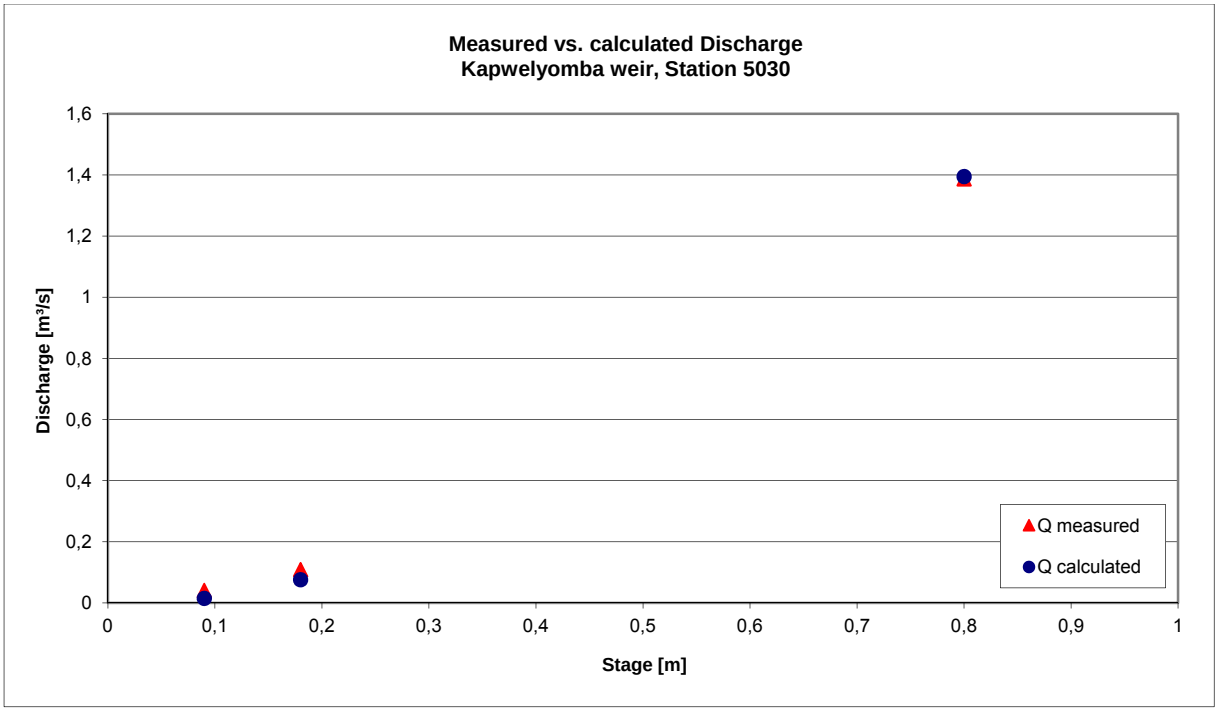

Fig. 23 Q/h relation - measured and calculated data at Kapwelyomba weir

Unlike Ngwerere, the base flow at Kapwelyomba is small. During the dry season and parts of the rainy season the complete discharge flows through the small control (Fig. 22). The base of the wide control is 74 cm above the base of the small control. Hence, water flows through the wide control if the water level is at least 74 cm above the site datum.

The flow through the weir is therefore clearly bifid and the rating curve corresponds to this figure. There is a clear change at the level of 74 cm. Due to the loss of level data, only one measurement above this site datum is available (Q = 1.387 m³/s; h = 0.80 m)

Water levels were calculated with HEC-RAS and manually with a weir formula. The rating curve calculated by HEC-RAS is displayed in Fig. 24.

