National Environmental Monitoring Standard

Rating Curves

Construction of stage–discharge and velocity-index ratings

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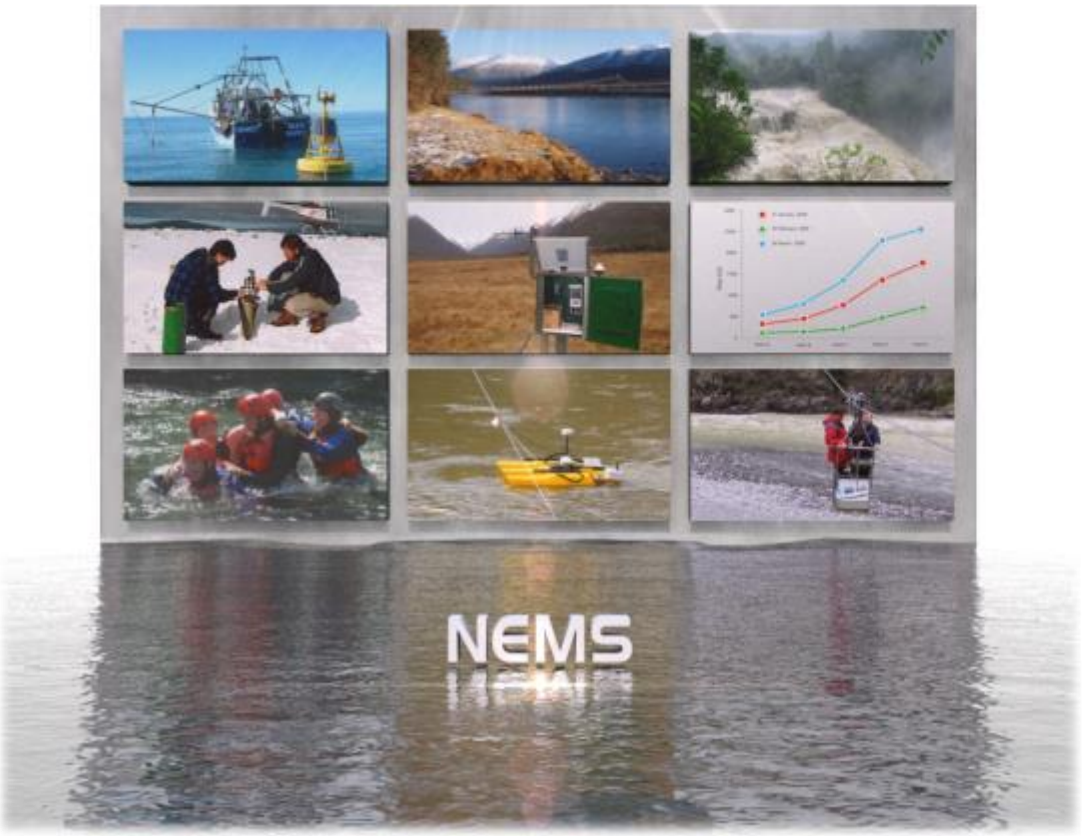

The National Environmental Monitoring Standards

The following National Environmental Monitoring Standards (NEMS) documents can be found at www.lawa.org.nz:

Standards

- Dissolved Oxygen
  Measuring, Processing and Archiving of Dissolved Oxygen Data
- Open Channel Flow
  Measuring, Processing and Archiving of Open Channel Flow Data
- Rainfall
  Measuring, Processing and Archiving of Rainfall Intensity Data for Hydrological Purposes
- Rating Curves (this Standard)
  Construction of Stage-Discharge and Velocity-Index Ratings
- Soil Water
  Measuring, Processing and Archiving of Soil Water Content Data
- Turbidity
  Measuring, Processing and Archiving of Turbidity Data
- Water Level
  Measuring, Processing and Archiving of Water Level Data
- Water Meter Data
  Measuring, Processing and Archiving of Water Meter Data for Hydrological Purposes
- Water Temperature
  Measuring, Processing and Archiving of Water Temperature Data

Codes of Practice

- Hydrological and Meteorological Structures
- Safe Acquisition of Field Data In and Around Fresh Water
- Site Surveys

Supplementary Material

- Glossary
  Terms, Definitions and Symbols
- National Quality Code Schema

Implementation

When implementing the Standards, current legislation relating to health and safety in New Zealand and subsequent amendments and the NEMS Codes of Practice shall be complied with.

Limitations

It is assumed that as a minimum the reader of these documents has undertaken industry-based training and has a basic understanding of environmental monitoring techniques. Instructions for manufacturer-specific instrumentation and methodologies are not included in this document.

The information contained in these NEMS documents relies upon material and data derived from a number of third-party sources.

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Development

The National Environmental Monitoring Standards steering group (NEMS) has prepared a series of environmental monitoring Standards on authority from the Regional Chief Executive Officers (RCEO) and the Ministry for the Environment (MfE). The strategy that led to the development of these Standards was established by Jeff Watson (Chair) and Rob Christie (Project Director). From 2014, the implementation of the strategy has been overseen by a steering group, and the current steering group comprises Phillip Downes, Martin Doyle, Michael Ede, Glenn Ellery, Nicholas Holwerda, Jon Marks, Charles Pearson, Jochen Schmidt, Alison Stringer, Raelene Mercer (Project Manager) and Jeff Watson.

The development of these Standards involved consultation with regional and unitary councils across New Zealand, electricity-generation industry representatives and the National Institute for Water and Atmospheric Research Ltd (NIWA). These agencies are responsible for the majority of hydrological and continuous environmental-related measurements within New Zealand. It is recommended that these Standards are adopted throughout New Zealand and all data collected be processed and quality coded appropriately to facilitate data sharing. The degree of rigour with which the Standards and associated best practice may be applied will depend on the quality of data sought.

The lead writer of this document was Marianne Watson of Hydronet Ltd, with workgroup members Graeme Horrell of NIWA and Martin Doyle of Tasman District Council. The input of NEMS members into the development of this document is gratefully acknowledged; in particular, the review undertaken by the NEMS steering group. Also acknowledged are many helpful discussions about method and data requirements with Stuart Hamilton of Aquatic Informatics Inc., and contributions on the topics of hydraulics and estimation of uncertainty, respectively, by Alistair McKerchar and George Griffiths of NIWA.

Funding

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- Bay of Plenty Regional Council
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- Northland Regional Council
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- Tasman District Council
- West Coast Regional Council
- Waikato Regional Council.

Review

This document will be reviewed by the NEMS steering group in February 2018, and thereafter once every two years.

Signatories

NEMS Project Director	NEMS Chair	MfE

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Terms, Definitions and Symbols

Relevant definitions and descriptions of symbols used in this Standard are contained within the NEMS *Glossary* available at www.lawa.org.nz.

Normative References

This Standard should be read in conjunction with the following references:

- NEMS *Glossary*
- NEMS *Open Channel Flow*
- NEMS *Quality Code Schema*
- NEMS *Water Level*
- Water Information Standards Business Forum. (2013). *National industry guidelines for hydrometric monitoring – Part 9: Application of in-situ point acoustic Doppler velocity meters for determining velocity in open channels.* WISBF GL 100.09-2013. Commonwealth of Australia (Bureau of Meteorology).

About this Standard

Introduction

The primary objective of a hydrometric station measuring water level in a river is to provide a record of flow at that location. It is difficult, if not impossible, to continuously measure flow directly in most natural water courses so we measure water level to a known datum (stage) and periodically measure discharge for a given stage (gauging). The continuous record of stage is then converted to a record of flow by means of a rating, typically a curve, which correlates stage with discharge.

Ratings are the most interpretative part of a hydrologist's work but need to be scientifically defensible, potentially in a legal context. Skilled preparation of rating curves following recognised procedures is an essential part of any hydrometric programme.

Under almost all circumstances the stage–discharge relation for open channel flow at a hydrometric station is governed by physical features at and downstream of the station, referred to collectively as the control. A control may be stable or may change due to scour or deposition, growth of vegetation, engineered activity such as mining of aggregate, or operation of a structure such as a gate. Each change in control alters the stage–discharge rating. Where controls are known or suspected to change over time, a gauging programme of suitable frequency is required to detect the movement and provide the necessary data to develop a new rating.

New knowledge may add to or alter interpretation of previous ratings and some or all previous curves for a site may need to be revised; thus, flows derived from rating curves are not static data.

Conventional methods for stage–discharge ratings are predicated on uniform and steady flow theory. At sites exhibiting significant hysteresis and/or subject to unsteady flows, the velocity-index method should provide a more reliable result. The velocity-index method employs two relations: one to derive area from the cross-section using stage recorded by the instrument, and the other to estimate mean velocity from velocities sampled by the instrument, using a velocity-index rating. Area and mean velocity are then multiplied together to obtain the record of flow.

Reliable records of stage and accurate discharge measurements are essential to developing accurate ratings; therefore, NEMS *Water Level* and NEMS *Open Channel Flow* are normative references for this Standard.

Objective

The objective of this Standard is to ensure that ratings for the determination of discharge are constructed, archived and applied in an appropriate, verifiable and consistent manner over time and throughout New Zealand to produce high-quality flow records suitable for at-site and comparative analysis.

Scope

This Standard applies to the following types of hydrometric station:

- open flow channels with natural controls or artificial bed control structures, and
- open flow channels with artificial flow control structures.

The primary reference for this Standard is ISO 1100-2:2010 (E) *Hydrometry – Measurement of liquid flow in open channels - Part 2: Determination of the stage–discharge relationship*, although the log-log method of rating curve construction is applicable under this Standard only in limited circumstances.

Normative references for this Standard are NEMS *Water Level* and NEMS *Open Channel Flow*.

This Standard applies to the following classification of ratings:

- archive ratings
- operational ratings, and
- provisional ratings.

This Standard covers processes associated with:

- stage–discharge rating curve construction at a new site
- maintaining the stage–discharge rating at established sites
- velocity-index methods associated with the use of ADVs
- quality assurance that is undertaken prior to archiving the discharge rating curve, and
- quality assurance that is undertaken for full flow series data audits.

This Standard considers stable and unstable controls, variable backwater and hysteresis. Methods for compensating for shifting controls and hysteresis are described. Empirical and theoretical techniques for developing rating curves are described for use as interim methods until a station is adequately gauged.

Exclusions

While this Standard may discuss the following concepts, it does not include the following methods of deriving discharge relations:

a) slope station (twin gauges; i.e. stage-fall or fall-ratio ratings)

b) rate-of-change in stage, or

c) unsteady-flow models.

This Standard does not cover the shift method of rating transitions used in North America. The method is considered unsuitable for a significant majority of rivers in New Zealand although it may be a preferable solution for weedy sites with underlying stable artificial controls.

This Standard is not intended to apply to flows monitored for industrial purposes.

The Standard – Rating Curves

The following shall apply for all ratings:

Accuracy	Contributing data (stage series and gaugings)	Shall conform to the requirements of the normative NEMS references. Stage shall be: • to a common datum, and • in agreement, within the resolution and accuracy of stage recording.
	Contributing data (velocity series)	A NEMS for in situ velocimeters is yet to be developed. *For ADVs, data collection shall, in the interim, be guided by the Australian Government Bureau of Meteorology National industry guidelines, Part 9: Application of in situ point acoustic Doppler velocity meters for determining velocity in open channels (WISBF GL 100.09-2013).*
	Individual rating curves	Shall be unbiased, hydraulically correct and conform to the calibration measurements.
	Rated flows	95% of the simultaneous rated flows shall be within ±8% of the measured discharges.
Frequency of Gauging	Sites with engineered structures with predictable control	In no circumstances shall there be more than 12 months between gaugings.
	Natural channels	In no circumstances shall there be more than three months between gaugings.

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Calibration of the Rating	Reliability of calibration data	Gauging stage shall be appropriately reconciled with the stage series to which the rating(s) will apply.
	Range	Curves shall explicitly cover the full applicable range of stage.
Timing of Ratings	Resolution	1 second
	Time zone	New Zealand Standard Time (NZST) *Note: Do not use New Zealand Daylight Time (NZDT).*
	Periods of applicability	The date and time from which a rating applies shall be specified. *A rating may have a specified end date and time, or this may be implied by encountering the next rating or end of the unrated series.*
Metadata	Scope	Shall be recorded for all aspects of rating curve development addressed by this Standard. Explanations of exceptional conditions, outliers and assumptions shall be included. All ratings shall be quality coded as per the Quality Codes flowchart.
Quality Assurance	Review of a new rating	A standard methodology shall be implemented. Procedures shall include: • review against previous ratings, and • confirmation of the resultant flow series. Shall be undertaken by a suitably trained and experienced practitioner.

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Quality Assurance (con.)	Review of an amended rating	A standard methodology shall be implemented. Procedures shall include: • comparison with the previous version of the amended rating(s) • review against unchanged prior and subsequent ratings, and • confirmation of the resultant flow series. Shall be undertaken by a suitably trained and experienced practitioner.
Archiving	Contributing data (stage series and gaugings)	Shall conform to the requirements of the normative NEMS references.
	Contributing data (velocity series) original and final records	File, archive indefinitely, and back up regularly: • raw and processed records • supplementary measurements • validation checks • calibration results, and • metadata.
	Rating curves	File, archive indefinitely, and back up regularly: • archive ratings • operational ratings used for compliance • periods of applicability • calibration data, and • metadata.
	Supporting evidence for adopted rating model	File, archive indefinitely, and back up regularly: • supplementary data • metadata • results of validations, and • audit reports.

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Data Release	Unaudited data	Shall be identified as unaudited on each occasion of release or distribution for use.
Exchange of Ratings Between Software	Quality codes	Shall endure only if: • algorithms that render, interpolate and apply the rating model are known to be identical in both software, or • a verified exchange format is employed that results in an identical flow series in both software.
	Rated flows	Shall be quality coded QC 200 'external and not coded to match NQCS' if rating curve quality codes are voided by the exchange.
Stationarity	Stationarity of record shall be maintained.	

Requirements

As a means of achieving QC 600 under this Standard, the following requirements apply:

Units of Measurement	Stage and Discharge	Shall conform to the requirements of the normative NEMS references.
	Velocity	Express units in: • metres per second, or • millimetres per second.
	Area	Express units in: • square metres, or • square centimetres.
	Flow	As for Discharge.
	Uncertainty	Express as % expanded uncertainty to 95% level of confidence; i.e. coverage factor 2.
Resolution	Stage and Discharge	Shall conform to the requirements of the normative NEMS references.
	Velocity	1 mm/s
	Area	1 cm^2
	Flow	As for Discharge.
	Uncertainty	To 1 decimal place.
	Sensitivity	No rating segment shall exceed 3% increment of flow per mm of stage change.
Timing of Measurements	Contributing data (gaugings)	Adequate to define all rating curves. Shall conform to the requirements of the normative NEMS reference.

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Timing of Measurements (con.)	Contributing data (stage series)	Shall conform to the requirements of the normative NEMS reference.
	Contributing data (velocity series)	A NEMS for in situ velocimeters is yet to be developed. *For ADVs, data collection shall, in the interim, be guided by the Australian Government Bureau Of Meteorology National industry guidelines, Part 9: Application of in situ point acoustic Doppler velocity meters for determining velocity in open channels (WISBF GL 100.09-2013).*
Frequency of Gauging	Adequate to detect all rating shifts.	
	Highly active sites	At least fortnightly during periods of: • instability at sites prone to movement; for example, during high flows or gravel mining, or • growth or flushing if weed or ice-bound, or • high sediment load; for example, after significant erosion or dam flushing.
	Alluvial sites	At least monthly.
	Sites with demonstrated stable natural control	At intervals of no more than three months.
Supplementary Measurements	Survey data	• cease to flow level of any section control, if it is measurable • relevant cross-section(s) to full anticipated flood extent; surveyed at the instrument at least once every three years for in situ velocimeter sites • dimensions of control structure(s) • bankfull stage.

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Supplementary Measurements (con.)	Parameters essential to quality of the contributing data (stage series and gaugings)	Shall conform to the requirements of the normative NEMS references.
	Parameters essential to quality of the contributing data (velocity series)	A NEMS for in situ velocimeters is yet to be developed. *ADVs, data collection shall, in the interim, be guided by the Australian Government Bureau Of Meteorology WISBF National Industry Guidelines Part 9: Application of in situ Point Acoustic Doppler Velocity Meters for Determining Velocity in Open Channels WISBF GL 100.09-2013.*
	Ancillary information	Field observations relating to the period of ratings shall be accessible and reviewed. Knowledge is required of: • possible backwater effects, and • hydraulic characteristics of the relation.
Timing of Ratings	Transitions	A shift or change in rating shall be smoothed (phased) over the duration of the event deemed to have caused the shift or change. Instantaneous transitions shall apply only: • at the start of a flow record, or • when the causal event is known to have occurred within a recording interval, and • as an exception that must be supported by an appropriate justification recorded in the metadata; for example, a filed comment.

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Calibration of the Rating	Reliability of calibration data	All gaugings shall be in accordance with methods described in NEMS *Open Channel Flow*. Uncertainty of the stage and gauging records shall be known. *Note: If gauged by moving-boat ADCP, review its quality code determination.*
	Minimum sample	A minimum of five gaugings within a period of stable control, but over as wide a flow range as practicable, are required to establish the rating for a new site.
	Range	Extrapolations shall be derived from the methods in this Standard. Default extension of curves by computer algorithm is unacceptable.
	Curve fit	All residuals > ±8 % shall be investigated and explained. There shall be no bias evident.
	Curve integrity	Curves shall be smooth; any break points must correspond to physical features of the channel.
	Curve representation	When rendered in natural space there shall be no undulation (scalloping) of the curve at segment boundaries. Unless defined at the resolution of the contributing data: • curve interpolation shall be non-linear in each segment, and • the method used to interpolate the curve when applying the rating shall be the same as used to fit the curve to the gaugings.

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Metadata	Contributing data (velocity series)	All changes from raw record shall be documented in the metadata. All data shall be quality coded QC 200. *Note: QCode(s) may change in future if a NEMS for in situ velocimeters is developed.*

Other Guidelines

The following table summarises best practice under this Standard that is either not relevant to or required for QC 600.

Timing of Ratings	Periods of no relationship	Gap or null ratings may be filed to indicate periods for which no relationship has been determined. If a gap or null rating cannot be filed, a rating with all segments quality coded QC 100 should be filed instead.
	Periods of apparent rating shift unsupported by measurement	Ratings unsupported by gauging may be filed if the: • degree of shift can be reliably estimated • curve shape can be assumed to conform to the shape of adjacent ratings.
Calibration of the Rating	New sites	All curves shall be regarded as provisional until the rating is suitably established and/or adopted. The data necessary to establish the rating shall be collected promptly after site installation. Upon suitably establishing and/or adopting the rating any provisional ratings shall be reviewed.
Supplementary Data	Measurements	• flood slopes and levels • channel slope • historic gaugings
	Estimates of key hydraulic parameters	• estimate of cease-to-flow level if unable to be measured • roughness coefficients
	Ancillary information	• knowledge of fluvial or seasonal trends • seasonal photographs of the control(s) • estimate of extreme flood height

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Metadata	Provisional ratings	Shall be quality coded QC 200.
	Ratings without gauging(s)	Shall be quality coded QC 300. Justification and derivation shall be explained in the metadata.
	Gap or null ratings	A quality code of QC 100 must be transferred to the flow series over the period(s) of applicability of all gap or null ratings.
Validation Methods	Calibration	Departure of a new measurement from the current rating, by more than the uncertainty of the measurement, shall be confirmed by repeat measurement as soon as practicable, preferably within seven days.
	Visual check	Inspect deviations for overall fit, trend and/or bias.
	Statistical test(s)	Test curve fit to relevant gaugings using statistical methods.
Audit	Review of adopted rating model	Shall: • include no less than two consecutive years' rated data. • be undertaken regularly at a planned frequency appropriate to the needs of the agency and user • include all periods of amended and new ratings since last audit plus a period of 12 months preceding, or since station inception if less than 12 months prior • be undertaken by a suitably trained and experienced practitioner

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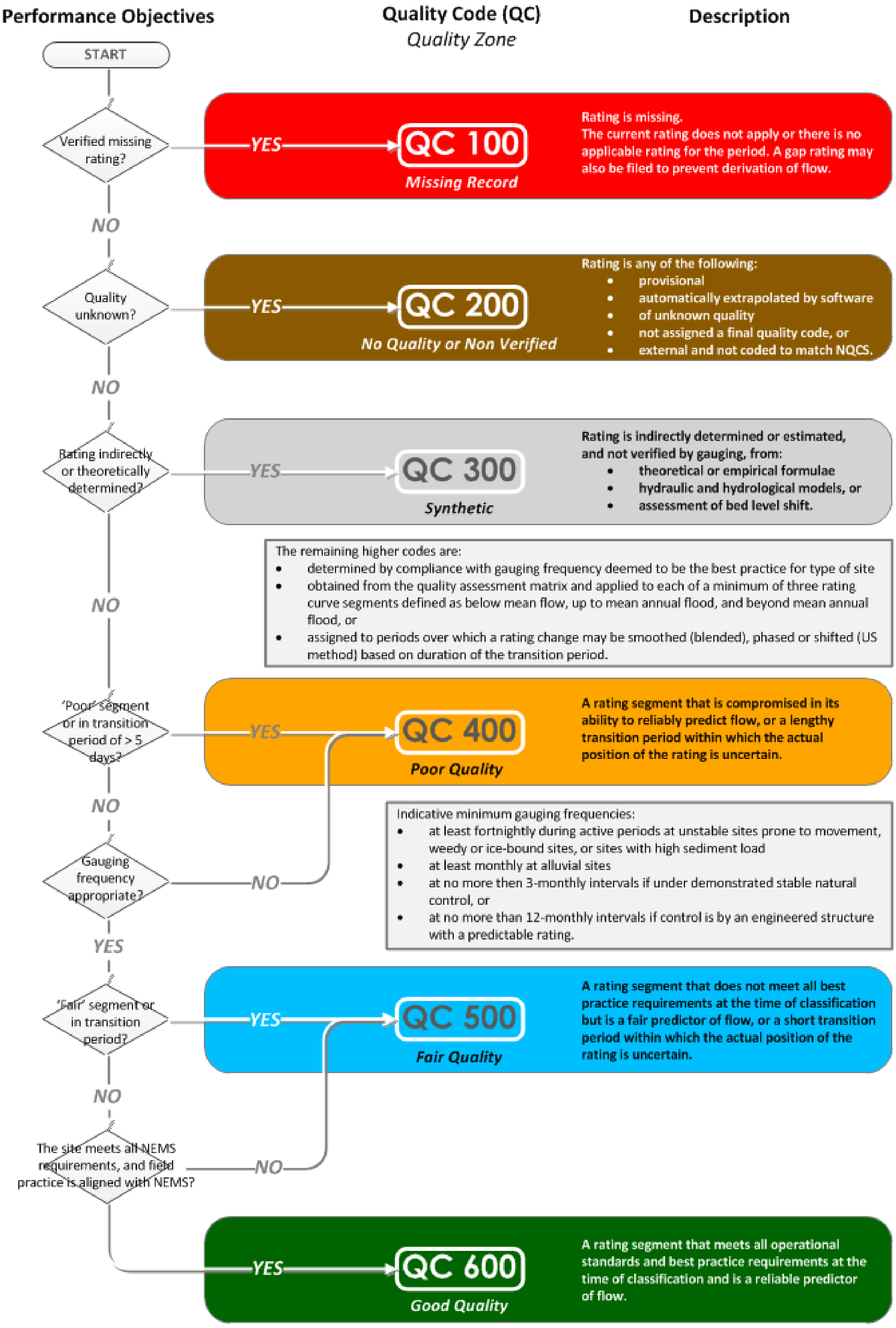
Audit (con.)	Review of adopted rating model (con.)	• culminate in a formal report which includes graphs and summary tables that demonstrate whether the rating model and resultant flow series meets the requirements of this Standard • be signed and dated when complete.
	Change of software	Unless the algorithms for development, rendering, interpolation and application of the rating model are known to be identical, a change of software voids all previous audits.