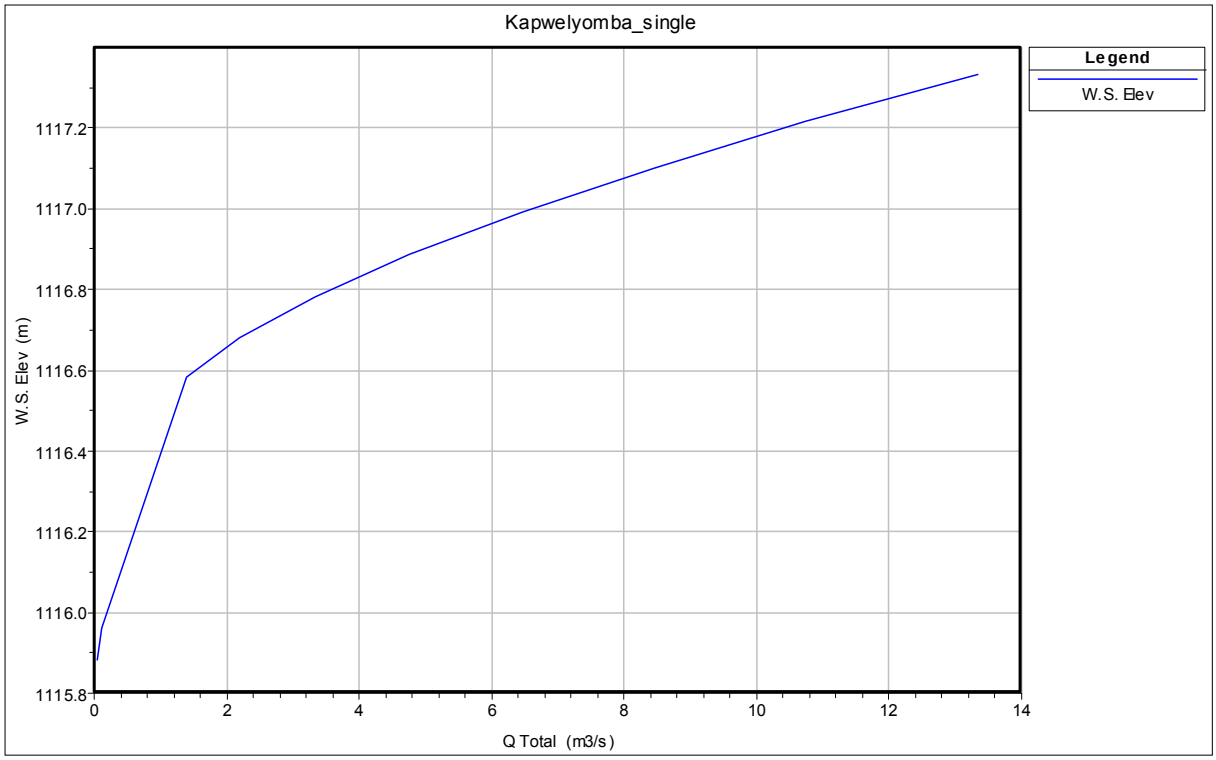

Fig. 24 Rating curve for Kapwelyomba generated with HEC-RAS from modelled data

The manually calculated rating curve containing measured values, values calculated with a weir formula and modelled values is shown in Fig. 25.

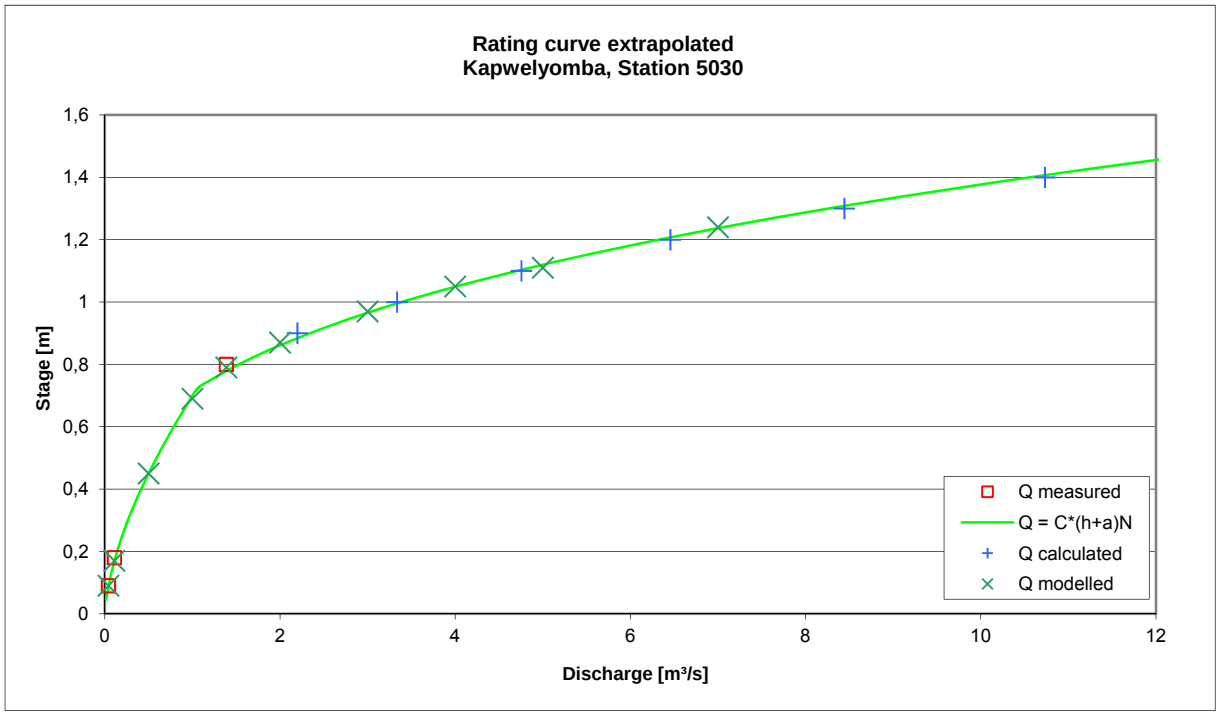

Fig. 25 Rating curve for Kapwelyomba (Station 5030)

Rating equation for Kapwelyomba at water levels below 74 cm:

$$Q[m^3/s] = 1.75 \cdot (h[m] + 0.004)^{1.588} \quad (16)$$

For water levels above 74 cm the equation is as follows:

$$Q[m^3/s] = 5.74 \cdot (h[m] - 0.17)^{2.9} \quad (17)$$

Water levels above 80 cm seldom occur at Kapwelyomba station. This minimises the possibility of submergence of this weir. Here the calculation of the weir as a clear overfall is considered sufficient.

4.5 Chalimbana

At Chalimbana River eleven discharge measurements were carried out between June 2009 and February 2011. Data of measurements from between 1996 and 2004 by DWA are also displayed in Fig. 26.