Quality Codes – Rating Curves

All ratings shall be quality coded in accordance with the National Quality Code Schema. The schema permits valid comparisons within and across multiple data series. Use the flowchart below to assign quality codes to all rating curves.



Rating is missing.
The current rating does not apply or there is no applicable rating for the period. A gap rating may also be filed to prevent derivation of flow.

Rating is any of the following:
- provisional
- automatically extrapolated by software
- of unknown quality
- not assigned a final quality code, or
- external and not coded to match NQCS.

Rating is indirectly determined or estimated, and not verified by gauging, from:
- theoretical or empirical formulae
- hydraulic and hydrological models, or
- assessment of bed level shift.

The remaining higher codes are:
- determined by compliance with gauging frequency deemed to be the best practice for type of site
- obtained from the quality assessment matrix and applied to each of a minimum of three rating curve segments defined as below mean flow, up to mean annual flood, and beyond mean annual flood, or
- assigned to periods over which a rating change may be smoothed (blended), phased or shifted (US method) based on duration of the transition period.

A rating segment that is compromised in its ability to reliably predict flow, or a lengthy transition period within which the actual position of the rating is uncertain.

Indicative minimum gauging frequencies:
- at least fortnightly during active periods at unstable sites prone to movement, weedy or ice-bound sites, or sites with high sediment load
- at least monthly at alluvial sites
- at no more then 3-monthly intervals if under demonstrated stable natural control, or
- at no more than 12-monthly intervals if control is by an engineered structure with a predictable rating.

A rating segment that does not meet all best practice requirements at the time of classification but is a fair predictor of flow, or a short transition period within which the actual position of the rating is uncertain.

A rating segment that meets all operational standards and best practice requirements at the time of classification and is a reliable predictor of flow.

1 Overall Process

1.1.1 In this Section

This section describes the overall process of developing rating curves for a station and the key requirements and generic best practices to ensure a reliable and defensible resultant flow series.

1.2 Process Description

A rating curve is a mathematical model of the relation between stage and discharge, whether we choose to describe it with equations or by drawing the curve. One model may not suffice if the relation changes. We must then model not only the changed relation but also how to represent the transition between the original and new model. Thus the process of rating a hydrometric station is essentially a modelling exercise using the results of periodic discharge measurements (gaugings) as calibration data.

In the absence of calibration data, theoretical solutions must be applied that are usually generalised conclusions drawn from compilations of internationally sourced observations at sites and from experiments that are often unrelated and atypical of the station being rated.

This Standard must therefore focus on process and methods rather than specifying requirements for any particular outcome.

1.2.1 Requirements

Key requirements of the overall process are:

- an informed view of what is required and why
- a system for collecting the necessary data
- an appropriate method to develop an appropriate model of the relation
- data and methods to test the model
- actions to correct and/or refine the model
- records of all aspects of developing and maintaining the model, and
- tests of model output against requirements, using results to refine the process.

1.2.2 Process Chart

Figure 1 presents the overall process for rating a hydrometric station as a flow chart.

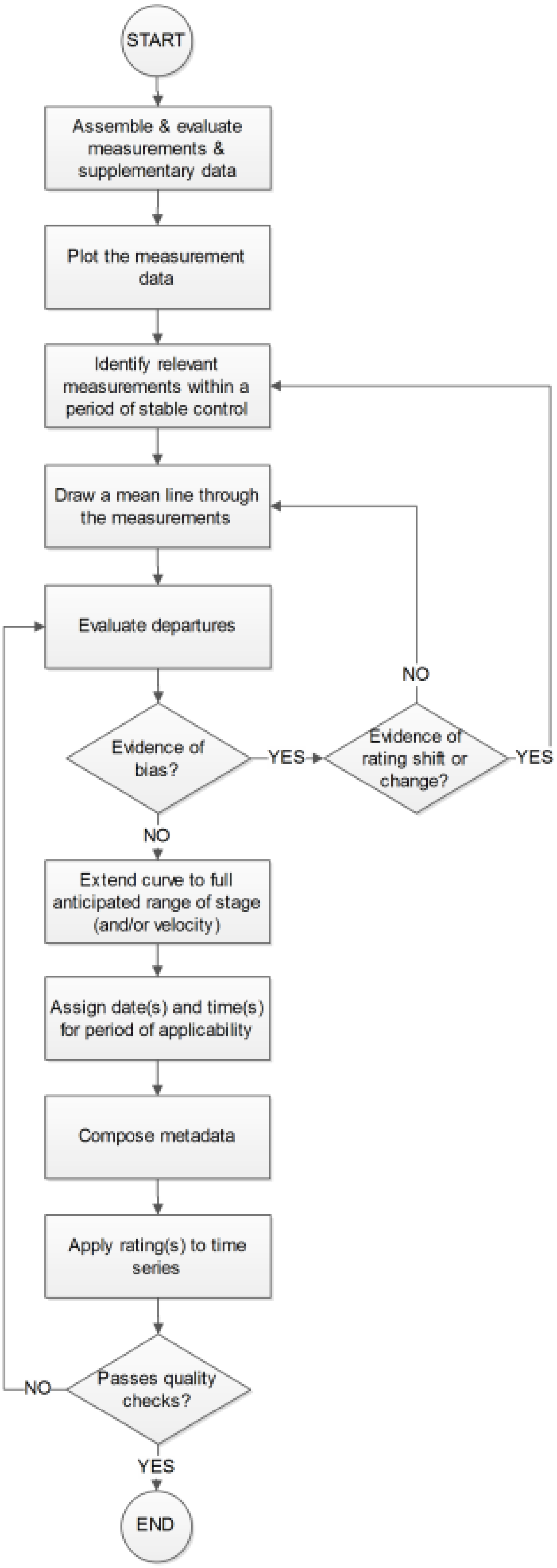


Figure 1 – Flow chart of overall process for rating a hydrometric station

Source: Adapted from Hamilton and Watson (2013).

1.3 Stationarity of Record

Stationarity of record:

- is maintained when variability of the parameter being measured is only caused by the natural processes associated with the parameter, and
- ceases when variability is caused or affected by other processes, e.g. upgrading equipment, moving location within a site, altering a procedure or changing a method.

Without stationarity, a record cannot be analysed for changes over time (such as climate change). It is critical that variations in procedures, methods and instruments do not introduce bias over the lifetime of a site's record nor between concurrent records at different sites.

Methods and instruments to collect the calibration data, and methods and processes offered by various software packages to construct, render and apply ratings curves, are constantly evolving as new technology becomes available. Such changes can and do introduce bias, and the reasons for which must be fully investigated and understood.

New data may challenge previous assumptions. Radical changes to gauging frequency may influence determination of rating shape and timing of shifts. Variations in water level gauge datum may compromise the ability of rating curve analysis to detect trends in riverbed degradation and aggradation.

To preserve stationarity, previously archived ratings must be reviewed and possibly amended under these circumstances. Thus, a set of rating curves and the resultant flow series are never static data.

1.4 Generic Best Practice

1.4.1 Planning for Data Collection

Have a plan for any site intended as a continuous flow monitoring station that:

- considers all programme requirements, which may include:
  – real or near-real time availability of data
  – quality assured data for resource management purposes
  – quality assured and archived data for inter-generational use
- aligns with NEMS methods
- details the observations required and procedures specific to each station
- considers, and if practicable minimises, limitations posed by the site, which may include:
  – gauging conditions
  – variable controls
  – unsteady flows
  – highly mobile beds
  – uncontained flows; for example, leakage, spills or overland flow
  – control insensitivity, or
  – fluid density; for example, during high sediment loads
- monitors gaps in rating coverage, and
- actively schedules measurements to target closing those gaps.

The plan must be:

- documented
- followed by all involved
- updated as new information is obtained, and
- routinely regularly reviewed.

The plan may be formally audited by an accrediting agency.

1.4.2 Understanding the Science

Understand the science behind discharge relations and of numerical modelling, specifically the:

- hydraulics governing dynamics of flow
- applicability of assumptions made to simplify representation of the relation
- assumptions and limitations of statistical optimisation of curve fitting, and
- the need to address all constraints on the model – mathematical, statistical and physical.

1.4.2.1 Application of US Methods – A Caution

The United States does not use the metric system of measurement. Formulae quoted, tables of coefficients, and graphs and examples presented in US publications are unlikely to be in metric units. Unless dimensionless, coefficients as well as parameters used in the US require metrication and therefore may take different values, or additional coefficients may have been introduced in US formulae that are not needed if using the metric form.

1.4.3 Systematic Application of Knowledge

Systematically apply knowledge, which apart from the calibration data themselves, includes careful evaluation of:

- field notes, images, descriptions of events, and other anecdotal data
- rating curve residuals, including actual deviation, bias and/or trend
- the unrated time series
- curve shape and extrapolation, and
- prior history of curves.

1.4.4 Control of Variance

Control the variance demonstrated by residuals from the rating. Deviations are the sum of physical changes in control conditions and measurement error.

- Systematic deviations are indicative of rating change, incorrect curve shape or measurement bias.
- When all such systematic error has been addressed, what remains should be random error, which:
  - can be reduced by increased sampling; that is, more discharge measurements to support the rating curve, or
  - controlled at source; for example, improving measurement conditions or changing the way measurements are done.

Evaluate variance within the context of site limitations. Information needs of the customer may require a site be installed at a location less than ideal for determination of flow. It may not be possible to obtain a 'good' quality (QC 600) discharge series from some sites. Over-refinement of the rating model, e.g. fitting a complex curve or applying frequent changes in rating to obtain good statistical fit, may compromise its hydraulic integrity.

Consider whether there are too few measurements to adequately detect variance; that is, there may be undetected rating shifts.

1.4.5 Qualification of Results

Qualify and convey confidence in the model results by:

- ensuring all contributing data is independently checked
- logging every step of rating development
- assessing, grading, then approving or censoring results
- disclosing in a planned, organised and methodical manner all information necessary for end users of the discharge data to make an informed decision as to fitness of the data for their purpose.

2 Constructing the Stage–Discharge Rating for a New Site

2.1.1 In this Section

This section describes the methods to be applied and the data and information necessary to be able to derive the initial stage–discharge rating for a new site.

2.2 Data and Information Requirements

The variety, quality and quantity of relevant raw data and information that is available when constructing the initial rating for a site has a direct impact on confidence in the rating that is determined.

Timeliness of data collection reduces the time over which the rating for a new site must be regarded as provisional and reduces the risk of a rating shift or change occurring before shape of the rating for a new site has been adequately defined.

2.2.1 Gaugings

To meet this Standard, minimum requirements are:

- stage at the time of measurement recorded with comparable accuracy to discharge:
    - sufficient stage readings obtained during the gauging to adequately define the stage fluctuations, and
    - time noted every 10–15 minutes against the vertical being sampled, and more frequently when stage is changing rapidly
- measurements checked to ensure that:
    - mean gauge height for the measurement is appropriately calculated
    - date and time of the gauging is appropriately assigned to the time of mean gauge height

      Note: If gauge height is a weighted mean, time of mean gauge height will likely not be midway through the period of measurement.
    - gauging and recorded stage are to a common datum, and
    - discharge calculations are correct, with appropriate adjustments applied
- measurement results that include, as a minimum:
    - a unique identification number
    - date and time of the measurement
    - mean gauge height for the measurement (gauging stage)
    - rate of change of stage during the measurement
    - total discharge, and
    - uncertainty calculated according to NEMS *Open Channel Flow*.
- in all other respects, measurements that conform to requirements of NEMS *Open Channel Flow*.

To meet this Standard, minimum requirements when establishing the rating for a new site are:

- at least five measurements:
    - during a period of stable control
    - covering as wide a flow range as possible
    - well distributed over the range of gauge heights experienced, and
    - sufficient to define the shape of the relation.

Note: More measurements will be required if the rating is complex because of multiple section and channel controls, or if the site experiences an extreme range of stage.

All rating curves filed for a new site shall be regarded as provisional until the rating is suitably established and/or adopted (see section 3.1.2).

The data necessary to establish the rating shall be collected as promptly as possible after site installation. Establishing the rating for a new site should be a priority task.

Note: The most effective means of obtaining timely data for establishing the rating at a new site is to gauge and survey at installation then target the first significant event after site installation. Obtain as many gaugings as practicable over the course of this event, measuring as much of the flow range as possible, then follow with one or two further gaugings in the next few days as the river recedes to check for any shift in the rating as a consequence of the event.

The provisional ratings shall be reviewed for consistency with the newly established and/or adopted rating and amended where necessary to conform, unless there is other evidence to suggest such conformity is invalid.

2.2.1.1 Gauging Stage

Gauging stage shall be:

- to a common datum with recorded stage
- determined as the mean of stage variation over the duration of the measurement, and

  Note: For methods of computing gauging mean stage, refer to Annex C.
- agree with recorded stage within the resolution and accuracy of stage recording.

Note: Ratings will ultimately be applied to the recorded stage so it is essential to the accuracy of the resultant discharge series for the gaugings' stage used in the construction of the ratings to match, within tolerance, the recorded stage.

Where disagreement arises it may be the gauging stage or the recorded stage or both that require adjustment.

At sites where there is persistent bias between staff gauge and recorder due to site configuration, and particularly if bias is range dependent, assigning recorded stage to the gaugings will produce a better result in terms of accuracy of discharge determination and preservation of stationarity than adjusting recorded stage to available staff gauge readings, provided the recorder is functioning correctly and recorded stage is reliable.

Gaugings shall be archived at the time, to the nearest minute, corresponding to the mean gauge height (gauging stage) for the measurement.

2.2.1.2 Steady-state Approximations

Where a significant looped stage–discharge relation is evident or suspected, and if a looped rating model or velocity-index methods cannot be implemented, a rating representing the steady state must be derived and applied or the resultant flow record will be biased.

Gaugings during unsteady flow must be adjusted to approximate the steady state, and then the rating curve constructed to best fit the adjusted gaugings. The method employed and a summary of gauging adjustments shall be described in the metadata.

Note: A looped relation and its corresponding steady state may not be obvious simply by plotting unadjusted measurements because of a preference for gauging on falling stage. Measurements on rising stage may be much more difficult to obtain. Operators wishing to avoid damage to expensive equipment from floating debris wait until the river drops a little by which time most debris has passed through.

Approximations of discharge are preferred to adjustment of gauging stage when loops are evident. An implementation of the method described in ISO 1100-2:2010 (E), section 5.8.3, known as the Boyer method, is recommended, in part because it also provides a means of applying the inverse adjustment to the steady-state rating to obtain a resultant flow series that better represents the true discharge.

The Boyer method is fully described by Rantz et al. (1982a) and DHV Consultants BV & Delft Hydraulics (1999). (Both these publications are available online; for more details, see Annex A – 'List of Referenced Documents'.)

Note: Sauer (2002) refers to ratings so derived as Boyer ratings and as Rate-of-Change-in-Stage ratings.

2.2.2 Ancillary Information

To meet this Standard, the following information shall be accessible:

- field observations noted in the period for which ratings are being derived, reviewed for any information relevant to:
  - reliability of the discharge measurements
  - datum, shape or stability of the rating curve, and
  - period(s) of transition.

To meet this Standard, those tasked with constructing the rating(s) shall have prior knowledge of:

- hydraulic behaviour of the site, and thus hydraulic characteristics of the relation, including but not limited to:
  - what control(s) exist and where
  - geometry of the control(s)
  - conditions under which control(s) may be drowned
  - stability of the control(s)
  - possible backwater effects
  - possible critical flows, and
  - friction effects, particularly variation of Manning's *n* with stage.

Other information that may be useful includes:

- knowledge of fluvial trends
- knowledge of seasonal trends
- seasonal photographs of controls, and
- estimates of extreme flood height.

2.2.3 Historic Data

Historical information pertaining to the site may exist. Relevant items include:

- gaugings, particularly for high flows
- slope-area calculations
- flood heights
- flood slopes
- estimates of flood flows
- historic rating analysis
- photographs, maps or reports of flood extents
- extreme low flow surveys, and
- observations of zero flow.

Historical information shall be evaluated for suitability to assist in defining the rating. Necessary tasks may include one or more of:

- relating historic heights to current gauge zero
  Note: In many cases heights will have been measured relative to a significant structure; for example, a bridge that still remains or had been tied by survey to existing structure. In some cases a staff gauge and/or benchmarks may still exist. If so, survey data can still be obtained to enable all information to be related to a common datum.
- reviewing calculations, including reduction of levels
- reviewing values assigned to any hydraulic coefficients, e.g. Manning's *n*, used in calculations
- researching possible change in flow regime; for example, following construction of a dam, or planting or clearing significant areas of forest in the upstream catchment, or
- researching possible change in river morphology, either from natural changes or engineered works, that may have altered hydraulic conditions at the site; for example, significant degradation, construction of stopbanks.

Additional resources to those already listed that may assist with the above evaluation include:

- aerial photos
- maps or plans showing river course
- historic plans showing cross-sections and/or traverses
- level books
- plans of works; for example, bridges, dams, flood and/or erosion protection
- consent files
- scheme files
- newspaper clippings
- records of staff gauge readings, and
- local knowledge, such as of iwi, farmers, and other authorities operating in the area; for example territorial authorities, infrastructure asset managers, hydro-electricity generators.

Full use shall be made of any historic information that remains applicable to the current site and assists in defining the initial rating.

2.2.4 Survey

2.2.4.1 River Cross–sections

- River cross-sections shall be surveyed to:
    - help define rating curve shape, and
    - enable extrapolation of the rating curve to the full range of recorded stage (see methods described in Annex G), and
    - assist with validation of gauged area, or
    - provide a means of estimating missing, or correcting dubious, soundings

    Note: A conventional gauging with soundings affected by large vertical angles or difficulty detecting the bottom due to a highly mobile bed may be better adjusted to a suitable surveyed cross-section.

    An area can be derived from a suitable surveyed cross-section if only surface velocities were able to be measured.

- River cross-sections shall be surveyed at one or more of the following locations, as applicable to site characteristics, and as required for validation and rating construction purposes:
    - the section control, if identifiable and reasonably stable, or if a man-made structure

    Note: A high-flow control may be a section control; for example, a bridge. If the bridge is also used for gauging, survey the side from which the meter is usually suspended. A bridge acting as high-flow control may have little or no influence at low flow so the CTF level may not be on the bridge section.

- a typical section in the control reach at, or downstream of, the recorder, if a uniform reach under channel control

  Note: If a standard section is used for gauging that meets these criteria there are significant advantages to surveying at that section.

  Note: A site may have one or both of section and channel controls. Most high flows are channel controlled.
- the recorder section, particularly if
  - location of control(s), or nature of a channel control, varies frequently
  - equivalent gauge height cannot be readily or reliably determined from water levels at any other section because:
    - water surface slope through the control reach is variable, and/or
    - there is significant slope and/or distance between the recorder and standard gauging or typical control section, and/or
    - significant drawdown or heading up occurs at the section control, or
    - gauging location varies between above and below the recorder

      Note: Related curves (see section 2.3.3.5) must be in terms of the stage axis at the rated cross-section (usually the recorder). If the section surveyed is not the rated cross-section, corresponding water levels must be able to be reliably determined from those at the surveyed section.

      If the rated cross-section and surveyed section are some distance apart but the reach is channel controlled and the channel is reasonably uniform, adjustment using average water surface slope may be all that is necessary, and an additional staff gauge installed at the control or standard gauging section that is read at each site visit may assist.
- the gauging section, to its full flood extent, if usually confined to one locality; for example an adopted standard section or a structure used for gauging such as a bridge or cableway
- at the upstream and downstream ends, and in the middle, of any reach intended to be used for measuring water surface slopes for estimation of high flows

  Note: The slope reach should be straight with length at least 5 times width. In many cases the site's high stage control will serve as the downstream end.

  Note: "Over-estimates of flood discharges can generally be traced to an incorrect choice of cross-sections. During flood conditions the actual cross-section occupied by the high velocity flood waters is largely regulated by the constrictions in the waterway; the additional area in the intervening cross-

  - *sections being occupied by comparatively still water or back-waters. Cross-sections should therefore be taken at the more constricted sections in the reach and these sections are generally indicated by breaks in the water surface profile" (Morrissey and Toebes, circa 1963).*
  - a suitable section downstream of any control structure that may become drowned by downstream conditions, and which may assist in determining shape of the affected part of the rating for the drowned condition.
- The surveyed cross-section(s) shall:
  - be related to the gauge datum for the site
  - adequately define control geometry
  - adequately define the stream bed
  - include the cease to flow (CTF) level if a low flow section control
  - extend to fullest anticipated flood extent
  - identify bankfull stage
  - identify other significant features such as vegetation and barriers, and
  - be carried out with a survey-grade instrument (level or GPS)
    Note: Handheld GPS units currently available are not sufficiently accurate in the vertical for this type of work.
  - identify true left and true right bank
  - identify water's edge at time of survey (distance and level)
  - be archived with the date and time of the survey recorded.

    Note: 'Time' may be nominally midday if unknown, provided it is noted as such in the metadata.
- Cross-section surveys shall be carried out at:
  - time of site design/installation
  - five-yearly intervals thereafter, if no significant change is observed in the interim
  - time of site closure, and
  - any time a control is significantly modified.

2.2.4.2 Flow Control Structures

- Dimensions of control structures must be measured and recorded at:
  - installation
  - five-yearly intervals thereafter, if no significant change is observed in the interim
  - time of site closure, and
  - any time the structure is modified.

2.2.4.3 Cease to Flow (CTF) Level

- This is the lowest point of a section control expressed in terms of gauge zero. If the control is readily identifiable and accessible, then CTF can be explicitly and directly measured.
- In natural channels CTF can be estimated by measuring the water depth at the deepest location on the control section and subtracting this depth from the stage at the hydrometric station at the time of measurement, provided the reach is reasonably uniform.

  Note: If the control is some distance from the station, at very low flows an intervening feature may become the control and the above estimate will not be valid. If the reach is not uniform the assumption of parallel bed and water surface slope may not be valid, requiring an adjustment also for water surface slope.

2.2.4.4 Bankfull Stage

- This is the level in terms of gauge height below which discharge is confined to the active channel and above which water spills onto berms and/or the flood plain. It is easy to explicitly and directly measure.
- Bankfull stage is often a 'tipping point' for a rating; that is, the curve will change to a different shape, typically to a flatter gradient, above this level.

2.2.4.5 Flood Levels

- Evidence of previous flood levels at the site may exist as:
  - references to, or marks made on, local landmarks
  - photographs and/or reports of heights relative to structures
  - photographs and/or reports of extent of inundation, and/or
  - visible debris lines.
- To be useful for rating analysis, levels identified must be tied to gauge datum.
- If at all possible, determine the date of the event, and when during each event any photographs were taken; for example, 'at peak', 'half-hour after peak', etc.

2.2.5 Theoretical Method

The gauging programme should begin immediately a site is installed; however, until there are sufficient gaugings available, a theoretical rating solution may be required.

This method may also be applied to assist the initial development of relationships for weirs and flumes.