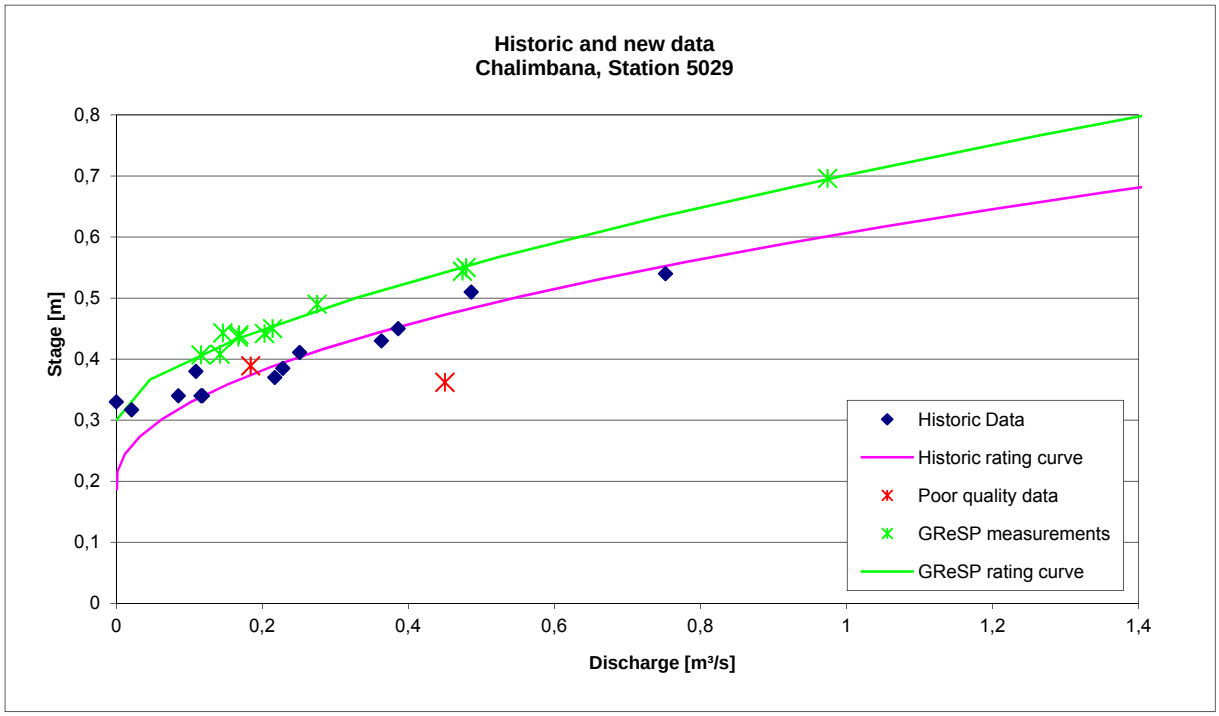

Fig. 26 Q/h relation at Chalimbana gauging station

For the calculation of the rating curve at Station 5029 (Chalimbana River) with HEC-RAS three measured cross sections were used:

1. the gauging station (it is located in a pool 10 m upstream of a weir)
2. the weir
3. a third cross section 20 m downstream of the weir

Chalimbana shows an unsteady morphology. The gauging station is located directly upstream of an old weir. The weir is in a bad shape and partly broken, but nevertheless has a substantial influence on the water level. Hence, excessive surveying downstream of the weir was not necessary.

For the development of the new rating curve, data measured by the GReSP project and modelled data (chapter 3.1.2) were used. As the weir has only one rectangular control, the stage/area curve can simply be linearly extended. Extrapolation of the stage/velocity curve was not reasonable by simple flow calculation after Manning, because the shape of Chalimbana is extremely unsteady.

A logarithmical extension of the stage / velocity curve led to the same result as the model.