See Annex E for description of the theory, equations and calculations.

As a minimum the following data is required:

- identification of the site control(s)
- identification of CTF level for the site
- a detailed cross-section of the control(s)
  - see section 2.2.4.1 above for what to choose to represent a channel control
- estimates of water surface slope
  - use the average of several observations along the profile
  - from a straight reach that is as uniform as possible
  - minimum length of reach 200 m upstream of the control
  - for unstable sites, reach length should exceed 200 m
  - stream bed profile may provide adequate substitute if reach is uniform and bed reasonably stable, and
- estimates of friction coefficients; for example, the discharge coefficient Cd for structures or Manning's *n* for channel controls
  - see Annex F for methods to estimate C_d
  - values for Manning's *n* can be assessed using the guidance provided by measured hydraulic data and photographs of representative New Zealand rivers in the Hicks and Mason's (1991) book *Roughness characteristics of New Zealand rivers: A handbook for assigning hydraulic roughness coefficients to river reaches by the 'visual comparison' approach*.

    Note: Manning's n *may vary with stage and/or season.*

Additional information that may assist includes:

- additional sections and profiles from sources such as Lidar to enable characterisation and possibly modelling of the reach from upstream of the uppermost of recorder or gauging cross-section to downstream of the most downstream control feature
- photographs of the banks, channel and flood plain viewed upstream and downstream to assist with friction estimation
- aerial and/or satellite imagery of the immediate vicinity to identify flow paths, relevant features of the flood plain, assess river morphology, and expose the possibility of backwater
- video that may assist with validation of control points and velocity estimates.

2.3 Fitting the Curve

Where possible a curve shall be derived employing empirical techniques before theoretical.

Log-log methods are not endorsed under this Standard other than

- as one of several options for
  – extrapolating beyond empirical evidence, or
  – theoretical determination in the absence of sufficient data, or
- to assist in defining the shape of a curve when
  – the general rating equation applies, and
  – hydraulic characteristics are fairly constant over the range of flows to be determined from the fitted parameters (see Annexes E and G).

Rating curves may be drawn by hand or using computer applications.

Note: It may be helpful to construct the first rating curve for a site by hand on large-format graph sheets to avoid constraints posed by the size of a computer screen.

2.3.1 Channels with Natural Controls or Artificial Bed Controls

The curve shall be developed from:

- relevant gauging data
- known channel geometry
- appreciation of the hydraulic characteristics of the channel and control, and
- known or estimated cease to flow level.

The shape of the derived curve shall be hydraulically correct, conforming to control geometry and the relevant calibration measurements.

Variations in shape of derived curves shall conform to changes in control geometry.

Curve fitting shall be unbiased, and result in a smooth curve with break points only where these align with changes in control cross-section profile. For compound channels, such as those with very wide berms or multi-barrelled structures, separate rating curves may be required for each constituent part of the geometry.

Until sufficient gauging data is available, an initial relation may be derived using theoretical methods supported by the necessary survey information. Hydraulic analysis and statistical or mathematical curve fitting may be used to aid the overall curve-fitting process.

In the case of theoretical, hydraulic, statistical or mathematical curve fitting:

- gaugings to validate the curve must be obtained as soon as practicable, and
- the curve must ultimately conform to those measurements.

2.3.2 Flow Control Structures

A theoretical curve may initially be applied.

Standard formulae have been developed for different structures, applications and flow conditions (see Annex F). The most appropriate relationship for the installed structure shall be adopted, taking into account:

- accuracy requirements for the derived flow data
- installation conditions
- degree of as-built adherence to design
- approach velocities, and
- tail-water effects.

Gaugings to validate the theoretical curve must be obtained as soon as practicable through a range of flows and conditions. The derived curve must ultimately conform to those measurements.

At least one gauging must be obtained in any subsequent 12-month period to validate, and if necessary guide modification of, the curve.

2.3.3 Methods

Detailed procedure for stage–discharge rating curve construction is contained in Annex G.

2.3.3.1 Gauging Data

All gauging data used to construct a curve shall be:

- from a period of stable control within the period of analysis, and
- reviewed to assess quality of each measurement and determine any unresolved measurement bias
  - – prior to curve construction, and
  - – if departure from the resulting curve is > ±8%.

Note: These requirements do not preclude consideration of measurements outside the immediate period of analysis nor that the period of analysis is static. You may wish to use other gaugings to guide shape or extension of the curve you are constructing, or be refining a provisional curve using new measurements, or be uncertain if the control is stable or not and wish to experiment with various measurement groupings before deciding the period of stable control.

2.3.3.2 Manual Construction

Drawings shall:

- be compiled on A2 graph sheet, or larger
- use natural metric scales, with discharge on the x-axis
- be labelled with a suitable title block
- be uncluttered
- have sufficient resolution to distinguish individual gaugings and interpret gauging uncertainty over the full range of flows
- display discharge measurement uncertainty
- identify which gaugings belong to which curve when there are multiple curves drawn on a sheet
- be inked when complete if required to be permanently stored.

2.3.3.3 Computer Fitted

Simple mathematical or statistical techniques, such as regression or curve fitting by mathematics to empirical data, are not appropriate in isolation and shall not be used as the sole means of deriving the curve.

Note: Such techniques assume all measurements lie on the same curve (which may not be the case for shifting controls) and that all measurements are of equivalent quality and therefore value, or may be simply weighted. Discharge rating curves are hydraulic functions that should conform to hydraulic theory. Interpretation is required and familiarity with open channel hydraulics and the uncertainty of field measurements is necessary.

2.3.3.4 Constructed Using Graphical Editor

Graphical editors, as are most widely used in New Zealand, are best described as computer-aided drafting (drawing) tools that mimic and facilitate the manual curve construction process, thus much of the procedure is the same.

The method, while implemented on computers, is not regarded as computer fitted. Most graphical editor applications do now contain tools that permit auto-fitting of curves either directly to selected gaugings or by analysis of conveyance, but these may only be used as a first-cut under this Standard.

Minimum facilities for best practice include:

- display of measurements and fitted curves in natural space with metric scales
- ability to determine chronological sequence of gaugings
- identification of individual gaugings and their uncertainty
- identification of individual curves and the measurements pertaining to each curve
- variable display resolution that enables over the full range of flows
  - control of clutter, and
  - individual gaugings to be distinguished, and
  - gauging uncertainty to be interpreted
- tools to manipulate curve fit, and
- methods for definition and non-linear interpolation of the curve that, when rendered in natural space, ensure it is smooth and free of break points except where applicable to physical features of the channel.

Desirable facilities for best practice include:

- display and/or analysis of deviation of measurements from curve(s)
- separation of measurements into rising, falling and steady stage
- corresponding display of cross-section and features
- simultaneous display of other curves stored for the site, and
- identification of periods of applicability for each curve, including periods of transition.

2.3.3.5 Related Curves

Curves for stage–area and stage–mean velocity should be plotted beside the stage–discharge curve, using the same stage axis.

Note: To achieve the same stage axis, compensation for water surface slope between the rated cross-section (usually at the recorder) and surveyed section may be necessary (see section 2.2.4.1).

A plot of stage-hydraulic radius may also be useful for discovering trends in channel changes.

2.3.3.6 Treatment of Outliers

Gaugings that deviate from the applicable rating curve by more than 8% shall be thoroughly investigated. If, after investigation, the deviation is allowed to persist, an explanation as to the cause of the departure must be recorded in the metadata.

Measurements with large deviations may be omitted only with rational and fully justifiable cause, after consultation with the gauging party involved if at all possible. Every decision to discard a measurement must be documented in the metadata.

Note: If standard methods are followed, it is uncommon to obtain a spurious result.

2.3.3.7 Extensions (Curve Extrapolation)

Curves must be defined over the full range of stage to which they will apply. In no circumstances shall flows derived from a rating be a result of default computer algorithms for curve extension.

Low flow

Extrapolation to minimum flow shall be achieved by one of:

- extension to Cease to Flow (CTF), surveyed or estimated, or
- appropriate application of general weir formulae.

High flow

It is recommended that, whenever possible, two or more methods are applied and results compared to improve confidence in the extrapolated portion of the rating.

Indirect measurement of peak discharge is preferred when the rating need only apply to data already collected.

Methods listed below are recommended when no measurements are available; see Annex G and the relevant references for method details.

Choice of method depends on many factors. Ramsbottom and Whitlow (2003) is the recommended guide under this Standard to choice of method and procedural best practice for extension of rating curves. The manual is publicly available and freely downloadable from the link given in Annex A –'List of Referenced Documents'.

Note: Methods in ISO 1100-2 are generally reasonable where the watercourse is confined within the channel by the river banks; however, there are many cases where the methods can be inaccurate, particularly when a flooded watercourse inundates flood plains or flow bypasses gauging sites (Ramsbottom & Whitlow, 2003).

WMO methods, in order of preference for New Zealand conditions:

1. conveyance-slope
2. flood routing
3. step backwater
4. areal comparison of peak runoff rates.

(Further information can be found in Chapter 1, Section 1.11 of the WMO 2010b publication; see Annex A – 'List of Referenced Documents'.)

Methods used in New Zealand, in order of common preference:

1. area-velocity
2. log-log
3. areal comparison of mean annual flood (MAF)
4. Q versus $\mathrm{A}\sqrt{\mathrm{d}}$.

Note: Q versus $A\sqrt{d}$ is regarded as superior to area–velocity. Conveyance–slope is regarded as superior to both and thus supersedes them in the WMO manual.

Methods described by Ramsbottom and Whitlow (2003), in order of increasing complexity:

1. Simple hydraulic techniques
    a. simple extension of the existing curve (general rating equation)
    b. logarithmic extrapolation of the existing curve (as for log-log)
    c. weir formulae for modular and non-modular (drowned control) flow
    d. velocity extrapolation (as for area – velocity) by
        - stage -velocity , or
        - velocity-hydraulic radius, or
        - Manning's equation
    e. slope – area
    f. Divided Channel Method (DCM); a variation of slope – area for sites with overbank flow
2. Computational hydraulic modelling
    a. 1-D
    b. 2-D
    c. 3-D.

3 Validation

3.1.1 In this Section

This section describes procedures for ensuring a stage–discharge relation is adequately defined, and any changes to the relation are detected and appropriately managed.

Methods for determining uncertainty in the relation are discussed but implementation is not yet required to comply with this Standard.

3.1.2 Provisional Ratings

A new relation between two variables shall be regarded as provisional if:

- the relation is still being determined, and/or
- the curve lacks the required minimum evidence, and
- collection of additional calibration data remains possible under normal circumstances; that is, notwithstanding opportunity to measure a relatively rare low- or high-flow extreme that may then initiate review of all ratings for a site.

A provisional rating may be altered and refined as new calibration data becomes available; thus, flows derived from the relation may change after each iteration.

Provisional ratings shall be quality coded QC 200 ‘of unknown quality’, ’not assigned a final quality code’.

The quality code(s) for all or part of the rating range may subsequently be revised when the rating is adopted for the record.

Note: Both operational and archive ratings may be provisional until deemed suitably defined, or until superseded by a subsequent rating shift that prevents more calibration data representing the prior state of control being obtained.

3.2 Maintaining Stage–Discharge Rating Curves at Established Sites

3.2.1 Gauging Frequency

The quality of a rating curve is determined in large part by the frequency of flow gaugings used in its construction. The number of gaugings and the period of time between gaugings vary depending on factors that include relative stability of the rating curve, and the occurrence of hydrological events such as floods, low flow and seasonal weed growth.

During flood or drought events additional measurements should be done to define these rare events and reduce the demand for rating curve extrapolation.

Water managers may require sites at locations less than ideal for hydrometric monitoring. Often they are lowland sites in braided or weedy reaches where maintaining a rating is challenging. These sites require more frequent gauging.

- Gauging frequency shall be at intervals sufficient to ensure:
  - accurate determination of the stage–discharge rating curve, and
  - detection of when this relationship may have changed.
- Gauging frequency may vary from year to year depending on the frequency of channel changing events.
- As a minimum the following shall apply:
  - In no circumstances shall there be more than 12 months between gaugings at sites with engineered structures with predictable control.
  - In no circumstances shall there be more than three months between gaugings at sites with natural channels and controls.

3.2.2 Gauging Coverage

Accurate determination of rating curve shape also depends on the dispersion and range of discharge measurements supporting the curve, commonly referred to as gauging coverage.

Within overall requirements for gauging frequency, attention must be paid to targeting measurement of key parts of the rating curve, e.g. where channel geometry is irregular or there are significant gaps in the coverage, while also attempting to measure as wide a range of flows as possible.

Effective gauging programmes will also take account of other supporting evidence, such as field observations and inspection of the stage time series, to identify whether gauging is only required to track bed shift within an already established curve set, or whether a whole new rating shape must be determined (see section 3.3).

3.2.3 Improvements to Historical Rating Curves

- All historic ratings for the relevant site shall be reviewed if there is:
  - successful measurement of rare floods or extreme drought, to either confirm or improve upon previous extrapolations, or
  - consistent bias in a more recent series of mid-flow gaugings that may indicate a different curve shape is required for all ratings.

3.3 Maintaining Stage–Discharge Rating Curves at Sites with Shifting Controls

Sites for which one stage- discharge relation applies over the full period of record are rare. Typically there are many rating curves required due to bed shifts and/or channel change.

3.3.1 Evidence of Shifting Controls

Significant scatter of subsequent gaugings about the initial rating curve may indicate a shifting control. There are, however, five possible reasons for the scatter:

1. the stage–discharge relation is affected by scour and fill of the riverbed, or overspill and ponding in areas adjoining the channel
2. the stage–discharge relation is affected by seasonal effects such as in-stream weed growth or ice formation
3. the station is affected by variable backwater
4. the stage–discharge relation is affected by unsteady flow, or
5. measurement errors.

Of the above, 1. and 2. are examples of simple ratings with shifting controls, 3. and 4. are examples of complex ratings where discharge is not only dependent on stage, one solution for which is discussed in the velocity-index rating section, and 5. is addressed in the relevant normative references for this Standard (see 'About This Standard – Scope').

3.3.2 Gauging Frequency

To ensure no rating is missed, a suitable frequency of gaugings is necessary. The frequency required to adequately detect all shifts depends on how often the control changes and the reason(s) for that change.

For natural bed controls, mobility depends on particle size and stream power as an inverse relation tempered by the degree of armouring; that is, in general, greater stream power is able to mobilise more and larger particles.

Rating shifts in reaches under channel control may also depend on particle size and stream power if the channel is alluvial and if it is a change in channel slope that alters the stage–discharge relation, or shifts may depend more on seasonal changes in the case of weed growth, ice or riparian vegetation acting as control.

Under this Standard, the frequency of gauging must be adequate to detect all rating shifts. Recommended minimum intervals are given in Table 1; methods for assessing required frequency are provided in Annex I.

Table 1 – Recommended minimum intervals between gaugings at sites with shifting controls

Site type	Recommended minimum gauging interval
Unstable site prone to movement	At least fortnightly during active periods; for example, during high flows or gravel mining.
Weedy or ice bound	At least fortnightly during growth or flushing periods.
High sediment load	At least fortnightly during active periods; for example, after significant erosion or dam flushing.
Alluvial	At least monthly.

3.3.3 Detecting a Shift

Shifts must be detected by sufficient gaugings and tracked by rating curve adjustments to ensure a reliable discharge series. A shift in the control may be indicated by:

- observation and/or activity at the site; for example:
  - the control rapid has moved downstream
  - weed growth or dieback is evident in the control reach
  - cleaning the weir crest
  - visible change in the geometry of the channel, or
  - elements of the control feature such as boulders, logs or weir boards have moved
- a gauging that deviates by more than the uncertainty of measurement from the current rating
- a change in the correlation between derived flows at this and an upstream, downstream or neighbouring site, or
- a persistent bias or trend in the deviations of gaugings from the current rating.

Note: A trend in deviations that is also stage dependent may indicate that curve shape requires review rather than a shift in the control.

A potential rating shift shall be confirmed by repeat discharge measurement as soon as practicable, preferably within 1 week (7 days).

There is trade-off between frequency of shifts and accuracy of rating curve definition. An average curve drawn to fit several measurements is probably more accurate than any single measurement or set of curves drawn through those single measurements. A shift in rating should be supported by evidence other than one or two gaugings.

3.3.4 Timing of Changes

Shifting controls change with time. A shift in the control may occur:

- during a flood event that is sufficient to mobilise bed or bank material
- gradually over time such as weed growth, ice formation or silt accumulation
- as a result of human intervention; for example:
  - a change in recording datum
  - clearing weed from the control and/or control reach
    Note: If prolific, the weed itself may be the control.
  - gravel mining in the control reach, or
  - in-stream activity; for example, installing weirs, creating swimming holes, bar-ripping, installing or maintaining erosion protection
- several times over the course of an event, or
- continuously over the course of an event.

When a change is detected, the nature and timing of the shift must be identified, including duration of the transition. The change event can be identified by searching a plot of the stage series with gaugings marked, supplemented by field notes and photographs, for one or more of:

- events of sufficient size to cause a change
- inconsistency of recession level and/or shape between floods
- steps in recession level associated with activity at site; for example, datum shift or weed clearance or gravel mining, and/or
- gradual rise in recession level in absence of rain or other inflow.

If constructing ratings manually on paper, each curve drawn should be identified on the drawing with its corresponding period(s) of applicability.

3.3.4.1 Changes Initiated by Floods

The period of transition will be over the flood event, typically no more than a few days, beginning when shear stress on the bed is sufficient to initiate motion, usually when the hydrograph is rising most rapidly, and ending when velocity drops sufficiently for bedload movement to cease or deposition to occur, typically around the inflexion point of the falling hydrograph.

If the flood event has multiple peaks, it is acceptable to define the transition period over the entire event.

If there are several candidate events, it is acceptable to choose the largest.

If the shift is extreme, the transition may need to be confined to the rising stage for degrading control or the falling stage for aggrading control. The primary consideration is always to time the rating change in a way that appropriately models the behaviour of the control and its effect on the stage–discharge relation.

3.3.4.2 Gradual Changes

If the change is due to weed growth, ice formation or silt accumulation, it may occur gradually over weeks or months.

If there are gaugings in the period, it is acceptable to define a curve through each gauging and transition gradually through the whole period between measurements, provided the gaugings are in the same phase of growth or accumulation; that is, there must be no flushing events in the period between the gaugings.

3.3.5 Applying Changes

A change in rating may be applied by:

1. developing a whole new curve to describe the new relation, or
2. using the shift-curve method, which applies a temporary shift to all or part of the current relation by operating on the stage value prior to looking up the discharge.

In this Standard the preferred method is to develop a whole new curve.

Note: The former has been the preferred method in Australasia and the latter in North America. The shift-curve method has been adopted by the WMO (WMO Publication No. 1044, 2010b) and ISO 1100-2:2010 (E). It is predicated on the notion that a 'base' or 'master' rating for a site can be established and that shifts in control are merely temporary aberrations from the base rating. There are situations in New Zealand where this notion is applicable, e.g. weedy sites with artificial control structures, but for many New Zealand sites the notion of a base rating is wishful thinking, established only by assuming the initial rating to be the base. The temporary nature of the method is underlined by the fact that should a new relation ultimately be required in retrospect, the shifts already defined must be recalculated.

Transition to the next relation must be applied so that there is no discontinuity in the rated discharge series as a result of the transition.

Unless the shift is known to have occurred suddenly, i.e between stage recording intervals, the transition must be introduced gradually over the period of the event that caused the change. This process is known as **smoothing** in New Zealand, **phasing** in Australia, and **blending** in Canadian software that is used in New Zealand.

Note: Implementation differs between the various software, but if used appropriately the outcome, in terms of transition, should be the same. However, the derived discharges may not be identical due to other factors such as differences in curve interpolation method(s).

3.3.6 Master Rating Curve

The general shape of a rating curve is determined by the control geometry. Provided geometry hasn't changed significantly, bed shift may alter the rating without departing from the general shape. The general shape may be termed the 'master rating curve' or 'master curve'.

Rating curves that cater for bed shifts tend to form sets conforming to shape of the master curve. The shape of the master curve will change if control geometry changes.

3.3.7 Curve Sets

Curve sets arise when there are shifts in control but the overall geometry of the control section and/or channel does not alter significantly, and therefore the general shape of the rating can be assumed to be consistent.

3.3.7.1 Type Curves

Scour or deposition of a natural control changes the actual or effective CTF. If the change is uniform, or assumed to be uniform, across the section and/or along the channel, and the stream banks are steep and confining, the rating may be assumed to have shifted by the same amount as the change in CTF, resulting in a curve that is parallel to the original curve in the direction of the stage axis and therefore does not go through the same top end. This is known as a 'type curve'.

A type curve in logarithmic space may result from a change in width of a channel control with no accompanying change to bed elevation. The effect in natural space is to change discharge for a given stage by a fixed percentage.

Note: Type curves were promoted as a useful approximation, first by Stout (1899) then Liddell (1927) and then Ibbitt (1979), to reduce the amount of work required to maintain rating curves at highly mobile and/or braided river sites.

3.3.7.2 Family of Curves

If the change in control is confined to a part of the section, for example:

- only the active portion of a wide shallow riverbed, or
- from partial removal of weed by only the fastest flow, or
- from bank erosion at the side(s) of an otherwise stable section control, or
- affecting only the flood plain

then the effect of the shift will reduce with stage. The result is a rating that merges with the original curve. This is known as a 'family of curves'.

In the first two examples, the low to medium segments of the rating may shift but the effect of the shift will diminish as water rises into the unchanged parts of the cross-section. The new rating will converge and may merge into the top end of the original curve.

In the final two, less-common examples, the change has increasing effect as water rises into the altered parts of the cross-section. The new rating will diverge from a low segment in common with the original curve as stage increases.

3.3.7.3 Departure from Curve Sets

In braided and avulsing rivers, scour and deposition may also work the bars, moving them progressively downstream. This process may alter the shape of the control as well as its level and the assumption of unaltered geometry is therefore false.

The family in this case may include curves that cross each other below a gauge height corresponding to flow occupying the entire active channel. Flatter curves will be evident for periods when the geometry is a wide shallow rectangle and steeper curves when the flow is confined between encroaching bars.

Because curves crossing each other may also indicate a missed rating change, changes in shape should be confirmed by additional evidence, e.g. additional gauging or cross-sections, field observations, change in shape of recorded stage recessions and photographs, and these should be either included or described in the metadata.

3.3.8 Loop Ratings

As flow events pass through a reach, the slope of the water surface changes. In low-gradient rivers the change may be significant and result in a greater discharge on the rising limb than the falling for a given gauge height. Discharge must then be related to stage and some other variable because the relation between stage and discharge is no longer unique for any event.

The effect is known as 'hysteresis' and the resulting complex rating forms a loop. The loops may vary in size for each event.

Backwater curves are a special case of loop ratings where the steady state is the lower bound of the loop.

If only the mean discharge is required at affected sites, it is sufficient to construct a mean curve through the loops, which represents the steady state. Gaugings on the rising limb should plot to the right of the mean curve and falling limb gaugings to the left. Some bias to the left may be justified if the river is usually in recession for longer than a state of rise.

ISO 1100-2:2010(E), section 5.8.3 provides a method of estimating unsteady flow from the steady-state discharge using rate of change of stage with time. The same method is more fully described by Corbett et al. (1943), who also present four adaptations of the inverse calculation. The four adaptations, known as the Jones, Wiggins, Boyer, and Lewis methods, may be used to adjust results from gauging in conditions of unsteady flow to estimate the steady-state discharge; the mean curve then being drawn through the adjusted gaugings. Refer to Corbett et al. (1943) in Annex A –'List of Referenced Documents' for more detail and examples of these methods.

Note: A. C Hopkins (1959) used the Lewis method on the lower Whanganui River Paetawa station.

Methods for deriving and applying complex ratings are comprehensively covered in North American guides, e.g. Sauer (2002) and Kennedy (1984), but in reality it is just as practical to install ADV equipment and develop discharge ratings using velocity-index methods.

3.4 Uncertainty in the Stage–Discharge Relation

3.4.1 Sensitivity of the Rating Curve

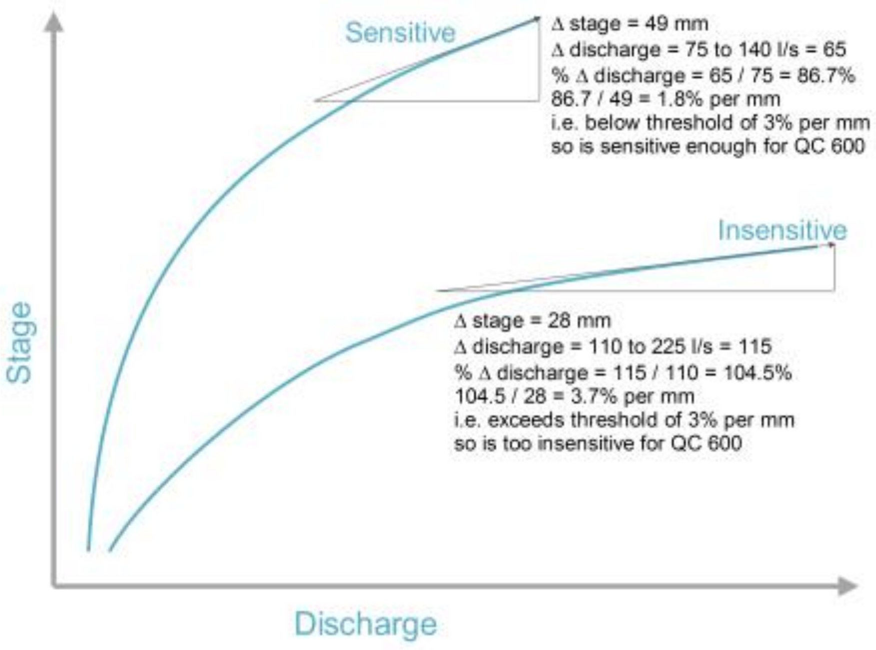
Sensitivity of the rating curve is the ratio of change in stage for a given change in discharge; the higher the ratio, the greater the sensitivity. Sensitivity is governed by the control section geometry and reflected in the gradient of the rating curve (see Figure 2).

Increased sensitivity enhances accuracy of the flow record and assists in achieving the performance measures of this Standard.

In general a wide shallow riffle control will be much less sensitive than a 90° V-notch weir. However, streams with median flows less than 20 l/s with stage measured to ± 3 mm may produce errors as high as 5%, which is considered large when compared with all other flow stations (Freestone, 1983), and is caused by such small flows having a large absolute flow change for a small change in stage.

- The stage–discharge rating curve shall be sensitive to changes in discharge, appropriate to the accuracy expected of the flow series given the resolution of stage recording that is practicable.
- To meet requirements of this Standard, i.e. to achieve a quality code of 600, no rating segment shall exceed 3% increment of flow per mm of stage change.

Note: Sensitivity is usually considered during site selection, and further assessed during station design.



Δ stage = 49 mm
Δ discharge = 75 to 140 l/s = 65
% Δ discharge = 65 / 75 = 86.7%
86.7 / 49 = 1.8% per mm
i.e. below threshold of 3% per mm
so is sensitive enough for QC 600

Δ stage = 28 mm
Δ discharge = 110 to 225 l/s = 115
% Δ discharge = 115 / 110 = 104.5%
104.5 / 28 = 3.7% per mm
i.e. exceeds threshold of 3% per mm
so is too insensitive for QC 600

Figure 2 – Sensitive and insensitive stage–discharge rating curves

3.4.2 Estimating Uncertainty in the Relation

Methods of rating curve construction and application in New Zealand do not make this task straightforward. This section of the Standard is offered for information only and is not a requirement at this time.

The conventional approach (Herschy, 1999; Schmidt & Yen, 2008) is to model the rating using a simple power law or type curve defined by the general rating equation; that is, conforming to log-log methods of rating curve construction. Implementation of this method is described in Annex J, based on ISO 1100-2:2010(E), section 7.

A quadratic may be fitted to a rating curve, with errors in stage assumed negligible, but estimation of uncertainty is problematic. Various methods are available to give asymptotic errors or linear estimators are employed, but both yield very approximate results. For precise work, Monte Carlo or similar approaches need to be used and a specific study of typical rating curves in New Zealand would be needed to determine a way of characterising uncertainty so that a standard could be set (G. Griffiths, NIWA, personal communication, 2014).

Ibbitt and Pearson (1987) provide methods for quantifying the probability of error in a flow series derived from type curve ratings, based on analysis of gauging and rating shift frequency (see Annex I).

Quantifying rating curve and thus flow series uncertainty is at the forefront of current international research. Significant recent contributions have been made by Birgand (2012), Domeneghetti et al. (2012), and Le Coz (2012), who introduces Bayesian concepts.

Note: Uncertainty criteria should not be confused. In particular, 'discharge measured to within ± 8% of the true value at 95% confidence level' (gauging accuracy) is not the same as '95% of simultaneous rated flows lie within ± 8% of measured discharges' (goodness of rating curve fit to calibration data), which in turn does not imply that the resulting flow series is within ± 8% of true flows to 95% level of confidence (reliability of the overall rating model).

4 Data Processing and Preservation

4.1.1 In this Section

This section describes requirements and methods for computerised application and management of rating curves.

Handling of data from the field, both the rating calibration data and the time series to which the rating(s) will be applied, is addressed in the normative references.

4.2 Data Storage

4.2.1 Storage

Ratings intended to transform a time series may be stored within a recognised time-series manager, or in a standard relational or proprietary database linked electronically to a recognised time-series manager.

Ratings prepared manually and intended merely for ad-hoc look-up of discharge may be permanently stored on paper, provided the document is comprehensively labelled and suitable measures are in place to preserve the paper record indefinitely.

4.2.2 Scales, Units and Resolution

Discharge rating curves shall be derived and presented using natural scales in the International System of units (SI).

Measurements shall be expressed in the following units to afford the appropriate resolution:

- Stage
  - metres (m) to 3 decimal places, or
  - millimetres (mm)
  - resolution 1 mm
- Velocity
  - metres per second (m/s or ms^{-1}) to 3 decimal places, or
  - millimetres per second (mm/s or mms^{-1})
  - resolution 1 mm/s
- Area
  - square metres (m^2) to 4 decimal places, or
  - square centimetres (cm^2)
  - resolution 1 cm^2
- Discharge and flow
  - cubic metres per second (m^3/s or m^3s^{-1}) to 3 decimal places, or
  - litres per second (l/s or ls^{-1}), or
  - millilitres per second (ml/s or mls^{-1}) for very small flows where measurement uncertainty is < ± 50 ml/s
  - resolution 1 l/s, or 1 ml/s for very small flows
- Uncertainty
  - per cent (%) to 1 decimal place
  - expanded uncertainty to 95% level of confidence; that is, coverage factor 2
  - resolution 0.1 %.

Curves may be supplied in other units when required by regulations or client requirements.

Note: 'Cubic metres per second' is often shortened to 'cumecs' and sometimes abbreviated to 'cms' neither of which are SI units. Use of 'cms' may confuse with area and should be avoided.

Units and resolution of the calibration data, and of the coordinates of the unrated and corresponding rated curve, must be described in the metadata.

4.2.3 Data Files

If required for evidence of compliance or activity, an organisation may need to separately maintain and permanently store an operational data set in addition to the archive data set.

In most cases considerable efficiency can be achieved by regarding operational ratings as a first-cut of those destined for archive. If operational ratings are constructed using best-practice techniques, a rationalisation and general tidy-up of curve shape and fit, and reassignment of dates and times of applicability, is all that should be necessary to produce the archive set.

4.2.3.1 Operational Data set

Organisations may need to provide near-real-time flow data for operational purposes such as hydro-electric generation, irrigation scheduling or consent compliance.

Operational data sets are typically comprised of:

- raw logged unrated data, or
- telemetered and possibly auto-filtered unrated data, and
- quality checked discharge measurements, and
- operational rating curves maintained in near-real time.

An operational rating is:

- determined, defined and quality assured using all available calibration data at time of construction
- applicable for a specified site and parameter
- applied from date and nominal time of acceptance forward
- stored as part of a real-time or near-real-time record.

Operational ratings are often used to determine compliance. If new data indicates an existing operational rating should be amended, it is usual to implement the alteration as an entirely new rating so as to not disturb the integrity of prior compliance tests.

An operational rating curve may be provisional for a time, but once superseded by another curve and no longer current, it is no longer provisional.

This Standard is not intended to apply to operational data sets intended for internal organisational use; however, best practice with regard to rating curve construction is desirable in any case.

4.2.3.2 Archive Data set

Archive data sets are comprised of:

- quality assured unrated data
- quality checked discharge measurements, and
- quality assured rating curves maintained on a periodic basis.

An archive rating is:

- determined, defined and quality assured using all possible relevant calibration data
- applicable for a specified site and parameter
- applied from the latter of the start of the record or the date and time of the event identified as establishing the state of hydraulic control that the relationship determined represents
- stored as part of the historic site record, and
- periodically reviewed and possibly modified from time to time, particularly if new information such as measurements of extreme events becomes available.

A mechanism must be in place to prevent continued application of any rating curve beyond its appropriate period of applicability. In particular, the last rating curve in a set must not be permitted to continue to apply beyond an indicated change in rating as new unrated series is added to the archive. The mechanism may be controlled by software or office practice.

Review may result in additional curves, deletion of existing curves, or change to the period of applicability and/or transition period of a curve. The archive update process must ensure that no remnants of superseded curves remain in the data set or unintended overlap of curves as they are applied.

4.2.3.3 Supporting Data

In addition to the data sets and calibration data, supporting data used to assist with determination of rating shape and applicability, and evidence of shifts, shall also be stored or referenced. This may include, but is not limited to:

- results of indirect discharge measurements
- surveys of stream controls, cross-sections and profiles
- estimations of Manning’s *n* and other hydraulic parameters
- photographs
- non-standard techniques and procedures employed
- information used to assist extrapolations, and/or
- evidence of instability in the control reach.

4.3 Data Processing

Data processing for rating curves includes:

- loading curve specification(s) to computer, as point-pairs and/or equations, as required to ensure accurate representation of each rating curve, and reliable interpolation of the curve(s) when deriving a flow series
- identifying and associating appropriate periods of applicability to each curve to ensure the correct rating is applied at any given time, including specification of transition periods, and periods for which no valid rating applies
- assignment of quality codes to ratings and/or rating segments
- compilation of other metadata so that all aspects of rating curve development addressed by this Standard are documented including, but not limited to, full description of construction methods, accuracy and limitations of the rating model
- careful and appropriate management of revisions to rating curves, particularly retrospective changes of applicability period(s) that may result in unwanted curves or overlapping periods of applicability remaining in the data set
- management of multiple data sets where operational ratings may be required for production of near-real-time flow information.

4.3.1 Applying the Rating

Derivation of a flow time-series must be achieved by application of one or more ratings to a time series of stage (and velocity if using an ADV sensor) using a recognised time-series manager.

Rating(s) must be coded and manually entered into the computer if drawn on paper. Coding may be achieved by fitting equation(s) or by extracting coordinates (point-pairs) that describe the curve, with a suitable interpolation mechanism then provided by the computer application.

The computer application must have processes that adequately replicate the curve then apply it to the appropriate period(s) of unrated data, including a means of transitioning smoothly between definitions when a change in rating is specified.

4.3.1.1 Assigning a Date and Time

A rating must have a date and time assigned from which it applies, and which is specified with the rating curve definition.

If it is the first rating for a site, the date and time assigned is usually that of the first stage value recorded to which the rating will be applied.

A rating may continue to apply to subsequent stage records until another rating definition is encountered, or the end of the applicability period may be explicitly specified as part of the rating definition.

All dates and times shall be specified to one second resolution in New Zealand Standard Time.

4.3.1.2 Digitising the Curve

Point-pairs

This is the most common method in New Zealand. Most graphical editing software used in New Zealand employs point-pairs with interpolation to define curves, and permits manipulation of point-pairs to edit curves. Specific method(s) vary and depend on the package but the outcome is generally the same.

a. Select pairs of stage (unrated, independent variable) and discharge (rated, dependent variable) that define the curve shape.

b. Include the pairs that define the minimum and maximum extent of the rating.

c. Generally more pairs are required for the lower segment than for the upper segments because there is usually more curvature in the lower segment.

d. More pairs are also required to define the curve around break points.

e. Different software has different limits on the minimum and maximum number of point-pairs. Two point-pairs are required to produce a line and a minimum of three to produce a curve. Generally 10 to 15 are sufficient to describe a rating. Using as few as possible improves smoothness of the resulting curve provided the interpolation method is appropriate.

Interpolating the curve

Ratings software used in New Zealand provides for many different methods of both defining and interpolating a curve.

Curve interpolation shall be non-linear in each segment unless the rating is defined at the resolution of the contributing data; that is, unrated stage (mm) and gaugings (l/s) or (ml/s).

It is very important that the interpolation process used when applying a rating is the same as the method used when deriving the curve.

Ratings defined in logarithmic scale must also ensure the appropriate scale offset is used for interpolation as was used to develop the curve.

When rendered in natural space there shall be no undulation (scalloping) of the curve at segment boundaries.

Equations

A rating curve may also be described by one or more equations, in which case an interpolation process is not required to apply the rating. Each equation applies to a segment of the curve as defined by an upper and lower bound.

Theoretical ratings may be more easily defined and applied using equations.

When rendered in natural space there shall be no undulation (scalloping) of the curve at segment boundaries.

4.3.2 Exchanging a Rating between Software

There are several time-series managers marketed and used in New Zealand, including locally developed and internationally sourced and supported solutions. Organisations aligning to NEMS are under no obligation to use the same software nor does adoption of NEMS restrict any agency from migrating to a different solution.

Methods vary between packages, notably for development and application of rating curves. Particular operations where the different methods in different packages have potential to alter fit of curves to gaugings and the discharge time series derived are:

- Interpolation of the curve

Ratings defined by point-pairs are not directly transferrable between systems unless the interpolation methods match.

If transfer of a rating curve is necessary it should be by a look-up table produced at the resolution of the stage so that no interpolation is necessary.

- Definition of rating shifts

Shifts may be defined as a new rating curve (Australasian methods) or as a departure with respect to stage from an existing curve (North American and European methods).

All time-series software available in New Zealand has some capability to mimic part or all of the alternate method but switching from one method of definition to the other is not straightforward nor is identical derivation of rated flow guaranteed.

- Implementation of transitions

All time-series software available in New Zealand is capable of applying a time pro-rated transition between one rating and the next, but they specify and store them in different ways to the extent that some specifications violate the integrity rules of others.

4.3.2.1 Exchange Format

As yet there is no robust and verified rating model exchange format that addresses and caters for all necessary aspects of rating model replication between the various systems.

The flow series should be transferred between agencies, rather than the unrated series and rating curve definition(s) or internal look-up table(s), unless the software used by each agency is entirely compatible; that is, specification of curves and the algorithms that render, interpolate and apply the rating model are known to be identical in both software.

4.3.2.2 Quality Coding

Quality codes applied to rating curves shall only endure when exchanged between software if:

- algorithms that render, interpolate and apply the rating model are known to be identical in both software, or
- a verified exchange format is employed that results in an identical flow series in both software.

Rated flows shall be quality coded QC 200 'external and not coded to match NQCS' if rating curve quality codes are voided by the exchange.

4.3.3 Synthetic Rating Curves

- When a rating change is known or suspected to have occurred but there is no gauging information from which to construct a new curve, a synthetic curve may be derived and applied provided it is reasonable to assume the required curve conforms to the shape and type of other ratings filed in the set.
- Synthetic rating curves may be derived from one or more of:
  - theoretical or empirical formulae
  - modelling of flows
  - assessment of bed level shift either observed in the field or determined from inspection of stage hydrographs and/or stage deviation plots, and/or
  - observed changes in cross-section.
- All evidence used to derive the synthetic rating must be preserved.
- A quality code of QC 300 applies to all segments of a synthetic rating curve.
- A description of the method, summary of the evidence, and assessment of the accuracy of the synthetic rating must be included in the metadata filed comments.

4.3.4 Gap Ratings

- When a rating change is known or suspected to have occurred but there is insufficient information to construct a rating curve, a 'gap rating' shall be applied for the period.
- If the software permits, the gap rating will prevent conversion of stage records to flow for the period defined. The result will be a gap in the flow series despite the existence of corresponding stage records.
- If the software is unable to prevent conversion of stage records to flow, the gap rating shall be a copy of the rating applicable prior to the gap, but with period of applicability that corresponds to the gap period and all rating segments set to QC 100.
- A quality code of QC 100 applies for the period of a gap rating.
- An explanation of the evidence for a gap in rating continuity must be included in the metadata filed comments, time-stamped at the start of the gap period.
- If the alternative to preventing conversion of stage to flow is employed, the method must be described in the Rating Model comment and specific instances recorded as Gap Rating comments in the flow series filed comments.

4.3.5 Quality Coding Rating Curves

4.3.5.1 Performance

All rating curves shall be quality coded according to the National Quality Codes Schema.

Note: The National Quality Codes Schema permits valid comparisons within a data series and across multiple data series within and between agencies.

4.3.5.2 Application

When a rating is applied to the time series being transformed, each data element in the resultant flow series shall be assigned the lower of:

- the code assigned to the unrated data element, or
- the code assigned to the rating segment applied.

4.3.5.3 Considerations

Rating curves and/or segments of curves shall have a quality value assigned based on qualitative and quantitative performance objectives. The following points shall be considered when quality coding ratings:

- whether derivation of the curve as a whole meets one or both of the following criteria:
  – operational standards, and/or
  – best practice at the time of data acquisition
- methods for curve fitting and quality assurance practicable at the time of archiving
- the confidence with which:
  – curve shape can be determined, and

– rating shift or change can be detected and quantified.

4.3.5.4 Data that Does Not Meet the Standard

Any rating that is not supported by quality assured discharge measurement shall be assigned a quality value from QC 100 to QC 300.

Rating curve segments that do not meet this best-practice Standard shall be assigned a quality value less than QC 600.

Note: A quality value of QC 600 shall only be assigned where this Standard and associated best practice is achieved.

Rating curve segments derived from measurements subject to steady-state adjustments shall be quality coded QC 400 or less.

Theoretical ratings shall be assigned a quality code of QC 300.

Flows in a time series that are derived from transition (smoothed or phased) periods between rating curves shall be assigned a quality code of QC 500, or QC 400 if the transition period is more than five days.

4.3.5.5 Extensions Above or Below Range of Measured Discharge

The stage–discharge rating curve segment quality code estimation matrix (see Annex B) provides a means of determining a suitable quality code for curve segments extended beyond the range of applicable discharge measurements.

The matrix takes into account the extent of extrapolation required, the method employed, and the amount of supporting evidence considered other than direct discharge measurement(s).

4.3.6 Filed Comments

Filed comments are time-stamped plain-text annotations associated with the series data for a particular station and parameter. They form part of the station metadata and provide additional information on aspects of the data, intended for users of the data.

For ratings these aspects may include:

- method(s) of rating curve construction
- explanation of assumptions
- explanation of accuracy of individual curves
- assessment of measurement outliers
- sudden changes in rating, for which there is no transition period
- explanation of accuracy and applicability of the overall rating model
- observations during measurements that may impact or explain the quality of one or more ratings
- identification and description of exceptional conditions, and/or
- limitations a user of the discharge data series should be made aware of.

Examples of required comments may be found at Annex K.

4.3.6.1 Rating Coverage Comment

A Rating Coverage comment must be filed for each rated site. Its purpose is to provide a means of rapidly assessing the extent and reliability of rating extrapolations. The comment shall:

- be filed immediately following the station's initial comment
- include the date and time at which the comment was compiled
- be updated from time to time as new data becomes available, and
- detail the following:
  - maximum and minimum gauged flows
  - maximum and minimum recorded flows
  - corresponding stage for all above flows
  - mean velocity at maximum recorded flow, calculated from the rating curve
  - maximum and minimum gauged stage
  - maximum and minimum recorded stage
  - date and time of occurrence of each stated extreme.

4.3.6.2 Rating Model Comment

At least one Rating Model comment must be filed for each rated site. The comment shall:

- be filed at the date and time of the first filed rating
- include the name of the time-series manager used, and
- describe the rating model employed including, but not limited to, assumptions made and the method(s) of:
  - curve construction
  - curve interpolation, and
  - transitioning between shifts and/or changes in rating when applied to the time-series.

Note: The information required can usually be obtained from the application help, or if not, from the software support staff.

Further comments are required only when the model is changed; that is, this comment is not required for every rating filed if the model used is the same. These additional comments should be filed at the time of the change in system and/or method.

4.3.6.3 Gauging Deviation Comment

Any gauging that plots more than 8% from the applicable rating curve must be thoroughly investigated.

If after investigation the deviation is allowed to persist, an explanation as to the cause of the departure must be filed as a comment.

4.3.6.4 Comments for Synthetic and Gap Ratings

- A description of the construction method, summary of the evidence, and assessment of the accuracy of any synthetic rating must be included in the metadata filed comments, time-stamped at the beginning of the period affected.
- An explanation of the evidence leading to filing of a gap rating must be included in the metadata filed comments, time-stamped at the beginning of the period affected.

4.3.6.5 Comments for Instantaneous Shifts or Changes in Rating

Any instantaneous shift or change in rating, i.e. where no transition period is defined, shall be accompanied by a comment explaining the nature of the shift or change, including cause if known, and why no transition period is required.

4.4 Preservation of Record

4.4.1 Performance

The following information shall be archived, retained indefinitely and backed up regularly:

- all discharge and component relationships used to produce the flow series for a hydrometric station; for example, stage–discharge, stage–area, velocity-index, stage–velocity
- complete record of the periods of applicability of each rating, including shifts, synthetic and gap ratings
- supporting evidence for the adopted rating model, including:
  - supplementary data analysed to improve the model
  - all calibration and validation data used during analysis of the relationships, and development and maintenance of the rating(s), including analysis of outliers
  - records of techniques used to develop and apply the rating curves
  - a trace of changes or refinements to rating curves, including reasons for amendments
  - results of validation and calibration tests, and data audits
  - metadata relevant to understanding the relationship, its representation as a rating, and changes to the relation over time.

All original records shall be retained indefinitely by the recording agency.

Note: The original records may be required at a later date, should the archive data be found to be in error, becomes corrupted, or is lost.

4.4.2 Data Archiving

The archiving procedures, policies and systems of the archiving body shall consider:

- future data format changes
- off-site duplication of records, and
- disaster recovery.

4.4.2.1 Metadata

- Adequate mechanisms shall be put in place to store all relevant time-stamped metadata, i.e. quality codes and filed comments, with the actual data records.
- Results of rating curve quality assurance tests shall be stored as part of the metadata.
- Data audit reports shall be stored as part of the metadata.
- Site and station metadata pertaining to the unrated time series and rating calibration data shall be available to users of the rating curve(s) and derived flow series.