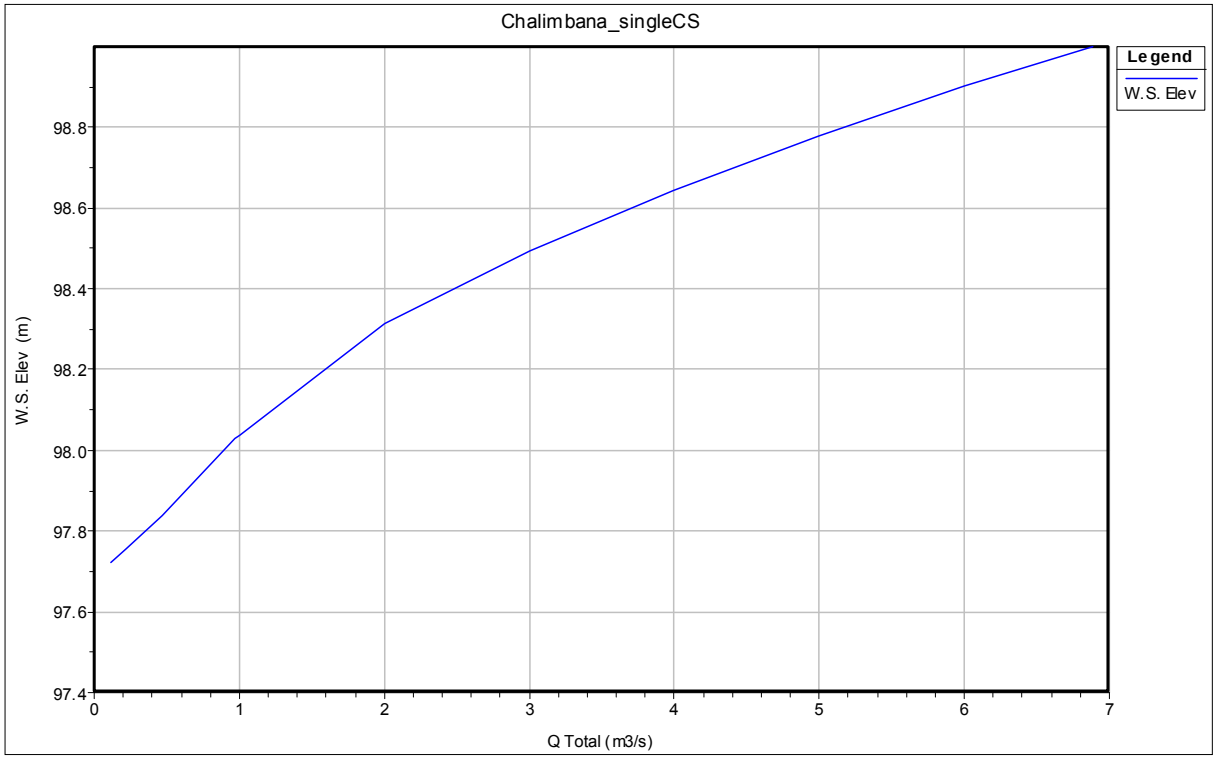

Fig. 27 Rating curve for Chalimbana generated with HEC-RAS from modelled data

The rating curve exported from HEC-RAS (Fig. 27) shows a similar shape as the curve that was generated from measured and calculated data (Fig. 28).

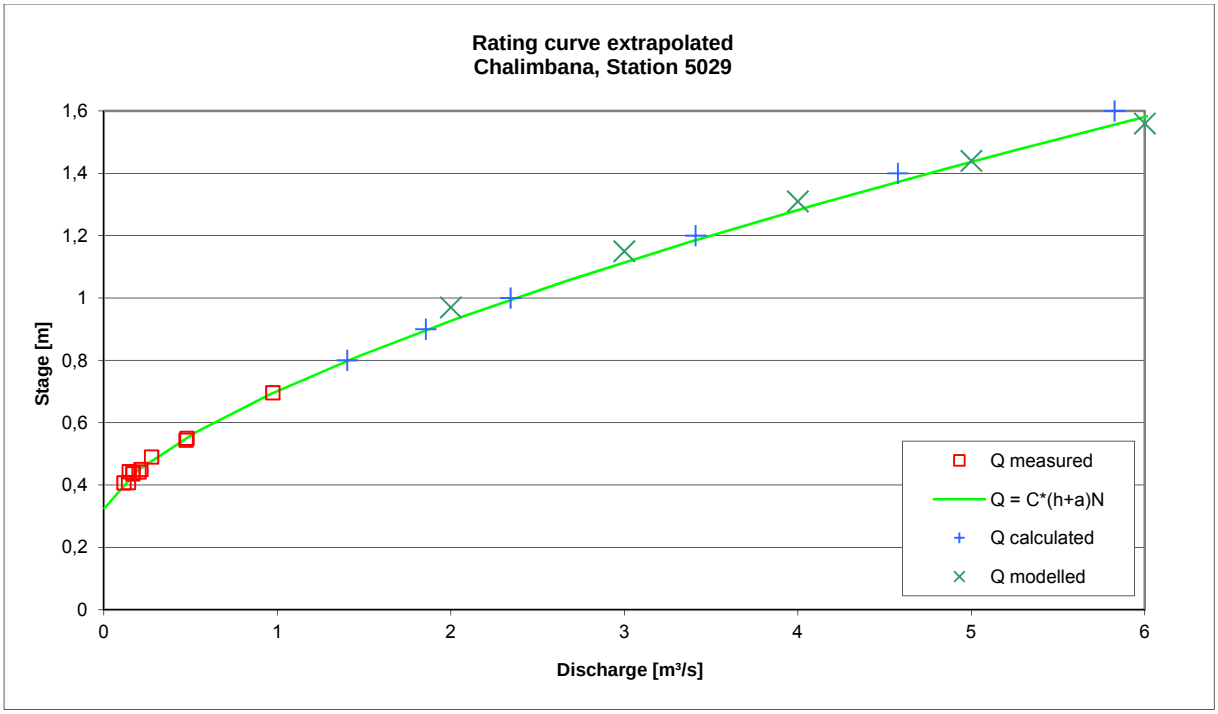

Fig. 28 Rating curve Chalimbana generated from measured and modelled data

Chalimbana rating equation is as follows:

$$Q[m^3/s] = 4.21 \cdot (h[m] - 0.32)^{1.507} \qquad (18)$$

4.6 Chilongolo

Discharge at Chilongolo River was measured twelve times. No gauging station was installed at Chilongolo, because this river is located in the Kafue flats where high water levels cause floods and no measurement of discharge is possible, thus no Q/h-relation can be determined. Results of discharge measurements at Chilongolo are summarised in Table 4.

Table 4 Measured discharge values at Chilongolo

Date	Time	Discharge (m^3/s)
09.06.2009	16:00	0.006
24.06.2009	12:00	0.019
29.07.2009	12:00	0.022
29.07.2009	13:00	0.029
25.08.2009	13:00	0.032
21.09.2009	14:00	0.042
17.10.2009	13:00	0.022
01.12.2009	15:00	0.393
15.12.2009	14:00	0.281
10.02.2010	16:00	0.44
31.03.2010	12:00	0.431
31.03.2010	13:00	0.399

4.7 Mwembeshi

Some historic stage and discharge data from Mwembeshi station are available. They differ strongly from the data measured by the GReSP project (Fig. 29).