- It is sufficient to store details common to the calibration and/or unrated data once only, and with that data, provided it is also available and readily accessible to users of the discharge series.

5 Quality Assurance

5.1.1 In this Section

This section sets out the quality assurance requirements and procedures for ratings, in particular stage–discharge curves. However, tests of the resulting discharge series are directly relevant to velocity-index ratings and tests of velocity-index component relations can be adapted from the stage–discharge tests.

Less formal quality review occurs as rating curves are constructed and maintained.

A regular but much less frequent cycle of more formal audit is also incorporated.

5.2 Requirements

All agencies shall implement standard methodologies for:

- review of new ratings
- review of amended ratings, and
- periodic audit of archived sets constituting the rating model for a station.

5.2.1 Quality Review

5.2.1.1 Initial Rating

Review procedures shall include:

- confirmation of datum for measurements of stage
- assessment against control geometry and hydraulic characteristics, and
- review of extrapolations, and
- confirmation of the resultant flow series.

This work shall be undertaken by a suitably trained and experienced practitioner.

5.2.1.2 New Ratings

Review procedures shall include:

- review against previous ratings, and
- confirmation of the resultant flow series.

This work shall be undertaken by a suitably trained and experienced practitioner.

5.2.1.3 Amended Ratings

Review procedures shall include:

- comparison with the previous version of the amended rating(s)
- review against unchanged prior and subsequent ratings, and
- confirmation of the resultant flow series.

This work shall be undertaken by a suitably trained and experienced practitioner.

5.2.2 Audit

Quality assurance processes shall include audit of the data.

Unaudited data that is released for use shall be identified as being unaudited.

Reliable records from other sites and/or agencies may be used for comparison, where available.

5.2.2.1 Audit Cycle

A data audit shall:

- be undertaken at regular planned intervals appropriate to the needs of the agency and users
- include no less than two consecutive years' rated data
- include all periods of amended and new ratings since last audit plus a period of 12 months preceding, or since station inception if less than 12 months prior
- be undertaken by a suitably trained and experienced practitioner, and
- culminate in a formal report that includes graphs and summary tables that demonstrate whether the rating model and resultant flow series meets the requirements of this Standard.

5.2.2.2 Minimum Audit Report Requirements

As a minimum, analyses and information required for an audit report for rating curves and the resultant flow series shall include:

- catchment details
- site details
- record details
- standard statistics
- list of periods of applicability and periods of transition
- filed comments
- evidence of quality coding
- data summary tabulations
- data plots, and
- results of tests of quality and accuracy.

Note: Catchment and site details may be uplifted from a corresponding Water Level audit report, or the Ratings audit may be combined with the Water Level audit.

5.2.2.3 Catchment Details

The following shall be included in the audit report:

- a Catchment Details Summary, which identifies key features of the catchment including:
  – catchment name, and region if relevant
  – catchment area
  – important tributaries and sub-catchments
  – associated water-level and rainfall sites used for comparisons
  – neighbouring water-level and flow sites used for comparisons
  – water-use characteristics, if any
  – activities in the catchment that may affect flows and/or rating curves, and
  – conditions in the catchment that may affect flows and/or rating curves, and

- a location map, showing:
  - the river or stream on which the site is situated
  - important tributaries
  - catchment boundary for the site
  - boundaries of any important tributary catchments
  - location of all stations for which data is presented in the report
  - catchment elevation, and
  - location of any significant abstractions or discharges upstream of any site reported.

5.2.2.4 Site Details

The following shall be included in the audit report:

- a Site Details Summary, which identifies key features of the site including:
  - location and description of control(s), including history of significant changes
  - stage and flow range
  - type of recording installation, including instrumentation
  - brief description of physical attributes
  - brief assessment of hydraulic characteristics
  - brief description of gauging methods
  - brief history of instrumentation, and
  - date and magnitude of any datum change(s), and
- a site plan, marked with locations of:
  - controls
  - structures
  - recorder installation
  - staff gauges
  - benchmarks
  - gauging section(s)
  - features affecting hydraulic characteristics, and
  - overflow path(s), if any.

5.2.2.5 Record Details

The following shall be included in the audit report:

- For each flow or rainfall series presented in the report, state:
  - the period of record included
  - the site name and number
  - map reference for site
  - data collection agency, and
  - status; for example, open, closed, low flow or flood flow only.

5.2.2.6 Standard Statistics

The following shall be tabulated in the audit report:

- For the full period of flow series subject to audit:
  - minimum and maximum recorded and gauged stage
  - minimum and maximum recorded and gauged discharge
  - mean velocity at maximum rated flow
  - mean flow from rated series (whole years)
  - median flow from rated series (whole years)
  - average annual instantaneous low flow
  - average number of gaugings per year
  - average number of rating changes per year
  - overall percentage of rated flow range measured
  - proportion of rated flow record in each quality code band
  - maximum interval between gaugings, and
  - overall percentage of simultaneous rated flows within ± 8% of gauged discharge.
- For the full period of flow series previously archived for the site:
  - minimum and maximum recorded and gauged stage
  - minimum and maximum recorded and gauged discharge
  - mean velocity at maximum rated flow
  - mean flow from rated series (whole years)
  - median flow from rated series (whole years)
  - average annual instantaneous low flow
  - average number of gaugings per year, and
  - average number of rating changes per year.

5.2.2.7 Comments and Quality Coding

The following shall be included in the audit report, for each flow record being reviewed:

- a copy of the filed comments for the total record period for the flow series and calibration measurements
- a table of the quality codes assigned to each rating or rating segment, or
- quality colour-coded plots of each curve.

5.2.2.8 Required Tabulations

The following shall be included in the audit report:

- list of periods of applicability, including transitions, for all curves in audit period, including and specifically identifying any synthetic and gap ratings
- results of tests on overall audit period, and individual curves, for:
  - gauging stage agreement with (unrated) recorded stage
  - gauging frequency
  - gauging coverage
  - rating curve fit to gaugings (deviation statistics), including bias and trend, and
  - rating curve coverage (range of stage encompassed).

5.2.2.9 Required Plots

The following shall be included in the audit report:

- plots of flow over time, with gaugings, and one or more comparison records, at sufficient resolution to identify:
  - spurious or faulty data
  - unexplained steps
  - unsubstantiated events
  - missing events
  - out-of-range values
  - inconsistent recession shapes and base flows, and
  - unexpected trends or cycles.
- plots of curves at natural scales, with gaugings including uncertainty bars, at sufficient resolution to identify:
  - poor curve shape and/or integrity
  - unsubstantiated changes of shape
  - undefined or questionable extrapolations, and
  - undesirable convergence or divergence
- plot of cross-section(s) representative of the control(s)
  - reduced to gauge datum, and
  - annotated with relevant features.

5.2.2.10 Outputs

Recommended report outputs include:

- a hard copy report
- an electronic report, or
- at a minimum, an electronic document that only identifies which periods of record have passed audit.

5.2.2.11 Audit Certification

The completed audit shall contain the name and signature of the auditor and the date that the audit was completed.

5.2.2.12 Change of Software

Exact replication of the previous discharge time series may not be possible regardless of the level of care and attention to detail applied to the migration of archives.

For this reason all previous audits are void if an organisation changes software unless:

- the algorithms for development, rendering, interpolation and application of any rating model are known to be identical, and
- the resultant discharge time series is proven unchanged.

After a change in software and migration of their archive(s), the recording agency shall:

- file a Rating Model comment for each rated site detailing the change, and
- if previous audits have been voided by the change, release any rated flow data as unaudited until audit can be repeated in the new system.

5.3 Tests for Quality and Accuracy

5.3.1 Requirements of the Standard

- Individual rating curves shall be unbiased, hydraulically correct and conform to the calibration measurements.
- 95% of the simultaneous rated flows shall be within ± 8% of the measured discharge.
- No more than 12 months between gaugings at sites with engineered structures providing predictable control, and no more than three months at other sites.
- Metadata shall be recorded for all aspects of rating curve development addressed by this Standard.
- Stationarity shall be maintained.

5.3.2 Curve Integrity

- Plot each curve, one at a time, without the gaugings, and confirm:
  - curve interpolation is appropriate and smooth, and
  - break points correspond to physical features of the channel.
- Plot the set of curves, without the gaugings, and confirm:
  - curves do not cross unless control geometry is confirmed changed
  - no undue divergence or convergence of curves, and
  - no discontinuities in curve shape caused by merging of curves.
- Assess gauging distribution and confirm:
  - curve shape is supported by measurements, or by other evidence if no measurements exist, and
  - extrapolation to full range of stage is defined and appropriate.

    Note: See Annex L for example output.
- Assess curve sensitivity (as required for quality coding).

5.3.3 Curve Fit

- Determine deviation of corresponding rated flows from gauged flows and confirm:
  - deviations are not unduly influenced by gauging stage disagreement with the recorded stage series
  - deviations are within tolerance
  - outliers are explained
  - no bias is evident, over time or through the flow range
  - no trends are evident, over time or through the flow range, and
  - percentage of the simultaneous rated flows that are within ± 8% of the measured discharge.

    Note: Flow deviation as a percentage is usually more informative, but stage deviation in mm may be more useful for type curve sets.

    - Test is $\left((Q_r - Q_g)/Q_g\right) \times 100$,
    - use recorded stage to derive Q_r, and
    - gaugings completed in periods of missing stage record are excluded.

      Note: See Annex L for example output.
- Plot each curve, with the gaugings and, if possible, the control cross-section, and confirm:
  - the curve is representative of the underlying hydraulic relation (see Annexes E, F and G)
  - excluded measurements are explained, and
  - the curve is not over-fitted to measurements

    Note: If curve fit is statistically perfect, all deviations will be zero. In practice a well-constructed rating will have small, random scatter around zero that is within the range of gauging error. 'Over-fitted' curves place too much weight on the measurements themselves rather than representation of the underlying relation and may result in shape errors, overly frequent shifts, and fewer measurements supporting each curve.

5.3.4 Periods of Applicability

- Inspect the assigned rating dates and times and confirm:
  - association with the correct curve
  - shifts align with evidence of changed control
  - transitions are smoothed unless explained
  - transition periods are limited to duration of the event causing the shift, and
  - applicability periods do not unintentionally overlap.

    Note: In some software an overlapping applicability period implements a gradual (blended) transition; in other software it causes an error.

- Assess the frequency of rating shifts and/or rating changes.

  Note: The relation may change more frequently following an event in the upstream catchment that releases more bed material, e.g. a severe storm, landslide or channel clearance, or during a period of increased flood activity. However, increased shift frequency, and/or change assigned to insignificant events, may indicate over-fitting and/or wrong curve shape. Increased shift frequency may also indicate prior inadequate gauging frequency, in which case the flow series prior to the increase should be carefully inspected for undetected changes.

5.3.5 Flow Series

- Calculate the extremes, and confirm:
  - flows are within expected range, and
  - mean velocity for maximum flow is reasonable.
- Plot the rated series, with the gaugings, and a nearby rain or flow station, and confirm:
  - recession shapes are consistent
  - recession levels are sensible; none perched above or hanging below others
  - hydrograph shapes are reasonable
  - significant events are corroborated
  - no unexpected trends or cycles evident; for example, periods of lesser or extreme floods, and
  - no steps have been introduced by rating changes.

5.3.6 Gauging Frequency

- Assess gauging frequency (see Annex I)
- If gauging frequency is inadequate for the site, confirm:
  - curve shape is supported by other data; for example, consistency with curve set and/or theoretical relationships, and
  - no rating changes were missed, or
  - undetected shifts are identified and addressed.

5.3.7 Metadata

- Confirm:
  - quality coding is complete and correct
  - required comments exist, are informative and factually correct, and
  - supplementary data and ancillary information is appropriately collated, referenced and stored.

5.3.8 Stationarity

- Test for stationarity and confirm:
  - stationarity is preserved, or
  - non-stationarity is flagged and fully explained.

Note: Double mass plots against two or three nearby sites can be used for this purpose, provided the comparison data is reliable and stationary (see Annex L for example).

6 Velocity-index Methods

6.1.1 In this Section

When the stage–discharge relation at a site is not unique for any given discharge and steady-state approximations fail to provide sufficient accuracy or looped stage–discharge ratings curves are impractical, velocity-index methods should be used to monitor flows.

The basic principle is to continuously determine area and mean velocity and multiply together to obtain a continuous record of flows. Area is derived from measurement of water levels and the cross-section surveyed at the instrument. Velocities are measured at a single location using an in situ velocimeter, and related to mean velocity by a calibration process similar to developing stage–discharge ratings.

The technology is varied and rapidly evolving. Most instruments measure Doppler shift but may employ acoustic, radar or laser signals. Most acoustic instruments (ADVs) operate submerged while radar and laser are non-intrusive. Large scale particle image velocimetry (LSPIV) is an emerging non-intrusive technology that does not involve Doppler shift.

In general terms the requirements of this Standard relating to stage–discharge ratings also apply to velocity-index ratings; however, there are some additional considerations and requirements when applying a velocity-index method.

This section describes those additional considerations and sets out requirements that are specific to velocity-index methods used to obtain a flow series from stage and velocity measurements logged by ADV instrument(s), which at present are the most commonly deployed velocimeters in New Zealand.

6.1.2 Other References

There is currently no NEMS Standard for continuous measurement using in situ ADV instruments. Data collection shall in the interim be guided by the Australian Government Bureau of Meteorology National industry guidelines, Part 9: *Application of in situ point acoustic Doppler velocity meters for determining velocity in open channels* (WISBF GL 100.09-2013).

Further guidance on method can be found at Chapter 2 of the *WMO Manual on stream gauging* (vol. II) – *Computation of discharge* (WMO Publication No. 1044, 2010b).

6.2 Data and Information Requirements

6.2.1 Contributing Stage and Velocity Series

It is necessary to monitor velocity and stage simultaneously then derive coincident relationships for both variables to produce values for the two parameters (section area, A, and mean velocity, V) needed for calculation of discharge using the equation $Q = VA$.

6.2.2 Discharge Measurements

Gaugings are needed to establish the velocity-index relation.

Measurements are not required to be carried out at the sensor location but the mean velocity used in the velocity-index relation must be mean velocity pertaining to the instrument cross-section.

At the time of each gauging, the velocity logged from the sensor (index velocity) must be noted as well as the stage.

All other gauging requirements are as for stage–discharge rating curves except that steady-state approximations are unnecessary.

6.2.3 Survey

A cross-section is required at the instrument, up to maximum expected flood level. The datum and measurement angle(s) of the instrument must also be recorded.

Survey shall be repeated whenever it is suspected that the stage–area relation has changed, or the instrument has moved or been replaced.

The maximum period between surveys shall be three years.

6.2.4 Supplementary Measurements

ADV instruments use speed of sound reflected from suspended particles to determine water velocity. Speed of sound is affected by other environmental factors. Depending on site conditions and the actual instrument used, some or all the following data may also need to be collected and the velocity data compensated for their effect:

- water temperature
- barometric pressure
- sediment concentration, and/or
- salinity.

  Note: At tidal sites, salinity may vary greatly in the water column as the saltwater wedge pushes up river and adequate compensation may be difficult.

6.3 Data Processing and Preservation

6.3.1 Field Data

Data shall be stored in a recognised time-series manager.

6.3.2 Data Processing

Data processing includes:

- assignment of quality codes
- adjustment of data based on additional environmental parameters such as temperature, barometric pressure, salinity, and sediment concentration, and
- data editing, to cater for step-changes or data deviations as a result of sensor recalibration, baseline drift, fouling or sensor maintenance.

6.3.3 Standards

6.3.3.1 Stage Series

The stage series shall be processed and preserved in accordance with the normative reference NEMS *Water Level*.

6.3.3.2 Velocity Series

The velocity series shall be processed and preserved as set out in this section, and guided by the Australian Government Bureau of Meteorology WISBF National Industry Guidelines, Part 9: *Application of in situ point acoustic Doppler velocity meters for determining velocity in open channels* (WISBF GL 100.09-2013).

6.3.4 Data Files

All of the following three versions of velocity series data shall be retained and maintained:

- raw data
- adjusted data set, and
- the edited data set.

6.3.4.1 Raw Data

Raw data is defined as unadjusted data taken directly from an in situ ADV sensor. The raw data is useful for tracking sensor deterioration over time and provides the means of revisiting data for reprocessing.

Raw data may include velocity data that has been corrected by the sensor for some or all of the following:

- temperature
- barometric pressure, and/or
- salinity.

6.3.4.2 Adjusted Data Set

The adjusted velocity data set shall take into account relevant temperature, salinity and barometric pressure adjustments.

The adjusted velocity data set shall take into account effects of sediment concentration; for example, whether too clear or too murky for adequate signal return.

6.3.4.3 Edited Data Set

Edits to the velocity series may include one or more of the following:

- compensation for changes in baseline due to sensor drift and/or progressive fouling; that is, where the baseline drifts steadily up or down.
- smoothing of noisy data, and/or
- point editing to remove sensor maintenance, calibration, or temporary fouling spikes.

Such adjustments are subjective and must be treated with caution.

All changes from raw velocity record shall be documented in the metadata filed comments.

Note: This is particularly important while no specific Standard exists for in situ ADV velocity series, and until velocity data may be quality coded using the full set of codes in the NEMS schema.

6.3.4.4 Gaps in Data

It is not appropriate to fill gaps in velocity series of more than 1 or 2 hours' duration, and not unless it is reasonable to assume constant trend and small variation in velocity during the gap.

Note: In most if not all cases, should the above conditions be satisfied, it will suffice to delete the gap marker and allow the time-series manager to interpolate over the gap.

Gaps in the velocity series must be marked and assigned quality code QC 100.

6.3.4.5 Supporting Data

In addition to the three velocity data sets, supporting data used to make adjustments, e.g. temperature, and when essential, barometric pressure, salinity and suspended sediment data, will also be stored or referenced.

6.3.5 Metadata

6.3.5.1 Site Details

Site details shall be recorded as required under the normative references.

6.3.5.2 Quality Coding

The stage series shall be quality coded in accordance with the normative reference NEMS *Water Level*.

The velocity series shall be quality coded QC 200.

Note: The effect of coding the velocity series QC 200 is that the discharge series ultimately derived is also limited to quality QC 200 or less. Until NEMS Standards are defined for the velocity series and the component stage–area and velocity-index relations, QC 200 'unknown quality' is a fair assessment of the resulting discharge series under this Standard.

6.3.5.3 Filed Comments

Requirements for the stage series and discharge measurements are as set out in the normative references.

For the velocity series, the minimum required are:

- description of the instrument
- details of calibrations
- description of environmental conditions and effects
- description of cause and treatment of gaps in the data
- periods of, and reasons for, changes from raw data, and
- periods of, and reasons for, raw data considered unreliable including gaps.

6.3.6 Preservation of Record

The following data shall be archived indefinitely and backed up regularly:

- raw and processed velocity series
- supplementary measurements
- validation checks
- calibration results, and
- metadata.

6.4 Establishing the Relations

6.4.1 Stage-area Relation

The stage–area curve shall be calculated from survey of the cross-section.

The stage–area curve should be applied as a rating or function to transform the stage recorded to cross-section area.

6.4.2 Velocity-index Relation

Mean velocities must be calculated from discharge measurements by dividing the measured discharge by the area calculated from the stage–area relation at the instrument.

Calculated mean velocities are then correlated with the instrument velocity readings at the time of each gauging to derive a relationship between the velocity recorded by the instrument and the mean velocity for the flow through the instrument cross-section.

The simplest case is when discharge is directly proportional to index velocity and the velocity-index curve can be derived by least-squares regression and described by a linear relation. More complex relations require plotting and analysis similar to that for development of stage–discharge ratings.

For installations comprising two or more ADVs positioned in different locations in the vertical or horizontal, the readings from each instrument should be combined into an average index velocity before correlating with the mean velocity calculated from discharge measurement.

In some cases stage may be a factor in the velocity-index relation and a multiple regression solution may be required.

6.4.3 Metadata

6.4.3.1 Quality Coding

Until specific Standards are defined for the component stage–area and velocity-index relations, each shall be coded QC 200 ‘not assigned’, or QC 100 if missing.

6.5 Applying the Relations

6.5.1 Calculating Discharge

Discharge is simply the product of the area retrieved from the stage–area relation and mean velocity retrieved from the velocity-index relation for any given coincident instrument readings of stage and (index) velocity.

Note: Most hydrological software in use in New Zealand provides suitable methods for looking up the required parameter values if each relation is stored as a rating, or calculating the required parameters if each relation is described by a function, then deriving the product to obtain a discharge at each required time-step.

Most software is also capable of interpolating one or other or both of the input stage and index velocity should the sampling not be coincident.

6.5.2 Managing and Applying Shifts

The stage–area and velocity-index relations (the component relations) can be analysed for shifts and managed in the same way as stage–discharge rating shifts if each relation is stored independently with its own periods of applicability.

If the process of obtaining the discharge is independent of maintaining the relations, no additional user intervention is required to apply shifts once the new relation(s) are defined, stored and the relevant periods of applicability for each specified.

Note: Typically the process to look up then calculate the product of the component relations is specified and implemented using simple user-programmable simulation tools available in each hydrological software suite.

If a multiple regression function is necessary to describe a component relation, depending on the software available, changes to the relation may need to be manually managed and application of the transition(s) user-controlled to derive the discharge series.

6.5.3 Quality Coding

The discharge series quality code applicable at any time-step shall be the least of the four codes retrieved from:

- the two contributing unrated data series, stage and velocity, and
- the two component relations, stage–area and velocity-index.

Annex A – List of Referenced Documents

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Annex B – Estimation of Quality Code for Stage–Discharge Rating Curve Segments

Rating curve segments shall have a quality value assigned based on qualitative and quantitative performance objectives.

The Quality Codes – Rating Curves chart included in this Standard sets out how rating curves are to be quality coded within the framework of the National Quality Code Schema. Implementation of the schema is described in section 4.3.5.

The stage-discharge rating curve segment quality code estimation matrix contained in this Annex assists with differentiating between the schema quality codes of 'poor' (QC 400), 'fair' (QC 500), or 'good' (QC 600). Other codes, which are applicable to entire curves, are determined directly from the Quality Codes – Rating Curves chart.

Curve Segmentation

Rating curves constructed from discharge measurements shall be partitioned into a minimum of three segments for quality coding, with bounds at the nearest convenient nodes to mean flow and mean annual flood.

Below mean flow is the bottom or low end of the curve, between mean flow and mean annual flood is the mid-section, and above mean annual flood is the high or top end.

The bounds of mean flow and mean annual flood have been selected because they:

- reflect intuitive separation of a typical rating curve into low-, mid- and high-range segments
- are readily estimated from regional studies, or by using existing tools; for example,. Regional Flood Estimation for new sites
- provide nodes with the same, or very similar, discharge values across all ratings for a site regardless of individual rating range
- are easily revised as additional data is obtained, and
- can be reasonably estimated from a few years' record

Mean flow is preferred to median flow because it sets a slightly higher, more reasonable upper bound to the low flow portion of the rating for unstable sites with highly variable flows.

Mean annual flood (MAF) is roughly equivalent to bankfull; that is, the rating curve tipping point for bermed cross-sections. It is the level below which the channel is most active and therefore most potential for ratings to change. In New Zealand it also often corresponds to significant change in bank vegetation which influences Manning's *n*. Gauging to MAF is usually reasonably achievable, so ratings can typically be defined by measurement up to this level.