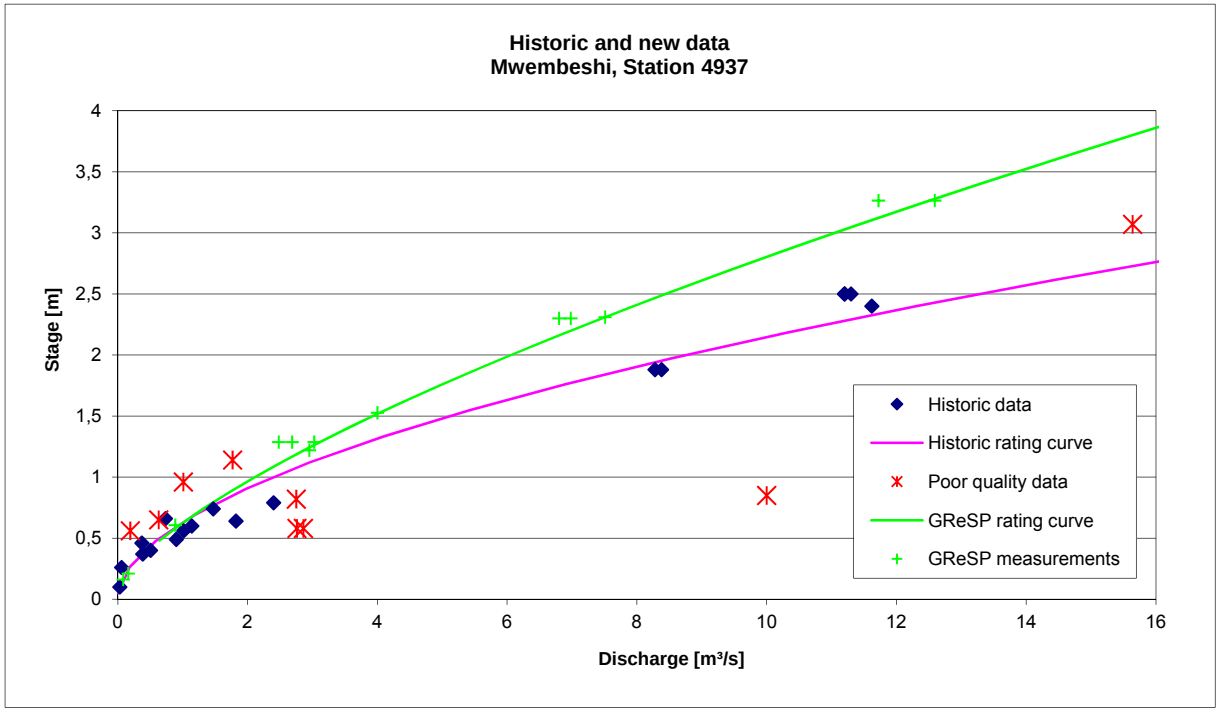

Fig. 29 Historic and new data at Mwembeshi gauging station (Station 4937)

For the elaboration of the rating curve for this station, only the newly gained data were evaluated. Discharge at Mwembeshi was measured fourteen times between June 2009 and February 2011. Stage and discharge values were gained in a wide range and fit well (Fig. 30). No further stage and discharge values were calculated.

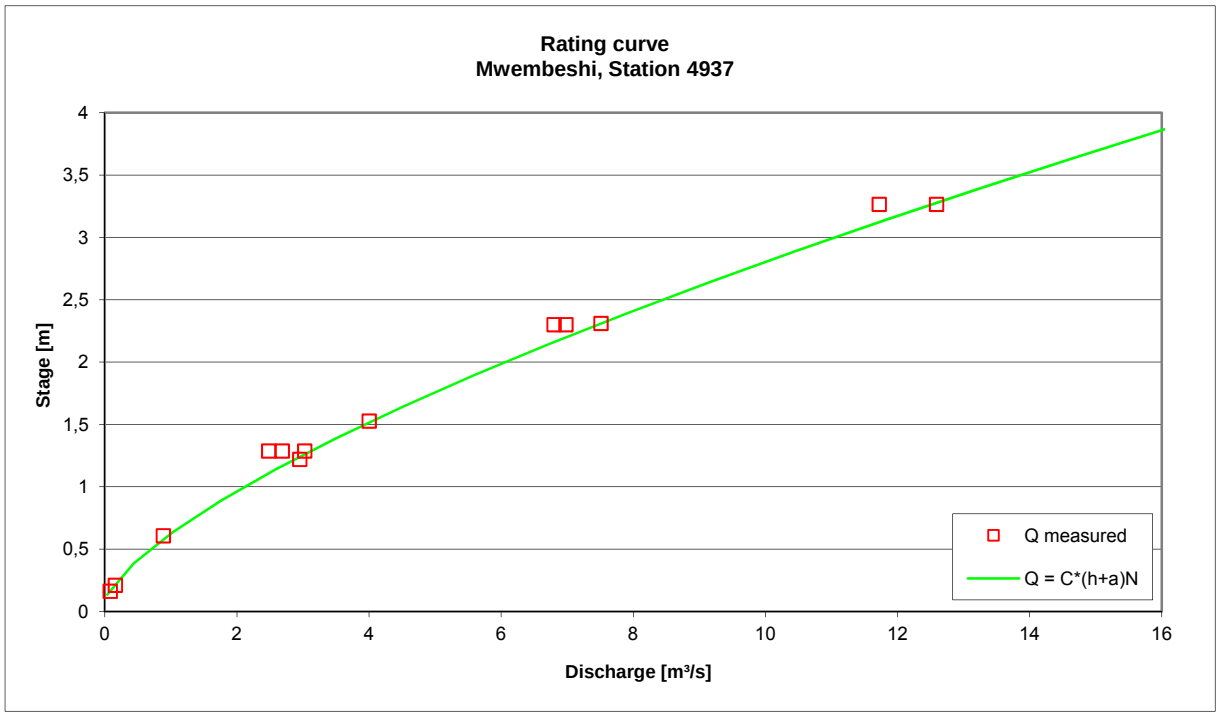

Fig. 30 Rating curve for Mwembeshi (Station 4937)