An agency may wish to partition all or any curves into more segments, which may be advantageous in some circumstances. For example, additional partitioning of a high end segment may result in an improved quality code for most flood events in a discharge series if several gaugings above MAF have been obtained, or additional partitioning may be desirable if a particular and relatively small range of flows are important for compliance.

Determining the Appropriate Code from the Matrix

The stage-discharge rating curve segment quality code estimation matrix uses a system of points to determine whether a particular rating segment attracts a quality of 'poor' (QC 400), 'fair' (QC 500), or 'good' (QC 600). The points are ascribed to various aspects of quality according to the degree to which each aspect might be compromised. Each aspect has one or more criteria that form the rows of the matrix.

When applying the matrix every row must have points assigned then the total points are tallied to arrive at the final quality code for the rating curve segment.

The final quality code for any segment from the matrix is:

Good (QC 600)	≤ 7 points
Fair (QC 500)	8 to 15 points
Poor (QC 400)	> 15 points

Matrix Implementation Notes

The notes below pertain to the corresponding numbered sections of the matrix that follows.

1.1 Desirable hydraulic conditions include assessment of the approach, contraction and exit conditions for the structure. These will vary with the structure and may vary with season and flow conditions; for example, the effect of weed growth in the channel.

2.3 A rating used to derive a flow record from a stage record must be drawn to filed stage to obtain agreement between gauged and rated discharge, but where a rating is required without stage record, the gauging stage can only be confirmed against the primary reference. Where disagreement exists between gauging and filed stage, both must be reviewed; the gauging stage may require weighting or adjustment, or the filed stage reprocessing.

2.5 Calculation is $\left((Q_r - Q_g)/Q_g\right) \times 100$. Any gaugings discarded must be either deleted from the final gauging series or identified in the metadata as excluded from use for rating derivation.

3.1 Failure to achieve a smooth curve may be a result of:

- inappropriate curve definition (either by rating points or equation segments)
- poor choice of interpolation method applied over the definition, or
- inappropriate exponent in equation(s).

Some software provides a linear interpolation option between rating pairs which may not provide a smooth curve unless the rating pairs are densely defined; for example at intervals no more than the stage resolution, such as every 1 mm as required by NEMS *Water Level.*

3.2 The extent of the curve must be explicitly defined. Some software will extrapolate a curve to the highest and lowest stage in the applicability period based on algorithms in the software; however, relying on such features does not produce consistent results, and is neither ideal nor best practice. Any such extrapolation applied by the software, i.e. values in the rated flow series extracted from beyond the filed rating points or defined range of equation(s), should automatically attract QC 200.

3.3 Calculated from the ratio over the entire segment.

3.4 It is expected that the various controls will be identified and described in the metadata and that evidence of transitions will either be filed with the data, e.g. cross-section(s), or if the evidence is photos or descriptive explanation, they will be included in the metadata.

3.5 At many sites it is possible to immediately state that unsteady flow will or won't exist. Some software cannot implement looped ratings. Any steady-state approximations are expected to be fully described in the metadata.

3.6 A site that has been gauged for some time may have a history of rating changes that provides significant evidence for drawing the rating under construction. Similarly, a historical rating under review can utilise gaugings and rating curves drawn later in time.

4.1 It is expected that hydraulic evidence, e.g. cross-section(s) and model outputs, be filed with the data set as data or metadata, and that any other supplementary evidence, e.g. photos, sketches, observations of channel change, etc., be stored as metadata.

4.2 Set may be either ‘type’, ‘family’ converging, ‘family' diverging, or other predictable cycle of change, e.g. weed growth or ice cover, or not applicable because control is stable and therefore only one rating need apply. Evidence may be gaugings or surveyed cross-sections, or photographs or sketches of observed changes to the site control geometry or hydraulic conditions. The evidence is expected to be filed in the data or the metadata.

5.1 ‘Applicable’ may include historic gaugings deemed relevant to and supporting of the current rating. Explanation is required in the metadata of the use of gaugings and other evidence from outside the period of applicablity of the current rating.

5.2 Alternate and indirect methods include survey of CTF, slope-area estimates of flood flows, hydraulic model outputs, observations of zero flow, etc. The required evidence is expected to be filed in the data or the metadata.

STAGE–DISCHARGE RATING CURVE SEGMENT QUALITY CODE ESTIMATION MATRIX

	Criteria	3 Points (Poor)	1 Point (Fair)	0 Points/NA (Good)
1	**'Prior knowledge' confidence in establishing the rating**			
1.1	Control feature: ‘pre-calibrated’ structure; for example, v-notch thin plate or crump weir, or flume **Assess**	Non-standard, poorly maintained and/or with variable approach and/or exit and/or contraction conditions unlikely to conform to general discharge equation; requires frequent gauging ☐	Non-standard shape, i.e. no applicable standard discharge equation, but if well-maintained provides stable conditions; once rating is established by gauging, it requires only annual gauging to confirm ☐	Standard shape, stable conditions and well maintained. First approximation of rating possible by standard discharge equation; requires gauging only to verify and refine first approximation ☐
OR	Control feature: other engineered structure’; for example, bed control weir or rocked grade control **Assess**	Unstable or poorly maintained or with undesirable hydraulic characteristics; requires frequent gauging ☐	Moderately stable, of consistent geometry, well maintained with desirable hydraulic characteristics; expected frequency of rating changes less than one per year ☐	Stable, of consistent geometry, well maintained with desirable hydraulic characteristics; once rating is established by gauging it requires only annual gauging to confirm ☐
OR	Control feature: natural **Assess**	Mobile control, e.g. sand, gravel or vegetated control that changes frequently; requires frequent gauging ☐	Moderately stable; rating change expected on average less than once per year ☐	Stable over time, e.g. bedrock sill; once rating is established by gauging it requires only quarterly gauging to confirm ☐
2	**Curve fit to gaugings**			
2.1	Sample size	No gaugings ☐	< 3 ☐	≥ 3 ☐
2.2	Reliability of measured discharge	Most gaugings < QC 500 ☐	Some gaugings < QC 500 ☐	All gaugings at least QC 500 ☐
2.3	Agreement between gauging stage and corresponding filed stage	Differences generally > ±10 mm ☐	Differences generally ≤ ±10 mm but > ±3 mm ☐	Differences generally ≤ ±3 mm ☐
OR	Uncertainty of gauging stage, if no filed stage	Most > ±10 mm ☐	Most ≤ ±10 mm but > ±3 mm ☐	Most ≤ ±3 mm ☐
2.4	Distribution of gaugings through stage range	No gaugings ☐	Clustered high or low; gauged flow range ≤ 50% of segment flow range ☐	Range of gaugings is similar to range of segment; gauged flow range > 50% of segment flow range ☐
	PAGE SUBTOTALS	☐	☐	☐

	Criteria	3 Points (Poor)	1 Point (Fair)	0 Points / NA (Good)
2.5	Deviation of rated flow from gauged flow	Most deviations ≥ ±8%, or no gaugings ☐	Most deviations < ±8% ☐	All deviations < ±8% ☐
2.6	Bias	Uncorrected and/or unexplained bias, or too few gaugings to test ☐	Some uncorrected but explained bias ☐	No significant bias ☐
3	**Definition of curve shape**			
3.1	Integrity of curve **Assess**	Curve not smooth due to poor definition and/or inappropriate interpolation within segment and/or poor merging to next segment ☐	Smooth curve not achieved only because of linear interpolation (applied at stage resolution or better) ☐	Smooth curve achieved ☐
3.2	Coverage of curve	**<u>Action required:</u> Amend curve definition**	**<u>Action required:</u> Amend curve definition**	Curve <u>definition</u> covers full range of stage to which the curve will be applied within period of applicability ☐
3.3	Sensitivity	Change in rated discharge per mm change in stage > 4% ☐	Change in rated discharge per mm change in stage ≥ 2% but ≤ 4% ☐	Change in rated discharge per mm change in stage < 2% ☐
3.4	Applicability to control geometry **Provide evidence**	Limited evidence or analysis of appropriate shape and transitions ☐	Shape consistent with geometry; where transitions occur they are realistic and explained ☐	Shape consistent with geometry; where transitions occur they are supported by measurement, i.e. gaugings or surveyed levels of known features ☐
3.5	Unsteady flow **Assess**	Loop ratings or backwater effects are known or suspected to exist and have not been otherwise compensated ☐	Possible loop rating or backwater effect but either the effect is within the margin of flow determination error, or the rating is fitted to represent the steady state ☐	No loop rating or backwater effect exists, or a looped rating has been defined ☐
3.6	Supporting gauging **Assess**	No gaugings available, previous or subsequent to this rating, that can be used as supporting evidence ☐	Some previous or subsequent gaugings and ratings to help define shape ☐	Extensive set of prior or subsequent gaugings and ratings exist which define shape ☐
	PAGE SUBTOTALS	☐	☐	☐

	Criteria	3 Points (Poor)	1 Point (Fair)	0 Points / NA (Good)
4	**Consistency of curve shape between rating changes**			
4.1	Set of curves consistent with character of channel **Provide evidence**	Anecdotal, limited, or no evidence ☐	By hydraulic evidence ☐	By hydraulic evidence and gauging ☐
4.2	Current curve consistent with rest of set for site **Assess**	Non-conforming; major change with limited evidence ☐	Non-conforming; minor change, or major change supported by evidence ☐	Stable control, or change conforms to set supported by evidence ☐
5	**Extrapolation**			
5.1	Extent	> 50% beyond nearest applicable gauged flow ☐	beyond 20% but within 50% of nearest applicable gauged flow ☐	within 20% of nearest applicable gauged flow ☐
5.2	Method **Provide evidence**	estimated by method not NEMS Rating Curves recommended, or without evidence of method ☐	estimated by NEMS Rating Curves recommended method, with all evidence provided ☐	NEMS Open Channel Flow recommended alternate or indirect measurement, with all evidence provided ☐
	PAGE SUBTOTALS	☐	☐	☐
	COLUMN TOTALS	☐	☐	☐

Final Quality Code

Poor (QC 400) = >15
Fair (QC 500) = 8 to 15
Good (QC 600) = ≤ 7

GRAND TOTAL ☐

Annex C – Computation of Mean Gauge Height for a Gauging

The mean gauge height for the period of the gauging shall be calculated according to the formulae below:

(a) For larger rivers, if the fluctuations are less than 50 mm, an arithmetic mean shall be used.

For smaller rivers, the time-weighted method (c) is most often preferred.

(b) If the fluctuation is 50 mm or more, ISO 748:2007 recommends using a discharge weighted calculation:

$$h = (q_1 h_1 + q_2 h_2 + q_3 h_3 + \dots + q_n h_n) / Q$$

where: h is mean gauge height

Q is the total measured discharge $= (q_1 + q_2 + q_3 + \dots + q_n)$

$q_1, q_2, q_3 \dots q_n$ = discharge measured during time interval 1, 2, 3, ... n, and

$h_1, h_2, h_3 \dots h_n$ = average gauge height during time interval 1, 2, 3, ... n.

(c) However, Rantz et al. (1982a) demonstrates that method (b) tends to overestimate stage height, and suggests that where the change in discharge with stage height is linear in the range of stage that occurred during the measurement, a time-weighted mean is better.

This is calculated from:

$$h = (t_1 h_1 + t_2 h_2 + t_3 h_3 + \dots + t_n h_n) / T$$

where: h is mean gauge height

T is the total time for measurement

$t_1, t_2, t_3 \dots t_n$ = duration of time intervals between breaks in the slope of the gauge height versus time graph, and

$h_1, h_2, h_3 \dots h_n$ = average gauge height during time interval 1, 2, 3, .. n.

(d) Where the change in discharge with stage height is curvilinear, neither method (b) nor (c) is reliable, and Rantz et al. (1982a, p. 173) recommend that the mean of the two estimates be used.

Note: Rantz et al. (1982a) also provide examples of the calculations.

Annex D – Bibliography

This Annex lists publications and other references that were consulted during the course of preparing this Standard but are not directly referenced, and/or may serve as useful background reading to provide a broader and/or deeper understanding of topics and/or requirements included this Standard.

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Annex E – Hydraulics of Flow Measurement in Open Channels

Introduction

Flow rate is the fundamental metric of hydrometry. It underpins a very large part of hydrological, water resource and flood hazard studies. It is unique because it is a single integrated measurement of the resultant effect of all the processes that operate over and within a catchment. None of these catchment processes such as precipitation, evaporation, transpiration and seepage to groundwater is amenable to a single point measurement.

A continuous series of flow rate (also termed 'discharge') is not measured directly but may be calculated from measured water levels using a relationship known as a 'rating curve'. The importance of rating curves has long been recognised, as is evident from the production of numerous technical publications over the years and current international discussion of methods.

This Annex outlines the features that control the level of water in a flowing channel and so determine the shape of the rating curve. The quality of rating curves is a critical determinant of the reliability of discharge data.

Controls of Water Levels in Rivers

The hydraulic control of water level is vital for siting a stream gauging station. The prime criterion for selecting a site for a permanent water level recorder on a natural river channel is to choose a place where there is a stable downstream channel control, which may, for example, be a long uniform river reach, a constriction caused by a gorge or approach works for a bridge, or a tight bend.

In practice, the control may vary with the discharge. At low flows, the control may be at the upstream end of a riffle, at a rock bar across the channel, or any other physical feature capable of maintaining a fairly stable relation between stage and discharge. At medium and high flows, the influence of riffles and other low flow controls may be drowned out by the backwater from other controls further downstream (Figure 3).

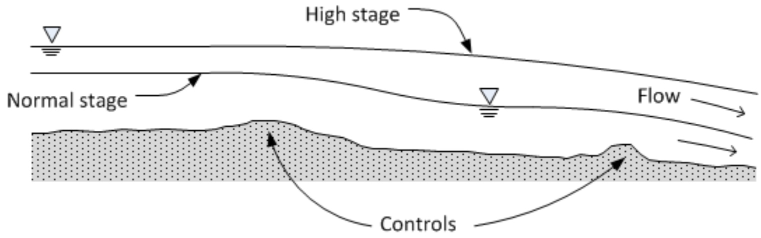


Figure 3 – Illustrating the effect of the drowning of a normal control by another control at higher stage

Illustration: Jon Marks.

Source: Reproduced with permission from McKerchar and Henderson (1987).

Manning's Equation

In long straight channels, flowing water assumes a depth and mean velocity that depends upon the channel slope, the cross-section geometry and the channel roughness. When the channel slope is constant and the water surface is parallel to the bed, the flow is said to be 'uniform'.

A common relationship for describing uniform flow is the Manning's equation:

$$v = \frac{R^{2/3} S^{1/2}}{n} \tag{1}$$

where: v is mean velocity (m/s)
R is hydraulic radius (m)
S_f is friction slope (assumed same as water surface slope and channel slope in uniform flow with no appreciable variation in velocity head), and
n is Manning's roughness coefficient.

Typical values of Manning's roughness coefficient n are in standard hydraulics textbooks and range from 0.02 to 0.10, or more. A rule of thumb value for alluvial gravel bed rivers in New Zealand is $n = 0.035$. Reference to local guidance that gives n values derived from measurements with accompanying photographs is recommended; for example, see Hicks & Mason, (1991).

Froude Number

The hydraulic radius R is defined as cross-section area A divided by the wetted perimeter P.

In typical river channels where the width usually exceeds 20 times the maximum depth, the wetted perimeter P is effectively equal (within 5%) to the water surface width W, so that R is nearly equal to the mean depth y.

In the context of open channel flow, the dimensionless Froude number F_r is an especially useful metric. It specifies the ratio of inertial to gravitational force and is written as:

$$F_r = \frac{v}{\sqrt{gy}} \tag{2}$$

where: g is gravitational acceleration (m/s^2).

F_r is also the ratio of water velocity to wave speed in the water. In most natural channels, apart from mountain torrents, F_r is less than unity ($F_r < 1$), the flow is said to be 'subcritical' or 'tranquil' and depth is controlled by downstream geometry and roughness. In contrast, 'supercritical' or 'rapid' flow, with F_r greater than unity ($F_r > 1$), occurs mainly over spillways, in steep flumes, and chutes on mountain streams and in specially designed channels where water is to be conveyed over a large change in levels.

Note: An excellent example of the latter is a length of concrete channel on the Leith Stream at the George Street Bridge in north Dunedin (Figure 4).

Figure 4 – Leith Stream chute, Dunedin

Source: Google Earth Street View, 2014.

In subcritical flow, waves and disturbances will propagate upstream against the current, whereas in supercritical flow, waves and disturbances are swept downstream. Where F_r is close to unity ($F_r \approx 1$), waves and disturbances move neither upstream nor downstream, but tend to form standing waves often seen in flooded rivers.

Critical Flow

Critical flow occurs at the lip of free over-falls and at dam spillway crests (Figure 5). Weirs and flumes are designed to induce the occurrence of critical flow.

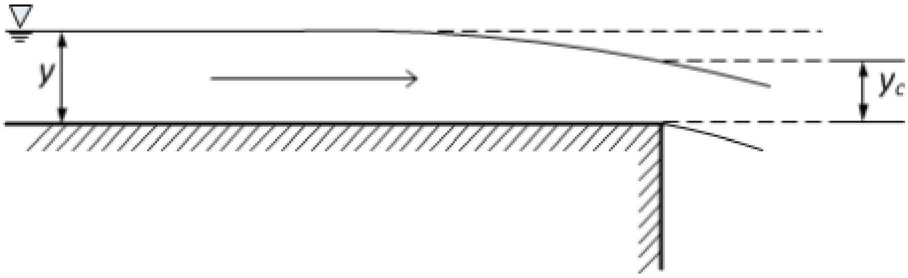
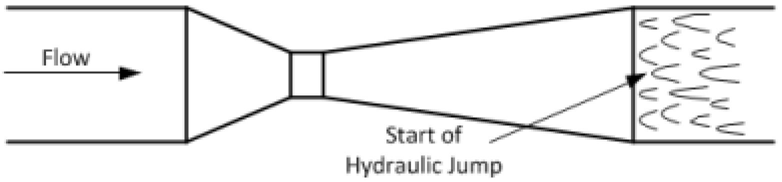


Figure 5 – Drawdown of uniform flow approaching a free over-fall

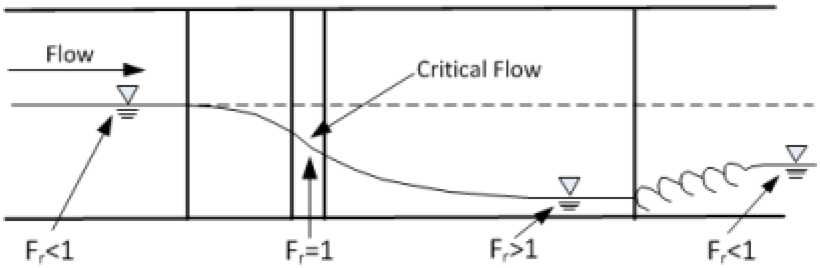
Note: y is depth for uniform flow and y_c is critical depth at over-fall.

Illustration: Jon Marks
Source: Reproduced with permission from McKerchar and Henderson (1987).

Constrictions in a channel also change the water depth and can induce critical flow, as illustrated in the sketch in Figure 6. In this case, the constriction controls the depth immediately upstream.



Plan (a)



Elevation (b)

Figure 6 – Sketch of flume with a gentle contraction and expansion: (a) plan view and (b) elevation, showing the effect on flowing water of the constriction and expansion and expected values for Froude Number

Note: The turbulent water just downstream of the constriction is termed a 'hydraulic jump'.

Illustration: Jon Marks.
(Adapted from McKerchar and Henderson (1987)).

From the critical depth, the mean velocity in the cross-section and hence discharge can be calculated. Although weirs and flumes that are properly installed and maintained provide excellent flow records, their installation is only practicable in smaller-sized streams. On larger streams and rivers, natural hydraulic controls have to be used.

Shifting and Variable Controls

In an alluvial channel, scour and deposition of bed sediment in the controlling reach alters the hydraulics of the control. The result is that, typically, shifts in the rating curve occur.

Downstream tributaries can cause a variable control when they either flood or bring large quantities of sediment into the main channel.

For example, the Kawarau River at the outlet of Lake Wakatipu is joined by the Shotover River at a short distance downstream (Figure 7). Here the discharge from the lake is a function of two variables: the level of the lake and the level of the Kawarau River just downstream of the lake outlet (Jowett and Thompson, 1978).

Figure 7 – Outflow of Lake Wakatipu into the Kawarau River, Otago

Note: This is an example of flow under variable control, due in this case to sediment deposition in the Kawarau River from the Shotover River.

Source: Google Maps, 2014.

Loop Ratings

Rating curves involving two variables can also be encountered in flood conditions. On the rising limb of a flood hydrograph, the discharge for a given stage exceeds the steady-state discharge for the same stage, whereas on the falling limb the discharge is less than the steady-state discharge, at least in theory.

Deposition of bed sediment and its subsequent erosion is one contributing reason.

The second reason, which relates to open channel hydraulics, is detailed in hydraulic textbooks such as Henderson (1966, p. 392). Looped ratings (Figure 8) arise when water surface slope varies as flood waves pass. Gaugings on rising stage will plot to the right of the steady-state curve and those on falling stage to the left. Size of loop is generally inversely proportional to gradient of the river and directly proportional to the rate of change of stage, but may vary with each individual event.

So called 'loop' ratings are most commonly encountered in low-gradient sand-bed rivers.

At most established sites in New Zealand the channels are so steep that the effect is too small to measure and the same rating may be used for both the rising and falling limb segments. However, the possibility of loop ratings must be considered at new sites, or if high flow gaugings at existing sites show undue scatter or bias, particularly if gradient is low and rate of change of stage is relatively rapid during high flow events.

Simply categorising measurements and/or their deviations into rising, falling and steady stage may reveal the presence of a loop.

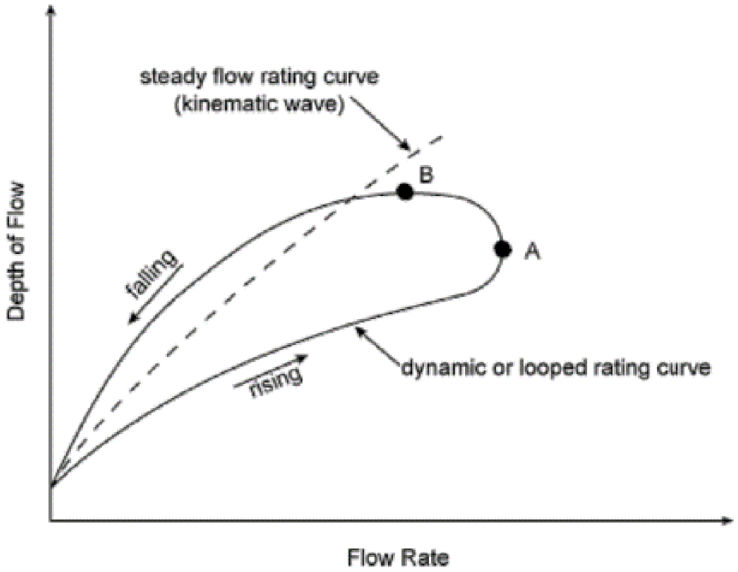


Figure 8 – Diagram of a loop rating

Note: Maximum flow occurs at A whereas B is maximum depth.

Channel Cross-section Shape

In natural channels where the width is considerably greater than the depth, the hydraulic radius R is approximated by the mean depth y. The discharge from Manning's equation is:

$$Q = \frac{A\,R^{2/3}S^{1/2}}{n} \qquad (3)$$

so equation (3) can be re-written as:

$$Q = A\,y^{2/3}\,k$$

where: $k = \dfrac{S^{1/2}}{n}$

The cross-section area A is also a function of the depth y so we can write:

$$Q = kby^{m} = C_d y^{m} \qquad (4)$$

where: b and m are constants, and

$C_d = kb$

Note: Equation (4) conforms to the generalised rating equation more usually expressed as $Q = k\ (h - e)^m$

For a rectangular channel where b is the width, such that $\mathrm{A} = by$, discharge is given by

$$Q = \ by\, y^{2/3}\, k$$

hence equation (4) becomes

$$Q = C_d y^{5/3}$$

and therefore the exponent m = 1.67 .

Values of the exponent m for other section shapes can similarly be determined provided the cross-section is very much wider than it is deep. Examples are presented in Table 2 (after Fenton, 2001).

Table 2 – Values of generalised rating equation exponent for various channel cross-section shapes

Source: After Fenton (2001).

Nature of cross-section	**Typical values for exponent m under uniform channel flow**	
	Manning	**Chèzy**
Rectangular	1.67	1.5
Shallower U-shaped	1.92	1.75
Parabola	2.17	2
Sharper U-shaped	2.42	2.25
V-shaped (triangular)	2.67	2.5

Note: Theoretical ratings for structures conform to Chèzy values. Semi-circular cross-section approaches that of triangular sections.

Note: Chèzy's equation is similar in form to Manning's equation but takes $\sqrt{R}$, hence the different values for m, and has an inverse roughness coefficient; that is, a larger value for less roughness.

This formulation is a useful guide to the form of a rating curve. If, for a series of flow measurements conducted over a range of levels, stage is plotted against discharge raised to a power that is the inverse of the appropriate value of m for the cross-section shape, measurements will form a straight line. This is the essence of curve fitting.

The commonly encountered parabolic channel cross-section has an exponent of around 2.0, indicating that an approximately parabolic rating curve is possible. This is the underlying assumption to stage versus $\sqrt{Q}$ as proposed by Fenton (2001) and the polynomial curve fitting implemented by TIDEDA and Hilltop Software. Similarly, the 'power 2/5' option available in Hydstra assumes a roughly triangular section.

The function can be fitted in log-log space using standard linear regression to determine the quantities C_d and m, and estimate standard errors. However, there are several difficulties with this approach (after Fenton, 2001):

- The cease to flow point must be found but cannot be shown.
- The same parameter values may not apply over the whole flow range (see Annex G). There may be different relationships at higher flows; for example, if different downstream controls become operative as flows increase.
- High flows may not be well fitted because small flows have undue influence.
- Extrapolation beyond the highest gauged discharge to flows corresponding to highest recorded stage values can yield unreliable results, particularly when the control section is a composite form; for example, narrow channel with wide berms.

These difficulties are important because extremes of flow are often of concern in hydrological studies, and are a reason for log-log methods not being used for preparation of rating curves in New Zealand hydrometric practice.

Annex F – Structures

Design Selection

Weirs or flumes are designed to force the occurrence of critical flow which greatly eases the task of preparing rating curves, but their construction is only practicable in small channels.

Weirs are essentially barriers constructed across a channel so that the upstream water level is contained by the structure and the bed is low enough on the downstream side so that free-fall occurs between the two.

Flumes consist of a symmetrical constriction in the sides or bottom of a channel which, for a particular range of flow, cause critical flow to occur within the channel.

Weirs and flumes that are constructed to specified standards have predetermined coefficients C_d and m in equation (4) Annex E, which are given in many references (Henderson, 1966; Ackers et al., 1978).

Warning: When selecting discharge coefficients from references, it is important to ensure the form of the equation for which the coefficient is quoted matches the form intended to be used for the calculation; some coefficients quoted may not be in SI units, while some references may combine other constants into the coefficient(s) quoted and others not.

When making a selection on weirs or flumes, Ackers et al. (1978) is recommended reading. More recent publications make reference to a set of ISO (International Organization for Standardization) Standards on 'Measurement of liquid flow in open channels'.

Things to consider

Advantages and limitations of each design must be weighed up between:

Requirements of:

- location
- purpose
- desired accuracy
- control stability
- rating sensitivity
- in-stream ecology

Constraints imposed by:

- access
- regulations
- costs
- safety
- need for ongoing maintenance
- avoiding in-stream barriers

Specific issues include:

- fish passage
- ability to pass sediment and debris
- accuracy over the range of flows to be measured
- resource consent requirements
- navigational hazard
- ease of installation
- ensuring sufficient fall while avoiding erosion, scour and wash-out, and
- safety, for construction and subsequent public access.

Fish Passage

Structures useful for discharge measurement create barriers to fish movement because of height, insufficient depth of water, or extreme velocity.

Requirements for fish passage should be checked with the relevant regional council and will likely form part of resource consent for the structure.

Additional advice on how to provide fish passage can be sought from organisations charged with protecting the fishery. Publications relevant to the species affected may also be consulted if more guidance is required.

The final design may be a compromise that allows for fish passage but renders a theoretical rating for the structure invalid. Retrospective fitting of a fish pass to an existing structure may also invalidate the current rating. In either case field calibration is required to establish the new rating.

Field Calibration

In theory, field calibration is unnecessary with weirs and flumes, hence they are often referred to as ‘pre-calibrated’ structures.

However, in practice they almost always require field rating, usually by volumetric or other gauging methods (refer to NEMS (2013) *Open Channel Flow*), because of difficulty:

- constructing the structure exactly to design, including conditions upstream and downstream, and
- achieving and maintaining the hydraulic conditions necessary for the theory to hold.

Field rating confirms whether or not the actual stage–discharge relationship conforms to the theoretical rating.

Care is necessary using data from flow control structures. Difficulties encountered that invalidate the specified standard conditions include:

- sediment accumulation upstream of the structure
- narrowing of the channel upstream of the structure
- aquatic weed growth
- encroaching riparian vegetation
- leakage under or around the structure
- scour downstream undermining the structure
- extreme high flows exceeding the applicable range of the structure or bypassing the structure
- stream channel migrating due to sediment load, and/or
- partial drowning due to backwater effects from a downstream control.

Weirs

Weir Terminology

A weir is a barrier across a channel, which controls the water-level upstream of it so that there is free-fall through the weir to the water level downstream of the weir.

Upstream is the head-water, and downstream the tail-water. There should be free-fall between these two. This falling body of water between the head- and tail-water is called the nappe. If the nappe does not contact the structure, it is said to be aerated (Figure 9).

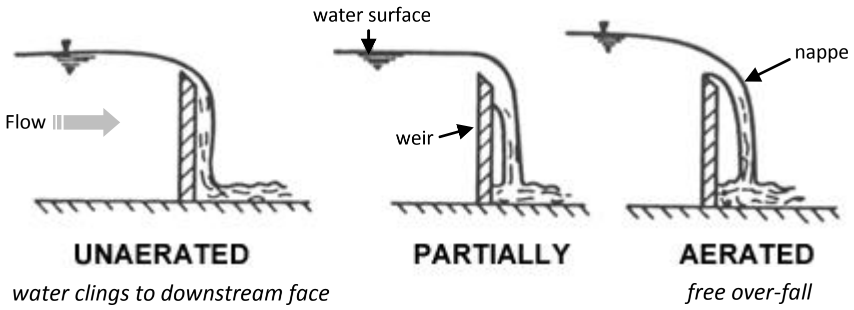


Figure 9 – Stages of nappe aeration

Source: Adapted from an image at www.openchannelflow.com

When the tail-water rises above crest level the weir is said to be ‘drowned’. A weir intended to operate in this drowned condition at all times is called a submerged weir, and special conditions apply.

When a weir constricts the width of the channel, the parts of the barrier between the weir crest and the river banks are called ‘end contractions’.

A weir crest that occupies the full width of the channel is termed a ‘fully suppressed’ weir; that is, the end contractions are suppressed.

When a narrow weir is placed in a wide channel, and the banks of the approach pool have no effect on the flow through the weir, it is said that the contraction is ‘fully developed’.

Standard Designs

There are a number of standard weir designs, each having specific limitations and discharge formula (Ackers, et al. 1978). Each type is outlined below, with only the most common type, the thin-plate V-notch, being covered in more detail.

The main types of weir include:

- thin-plate V-notch weirs that are suitable where:
    - the ratio of high to low flow is large, and
    - accuracy at low flow is important
- thin-plate rectangular weirs that are:
    - less sensitive, and thus
    - less accurate at low flows
- broad-crested weirs that are:
    - in common use, but
    - intended more as bed controls, which are wholly field rated rather than pre-calibrated weirs
- triangular profile (Crump) weirs that:
    - consist of a low dam built across a waterway
    - normally have a 1:2 slope on the upstream and 1:5 slope on the downstream face
    - are suitable for natural watercourses where:
        - minimum head losses are sought, and
        - there is a relatively high sediment load
- flat-V weirs (Figure 10) that are:
    - a modification of the triangular profile weirs, with
    - a shallow 'V' cross-section of 1:10 side-slope when viewed in direction of flow.

Note: This type of Crump weir is more sensitive than the horizontal-crested triangular profile weir. They are expensive, particularly if erosion downstream necessitates protective works.

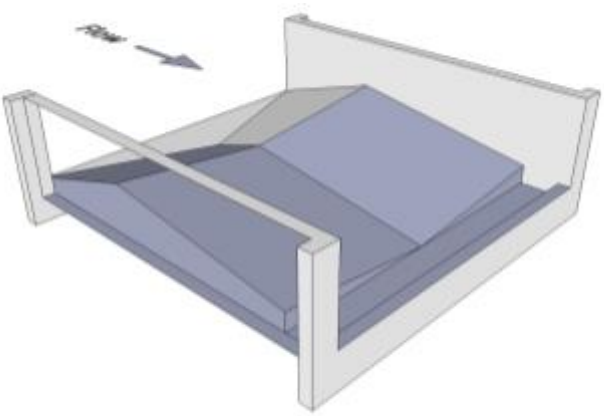


Figure 10 – Flat 'V' Crump weir

Illustration: Jon Marks
Source: Reproduced with permission from NIWA Field Manual.

Thin-Plate V-Notch Weirs

The most common, and the most accurate when properly installed and maintained, of weir designs are the sharp-crested or thin-plate weirs that come in a variety of forms.

Thin-plate weirs are well suited for temporary installations.

Normally they consist of a thin concrete wall with a straight sharp metal crest of steel or aluminium alloy. In smaller versions, the entire structure may be constructed of steel or alloy plate.

Free-fall of water over the crest at all flows, i.e. an aerated nappe, is essential for the theoretical rating to hold.

Configurations of V-Notch Weirs

Thin-plate V-notch weirs are a versatile design, which in various configurations have been widely used. Cross-section profile may be one of a number of more or less standard forms.

The angle enclosed by the straight sides of the V is usually one of a number of standard angles, such as:

- 150°
- 120°
- 90°
- half-90, or
- quarter-90.

Note: The terms half-90 and quarter-90 do not mean 45° and 22.5° but instead refer to the area for a given head of water above the apex. The actual angles are 53° 8' and 28° 4', respectively (Figure 11).

V-notch weirs are particularly suitable for accurate measurement of flows up to about 1.4 m^3/s. They can be used for greater flows if combined with another design that accommodates the larger flows.

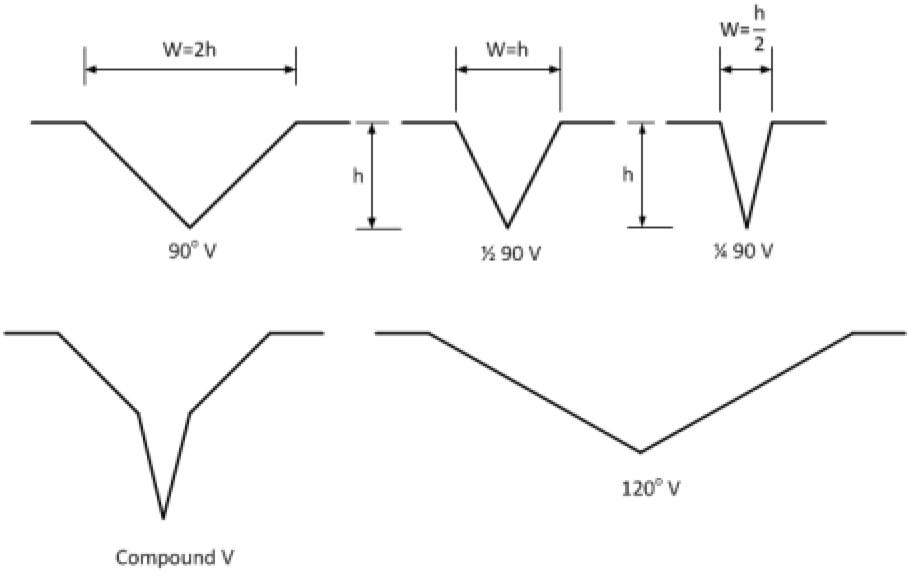


Figure 11 – V-Notch Weir Cross-Section Profiles

Illustration: Jon Marks
Source: Reproduced with permission from NIWA Field Manual.

V-Notch Weir Specifications

The specifications for a V-notch thin-plate weir, as set down in ISO 1438:2008, are:

- The notch is a symmetrical V-shape in a vertical thin-plate.
  The line that bisects the angle of the notch shall be vertical and equidistant from the sides of the approach channel.
- The weir is smooth and plane, especially on the upstream side.
  A 'smooth' surface shall be equivalent in surface finish to that of rolled steel.
- The weir is perpendicular to the sides as well as the bottom of the channel.
- The crest surfaces shall be plane surfaces of width between 1 mm and 2 mm, which shall form a sharp right-angled edge at their intersection with the upstream face of the weir plate
  These surfaces shall be machined (or filed) perpendicular to the upstream face. The edges shall be free from burrs and scratches, and untouched by abrasive cloth or paper, which will tend to unacceptably round them.
- The downstream edges of the weir shall be chamfered if the weir plate is thicker than the allowable crest width. The surface of the chamfer shall make an angle of not less than 45°, and preferably about 60°, with the crest surface.
- The weir plate is usually made from corrosion-resistant metal.

Practical Limitations

There are practical limitations to dimensions of the weir that optimise performance and therefore applicability of the theoretical discharge formula.

For the basic configuration of the V-notch thin-plate weir, the following shall apply (with reference to Figure 12):

θ between 20° and 100°
$H_u/Z < 2.0$ for $\theta = 90°$
$H_u/Z \leq 0.35$ for other values of θ
Z/b between 0.1 and 1.0 for $\theta = 90°$
Z/b between 0.10 and 1.5 for other values of θ
$H_u \geq 0.06$ m, and
$Z \geq 0.09$ m

where:
θ is notch angle in degrees.
H_u is measured head
Z is height of vertex of the notch with respect to floor of the approach channel, and
b is width of the approach channel.

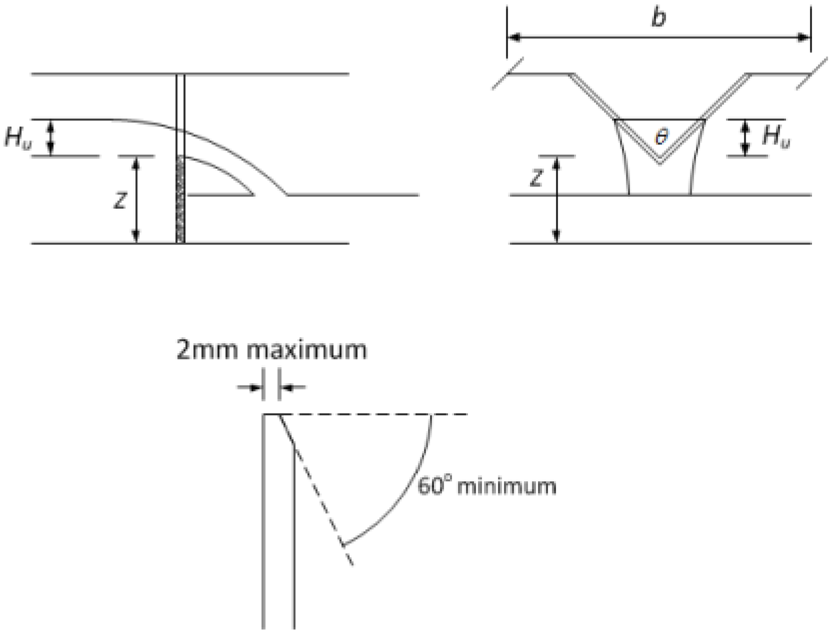


Figure 12 – V-notch Dimensions

Illustration: Jon Marks
Source: Reproduced with permission from NIWA Field Manual.

Stage Discharge Relationship and Weir Formulae

Because flow accelerates to critical velocity over the weir, a drawdown in water level exists for a short distance upstream. Accordingly the head measurement must be made at a sufficient distance upstream to avoid this area of drawdown.

Many weir formulae calculate discharge using equations that assume acceleration from rest; that is, the starting velocity or velocity of approach must be relatively low. This is accomplished by constructing a sufficiently large weir pond upstream, which must be maintained throughout the life of the structure or the equations become invalid.

Such equations therefore only apply under those conditions of low or zero approach velocity, conditions which are commonly exceeded during higher flows unless the weir pond is sufficiently large.

Both weirs and flumes can be affected by approach and backwater conditions being less than ideal, by leakage and by sediment and debris carried in the flow.

Why Weir Formulae Work

$$v^2 = 2g\Delta H \qquad (5)$$

Water dropping over a free-fall obeys the universal formula in (5). The head ΔH in this case is the loss in head that occurs between the upstream water level and the elevation of the water at the point of critical flow.

From the above it can be seen that if the depth at critical flow over a weir could be measured and subtracted from the upstream water level to give ΔH, the velocity could be calculated; and with the depth known, all that remains to be added to the formula is the width.

Fortunately we are spared the difficult task of measuring depth at that elusive point because there is a relationship between critical depth and the upstream water level (head).

For a simple broad-crested weir, for instance, if the velocity of approaching flow is negligible, the depth at critical flow is $^2/_3$ the upstream head H_u. Therefore, the head loss ΔH in the basic formula is $^1/_3$ of the upstream head H_u.

From the basic formula of discharge:

$$Q = W\ (width) \times D\ (depth) \times v\ (velocity)$$

if $v = \sqrt{2g\Delta H}$ (from (5) above), and

we substitute $\frac{2}{3}H_u$ for the depth and $\frac{1}{3}H_u$ for the loss in head ΔH, then:

$$Q = W \times \frac{2}{3}H_u \times \left(2g \times \frac{1}{3}H_u\right)^{1/2} \qquad (6)$$

Substituting 9.81 m/s^2 for g then calculating out gives us the theoretical discharge:

$$Q = 1.70\, W\, {H_u}^{3/2}$$

Other weirs have similar basic formulae to this, but with different relationships between head and critical depth, and with additional coefficients for the contraction effects of the various types of orifice.

Thin-Plate V-Notch Weir Formula

The general formula for a V-notch weir, from ISO 1438:2008, is:

$$Q = \frac{8}{15}\sqrt{(2g)}\,.\,C_d.\tan\frac{\theta}{2}.\,H_e^{5/2} \tag{7}$$

where: Q is discharge in m^3/s

g is the acceleration due to gravity (9.81 m/s^2)

C_d is the coefficient of discharge (corrects for head loss and contraction; see below)

θ is notch angle in degrees, and

H_e is effective head in metres (see below).

The coefficient of discharge C_d has been determined by experiment as a function of three variables, H/Z, and Z/b, where:

Z is height of vertex of the notch with respect to floor of the approach channel

b is width of the approach channel, and

$H_e = H_u + k_h$ (where H_u = measured head), and

k_h is a correction applied to compensate for the combined effects of viscosity and surface tension. The value of k_h varies according to notch angle.

For weir notches that are small relative to the approach channel, the velocity of approach will be negligible and the effects of H/Z and Z/b are also negligible. For this condition (the fully-contracted condition), Table 3 provides values of C_d and k_h as a function of θ , for selected notch angles.

Table 3 –Values of C_d and k_h for some notch angles for weirs with negligible velocities of approach

Source: ISO 1438:2008.

θ (degrees)	40	60	80	90
C_d	0.582	0.576	0.576	0.578
k_h (mm)	1.8	1.2	0.9	0.8

Rectangular Thin-Plate Weir Formulae

The general equation for a rectangular thin-plate weir is based on Bernoulli's principles.

$$Q = C_q \frac{2}{3} \sqrt{2g}\, bH^{3/2} \tag{8}$$

where: H is measured head

b is width of the notch, and

C_q is a coefficient of discharge that may be determined from measurements, or estimated, the form and value of which is then dependent on weir configuration.

Derived from the general equation (8), several variations cater for:

- weir configurations ranging from suppressed (full width) weirs to those with fully developed contractions, and
- compensation for the combined effects of viscosity and surface tension.

These more specific equations include, from WMO-1044-v1:

- Kindsvater-Carter

  Note: For various ratios of notch-width to stream width (ratio of 1.0 is full width; that is, suppressed weir)
- Rehbock

  Note: For the full width (suppressed) weir.
- Hamilton-Smith

  Note: For weirs with fully developed contractions.
- Hydraulics Research Station (HRS) (White, 1977)

  Note: For various notch widths and crest heights,

H_u is used in all the above equations. The total head correction is included in the equations.

Note: The location at which H_u is measured must be far enough upstream to avoid drawdown over the structure, but not so far that it becomes influenced by *significant friction losses. Guidance on the appropriate location for head measurement is provided in WMO-1044-v1 section 7.7.3.*

There are limits of application of each equation, as reproduced in Table 4.

Table 4 – Limits of application of rectangular thin-plate weir equations

Source: WMO-1044-v1.

Equation	Minimum head H_u (m)	Minimum width b (m)	Minimum crest height Z (m)	Maximum H_u/Z ratio
Kindsvater-Carter	0.030	0.15	0.10	2.0
Rehbock	0.030	0.30	0.30	1.0
Hamilton-Smith	0.075	0.30	0.30	-
HRS	0.030	0.40	0.15	2.2

Broad-crested Weir Formulae

The general formula for a broad-crested weir, from WMO-1044-v1, is:

$$Q = C_d\sqrt{g}\,.\,b.\,H^{3/2} \tag{9}$$

where: Q is discharge in m³/s

g is the acceleration due to gravity (9.81 m/s^2)

C_d is a coefficient of discharge (corrects for head loss and contraction; see below)

b is width of the weir, and

H is the total head in metres; that is, H_u plus head due to velocity of approach

such that a more serviceable form of the equation is:

$$Q = C_v C_d\left(\frac{2}{3}\right)^{3/2}\sqrt{g}\,.\,b.\,H_u^{3/2} \tag{10}$$

where: C_v is a coefficient of approach velocity (WMO-1044-v1 gives suitable values), and

H_u is measured head.

Various configurations of weir are catered for in WMO-1044-v1 including:

- triangular profile weir (Crump flat or rectangular)
- round-nosed horizontal crest weir
- rectangular profile weirs
- flat-V weir (Crump V).

Flumes

Flumes consist of a regular artificial channel with symmetrical contractions in the sides and/or bottom which, for a particular range of flow, cause critical flow and thus a standing wave (hydraulic jump) to occur within the channel.