Discharge at Mwembeshi station 4937 can be calculated after

$$Q[m^3/s] = 2.37 \cdot (h[m] - 0.08)^{1.434} \qquad (19)$$

4.8 Laughing Waters spring

At Laughing Waters spring, a new gauging station was established in 2009. Hence, there are no historic data available. Discharge was measured seven times between November 2009 and February 2012 (Fig. 31). The water level was recorded automatically by a pressure gauge.

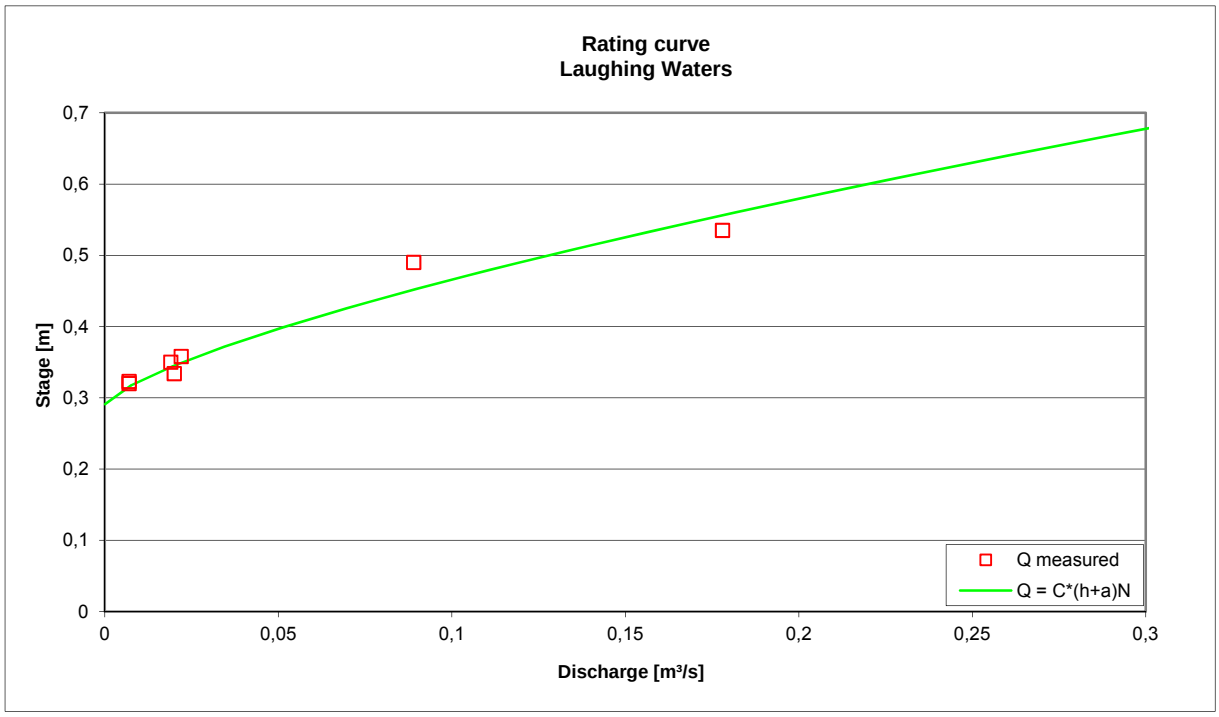

Fig. 31 Rating curve for Laughing Waters spring

Discharge at Laughing Waters spring can be calculated after

$$Q[m^3/s] = 1.12 \cdot (h[m] - 0.29)^{1.39} \qquad (20)$$

5 References

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