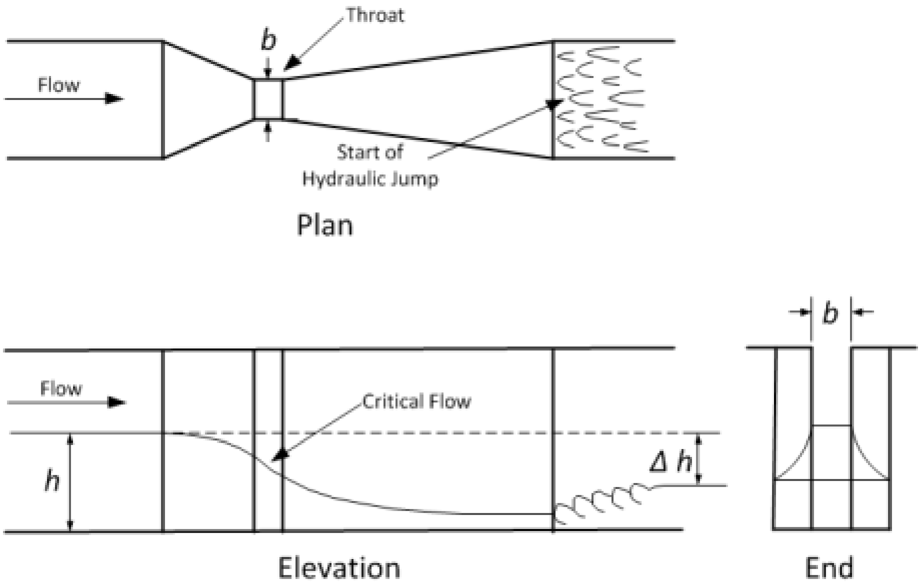


Figure 13 – Typical Flume

Illustration: Jon Marks
(Adapted from NIWA Field Manual).

Rectangular Flumes

These are also known as rectangular ‘standing wave’ or ‘critical depth’ flumes. They consist of a symmetrical constriction of rectangular cross-section, positioned centrally with respect to the approach channel, which will also be of rectangular cross-section.

The contractions can be either side or bottom contractions, or both.

Selection of a suitable design and site depends upon the:

- channel configuration
- approach channel length (10x width required)
- desired head loss, and
- downstream limitations.

Rectangular flumes are almost universally used for measuring the inflow to sewage treatment works.

Rectangular-throated Flume Formula

Discharge is calculated using equation (10), where b is throat width.

Coefficients of velocity C_v and discharge C_d may be found in Tables I.7.6 and I.7.7 of WMO-1044-v1.

Trapezoidal Flumes

The trapezoidal flume differs from the rectangular flume by having a throat, entrance and exit of trapezoidal cross-section.

Their application is also similar to rectangular flumes, being preferred if it is necessary to accommodate the structure in a trapezoidal channel.

They can give relatively high accuracy over a wide range of flows.

Trapezoidal-throated Flume Formula

Discharge is calculated using equation (10), where b is throat width and with the inclusion of a shape coefficient.

Direct application of the equation is not convenient so a theoretical stage–discharge rating curve is recommended; see ISO 4359:2013.

Figure 14 – Awanui Stream Flume Operating Semi-Submerged in the Top and Centre Images, and Under Free-Flow with Formation of a Hydraulic Jump in the Bottom Image

Note: Flow is from right to left through the flume in all photos.

U-throated Flumes

These are essentially a round-bottomed version of a rectangular flume. They are more sensitive in the lower range, and are better suited for some situations; for example, in sewage systems where the flow enters from a pipe.

U-throated Flume Formula

Discharge is calculated using equation (10), with the inclusion of a shape coefficient and diameter of the base of the flume substituted for throat width.

Direct application of the equation is not convenient; successive approximation techniques are required (see ISO 4359:2013).

Parshall Flumes

The Parshall flume accelerates flow though a contraction of both the parallel side walls and a drop in the floor at the flume throat. Under free-flow conditions, the depth of water at a specified location upstream of the flume throat can be converted to a rate of flow as in equation (4), Annex E where the coefficients C_d and m are determined by the flume's dimensions.

The design of the Parshall flume is standardised under ISO 9826:1992. The flumes are not patented and the discharge tables are not copyright protected.

A total of 22 standard sizes of Parshall flumes have been developed, covering flow ranges from 0.15 l/s to 93 m^3/s.

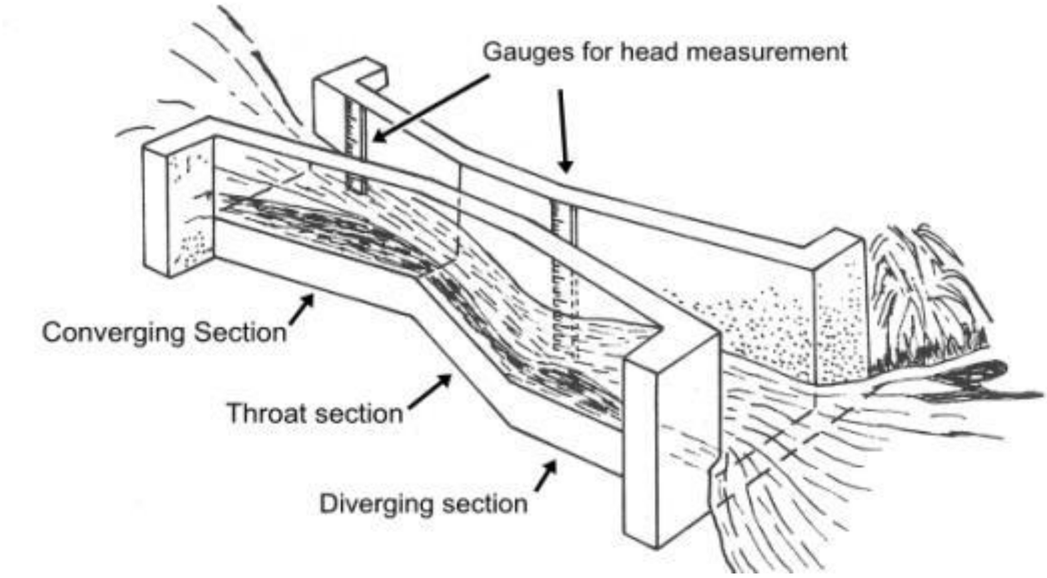


Figure 15 – Sketch of a Parshall Flume

Source: Adapted from 'Field Measurement and Runoff' (*FAO Soils Bulletin*, *68*).

Submergence transitions for Parshall flumes range from 50% (25-mm to 75-mm sizes) to 80% (3-m to 15-m sizes), beyond which point level measurements must be taken at both the primary and secondary points of measurement and a submergence correction must be applied to the flow equations.

Under laboratory conditions Parshall flumes can be expected to exhibit accuracies to within ±2%, although field conditions make accuracies better than 5% doubtful.

A wide variety of materials are used to make Parshall flumes. Smaller Parshall flumes tend to be fabricated from fibreglass and galvanized steel (depending upon the application), while larger Parshall flumes tend to fabricated from fibreglass (up to 3.6 m in size) or concrete.

In common with other flow measurement structures, Parshall flumes have several drawbacks:

- Parshall flumes require a drop in elevation through the flume. To accommodate the drop in an existing channel, either the flume must be raised above the channel floor (raising the upstream water level) or the downstream channel must be modified.
- As with weirs, flumes can have an effect on local fauna. Some species or certain life stages of the same species may be blocked by flumes, due to relatively slow swim speeds or behavioural characteristics.
- In earthen channels, upstream bypass and downstream scour may occur.
- Parshall flumes below 75 mm in size should not be used on unscreened sewage flows, due to the likelihood of clogging.
- The Parshall flume is an empirical device. Interpolation between sizes is not an accurate method of developing intermediate-size Parshall flumes as the flumes are not scale models of each other. The 30-inch [76.2-cm] and 42-inch [106.7-cm] sizes are examples of intermediate sizes of Parshall flumes that have crept into the marketplace without the backing of published research into their sizing and flow rates.

WMO-1044-v1 recommends field calibration of Parshall flumes using current meter measurements.

H-Flumes

The H-Flume is a hybrid of the V-notch weir and a rectangular flume. It was developed mainly by the US Department of Agriculture. There are designs available for small (HS), mid and large (HL) variants. Like weirs, the H-flume requires free-fall over the lip, and is sensitive at moderate flows but not at low flows.

Compounding it with a small-angle V-notch weir downstream is one way used to overcome the sensitivity problem. An advantage of the H-flume is its self-cleaning property, similar to a rectangular flume.

Equations describing discharge from H-flumes are complex polynomials. Reference to published discharge tables for the particular design installed is the recommended method for obtaining the theoretical rating. However, as for other flumes and weirs, the theoretical rating requires extensive field checking.

The configuration of an H-flume is shown in Figure 16.

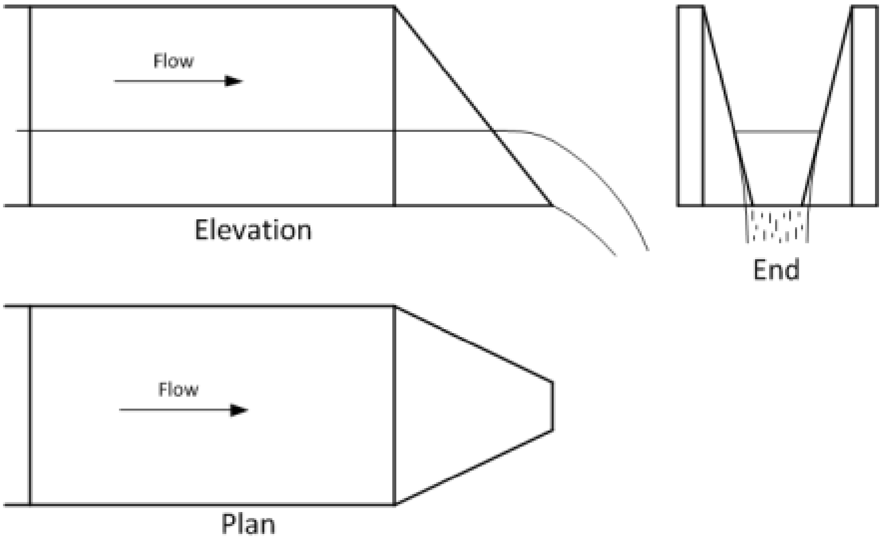


Figure 16 – H-Flume configuration

Illustration: Jon Marks
Source: Reproduced with permission from *NIWA Field Manual*.

Annex G – Procedure for Stage–Discharge Rating Curve Construction

Identify the Relevant Measurements

1. For an appropriate period between suspected change events, graph the stage series with the gaugings' stage overplotted.

Note: If you already have a rating, examine the deviations of successive gaugings to identify periods with similar deviation, between events likely to have caused change to the station control(s).

2. Identify sequences of gaugings on the same recession and/or during quiescent periods between significant flow events, or sequences of uniform rise if weed or ice affected (i.e. same phase of growth).

Note: A bankfull event is likely to shift all but the most stable natural controls; a FRE3 event will shift most alluvial or weed-affected controls (Clausen and Biggs (1996, 1997).

Assemble the Data

3. Collate gaugings in chronological order, ensuring discharge calculations have been checked, mean gauge height and time for the gauging is appropriately determined, and gauging stage matches the filed stage series to required accuracy.
4. Evaluate all available ancillary data including remarks, field inspections, photographs and sketches.

Plot the Measurement Data

5. If drawing manually:
    i. use pencil on a minimum of A2 sheet, preferably with 2-mm grid
    ii. complete a title block that includes:
        - station name and/or number
        - period covered by the ratings on the drawing
        - drawing number (from an appropriate register of drawings)
        - sheet number if multiples
        - your name, and
        - date of preparation of drawing, and any subsequent amendments
    iii. start a separate drawing for the lower part if the density of points on the drawing makes it difficult to distinguish individual gaugings
    iv. when the drawing is complete, ink it for permanent storage.

6. Add error bars on discharge for either the calculated measurement error or a default of ±8%; add error bars for stage if the uncertainty in stage is significant.
7. Plot in natural scale with stage in metric untis on the vertical axis and discharge in metric units on the horizontal axis.

   Note: The range of flows in New Zealand rivers generally does not preclude practical use of natural scales. While use of logarithmic scales may improve determination of rating curve segment shape, particularly where there are few available measurements, the method requires estimation of effective depth over the control(s), which is a difficult and laborious task for New Zealand sites without artificial flow controls. The pattern of rating shifts in the lower part of the rating is also easier to visualise using arithmetic scales. The logarithmic method is prone to some misuse and misinterpretation.[1] *It is discussed in this Standard as one of a range of techniques, notably for curve extrapolation, but not promoted as the sole means of curve construction.*
8. Choose scales so that there is a simple and intuitive ratio of stage to discharge, and that do not amplify the natural scale of the parameter, or overly contract either axis and, if drawing manually, interpolation is easy; for example, divisions of 1:2, 1:5, 1:10, etc.
9. Label each gauging clearly and sequentially, and with a '+' sign if on rising stage and a '–' sign if on falling stage.
10. Mark the stage equivalent of significant site features; for example, cease to flow (CTF), bankful, significant change in channel geometry.

Draw a Smooth Mean Line through the Gaugings

11. Use a suitable template, flexi-curve or computer application
    i. taking account of the relative accuracy of the gaugings (see Departures)
    ii. assuming an approximately parabolic shape (see Curve shape)
    iii. without extending beyond the gauged range (see Extensions), and
    iv. taking account of CTF and break points at changes in geometry.

Departures

Dispersion of gaugings around the line should be unbiased.

The line drawn should cut the error bars of each gauging.

Every excess departure must be investigated and explained.

---

[1] Fenton (2001), Kennedy (1984) and Sauer (2002).

Reasons for departure could be:

- poor measurement
- inaccurate gauge height for the measurement
- unsteady conditions during the measurement; check rate of rise/fall and consider if a loop rating is evident
- backwater effect during the measurement; a corresponding slope measurement permits adjustment for this (see Corrections)
- change in the control section, i.e. aggradation or degradation (scour or fill), which may be confirmed by one or more of evaluation of departure trends, overlay of sounded cross-sections, study of the stage–area curve and inspection of the stage time-series plot
- seasonal changes ,e.g. weed or ice, and consequent change in channel roughness, friction and/or cross-section area; a large number of gaugings is needed in these situations to characterise the influences on the discharge rating; and/or
- poor determination of the mean line.

Curve Shape

If flow is approximately uniform, the rating curve is parabolic and described by the general equation:

$$Q = k\,(h - e)^m \tag{11}$$

where: Q is discharge in m^3/s

k is a constant

h is the gauge height in metres

e is the gauge height for zero flow in metres, and

m is an exponent which varies with cross-section shape and determines rating curve shape. Typical values for the exponent m are given in Annex E – Table 2.

Equation (11) plots as a straight line on logarithmic scales.

Exceptions

The general equation may only apply for some of the stage range.

If the flow is non-uniform the general equation does not apply.

In natural channels in New Zealand, stage-discharge curves almost invariably plot as curved lines when logarithmic co-ordinates are used[2].

---

[2] George Griffiths, NIWA, personal communication by way of advice note to the workgroup, 12 Oct 2015.

The reason for this behaviour may be readily shown if the simple case of a wide, approximately rectangular channel cross-section is considered for which Manning's equation may be written as:

$$Q = \frac{1}{n} B y^{5/3} S^{1/2} \qquad (12)$$

where: Q is discharge in m^3/s

n is Manning's roughness coefficient

B is channel width

y is flow depth, and

S is energy slope.

In terms of equation (11), equation (12) may be expressed as:

$$Q = \left(BS^{1/2}/n\right)(h-e)^{5/3} \qquad (13)$$

Equation (13) will only plot as a straight line on logarithmic co-ordinates if $\left(\mathrm{BS}^{1/2}/\mathrm{n}\right)$ is constant and this is hardly ever the case in New Zealand rivers.

Data in Hicks and Mason (1991) indicates that B nearly always increases, and n decreases about 85% of the time and that about 65% of the time S increases, all with increasing discharge at a site.

Never the less, the curved stage-discharge relation on logarithmic co-ordinates may be approximated piecewise by a series of straight lines each defined by equation (11).

In irregular sections the exponent m varies. A change in exponent corresponds to a break in slope of the curve such as where:

- bank overflow occurs. The general equation may apply throughout the stage range but the value of m changes at bankfull stage
- controls become effective e.g. a mid to high stage constriction. The general equation may apply with a changed value for m or may not apply at all in the affected stage range
- the control may have shifted either gradually or abruptly due to aggradation or degradation. Normally only the lower portion of the curve is affected and a family of curves results
- seasonal changes, e.g. vegetation, cause variation in the exponent n or the equation.

Related Curves

Select the Cross-section

Cross-sections recommended to be surveyed are described in section 2.2.4.1. and recommended related curves are listed in section 2.3.3.5.

Depending on the information sought from the related curves, preference for plotting may be given to one or more of:

- the recorder section, if extending a station rating curve to higher flows by hydraulic calculation, area–velocity, or Q versus $A\sqrt{d}$
- the control section, or a section typical of the channel control, if confirmation of rating curve shape or rating change is sought, or if extending a rating to low flows, and/or
- the standard gauging section, if a check of gauging results or correction of soundings is required,

Note: At an ideal station where flow is gauged at the recorder and control is a single stable feature in close proximity, the recorder cross-section will serve all above purposes; intervening water surface slope being largely eliminated, features of the control can be directly associated with the stage axis at the recorder.

Stage–area

Cross-section areas for plotting should be calculated from survey, up to maximum expected flood level.

Gauged area should be plotted and clearly labelled on the stage–area graph after each measurement. Departure from the curve and/or trend may indicate measurement error or a change in the channel. Trends of channel enlargement or restriction may be revealed by biased departure of several successive measurements.

Stage–velocity

To ensure the stage–velocity curve depicts mean velocity through the cross-section used to derive the stage–area curve, the mean velocity curve should be plotted from velocities calculated by dividing measured discharges and/or discharges from a known portion of the rating curve by the area obtained from the stage–area curve at each corresponding stage.

Gauged mean velocity is also plotted on this graph and labelled as for the area.

Log-Log

If a parabolic equation applies, a rating curve plotted in logarithmic space will form a straight line provided gauge height for zero flow is zero; that is, rating stage is in terms of $(h - e)$.

Known as the log-log method, this may be convenient to:

- define an appropriate curve shape with few gaugings, or
- extend a curve beyond measured range (see Extensions).

When converting back to natural space, remember to add e again to return stage to gauge datum.

Extensions

It is recommended that, whenever possible, two or more methods are applied and results compared to improve confidence in the extrapolated portion of the rating.

High Flow

Extensions are relatively straightforward when flows remain confined and the channel is similar in character throughout the range of stage. Complexity arises when flow extends onto berms, or there is signficant variation in the type of vegetation or other physical features that become submerged with rising water levels.

Note: If flood information is the primary purpose of a station, ease of rating curve extrapolation should be considered when selecting a suitable site.

Indirect measurement

For a rating intended to apply to data already collected, the problem of extending to the full range of stage can be avoided if indirect methods are used to determine the unmeasured peak discharge. A rating is likely, however, to require further extension beyond peak discharge recorded to date for near-real-time applications.

The following methods are recommended when no discharge measurements are available. For full descriptions of the methods refer to the source documents, where applicable.

The WMO methods in order of preference for New Zealand conditions are: [3]

Conveyance-slope

The method assumes geometry of the discharge measurement section is representative of a long reach of downstream channel that is straight and uniform, thus it is unsuited to many stations, particularly those where the measurement section is constricted such as by a bridge or at cableways.

The method is relatively insensitive to errors in estimating Manning's roughness coefficient n.

Discharge can be calculated from conveyance K if slope S (energy gradient)and Manning's roughness coefficient n can be reliably estimated. Manning's equation can be rewritten as:

$$Q = KS^{1/2}$$

where: $K = \frac{1}{n} A\, R^{2/3}$

---

[3] *Manual on Stream Gauging* (WMO-No.1044), Volume II, Chap.1, Section 1.11: Computation of Discharge, Discharge Ratings Using Simple Stage–Discharge Relations, Extrapolation of rating curves

1. Plot using natural scales stage versus computed values of K for the complete range of stage then fit a smooth curve throught the plotted points
2. Plot using natural scales stage versus S; fit a curve through the plotted points then extrapolate the curve to the required stage.

   Note: S tends to a constant at higher stage, which is the slope of the stream bed, unless overbank flow occurs in which case S may reduce.
3. Obtain Q by multiplying corresponding values of K and $S^{1/2}$ from the curves.
4. Estimates of slope (energy gradient) S can be derived from:
   1. field measurement of flood marks (see slope-area method in NEMS *Open Channel Flow*)
   2. computing $S = \left(Q/_{K}\right)^2$ from each measured discharge , or
   3. at very high stage under uniform flow, slope can be assumed parallel to bed slope, which can be calculated from thalweg profile obtained from cross-sections or topographical/bathymetric survey; for example, LiDAR
5. Estimates of Manning's roughness coefficient n can be derived from:
   1. construction and extension of a stage-n curve, derived by back calculation from gauging results and corresponding field measurements of slope

      Note: Manning's n is unlikely to be constant throughout the range of stage so consideration must be given to how it might vary.
   2. calibrations used in river engineering design and hydraulic modelling (consult the local hydraulic design engineer), or
   3. reference to Hicks and Mason (1991).

Flood routing

Routing models are now relatively common and may be used to estimate discharge from known discharges at upstream or downstream stations. The method is limited to events that have occurred and been recorded unless rainfall-runoff models are incorporated. Observations are combined to evaluate an estimated peak discharge or hydrograph at the site of interest that may then be used with the corresponding stage record to construct and/or pin the stage–discharge relation.

Use of rainfall-runoff models should only be a first approximation and must be supported by one or more other methods.

Step backwater

For the usual situation of sub-critical flows, this method is predicated on the assumption that the stage–discharge relation is known or can be assumed at some location downstream and hydraulic modelling programs, e.g. HEC-2, can be used to propogate water surface profiles for selected discharges back to the station. The method requires sufficient cross-sections surveyed to a common datum to define the reach and suitable roughness coefficients to be estimated. It is computationally intensive and not recommended for manual calculations.

Areal comparison of peak runoff rates

If a storm is sufficiently prolonged and widespread to fully saturate a large area, peak discharge can be estimated from known peak discharge at surrounding stations. The method requires suitable storm events to have occurred, and for peak stage to have been recorded at all stations and reliably rated at surrounding stations.

1. Divide the known peak discharges by relevant catchment area to obtain peak yields; that is, $m^3/s/km^2$.
2. If rainfall intensity and yield is uniform over the area the unknown peak discharge can be directly inferred, otherwise correlate with some useful index of storm intensity; for example, altitude, individual basin intensity, etc.
3. The result should make hydraulic sense with respect to the general form of the rating equation.

Methods used in New Zealand, in order of common preference, are:

Area–velocity method

This method is more successful for complex channel geometries than the log-log method. It makes use of the related curves for stage–area and stage-mean velocity (see Related Curves).

The stage axis for all curves must be that of the recorder.

Note: Plotting the recorder cross-section eliminates the problem of relating water levels at the surveyed section to corresponding gauge heights at the recorder. However, depending on the range of the rating curve extension required, knowledge of the effect of the control(s) on water levels and velocities at the recorder may also be necessary.

The stage–area curve should already be extended to the full range of stage by analysis of the surveyed cross-section and thus one unknown in the calculation of flow is eliminated. What remains is to estimate the full extent of the stage-mean velocity curve (usually abbreviated to ‘stage-velocity’ curve).

1. Plot the ‘known’ stage–velocity curve by dividing measured discharges and/or discharges from the known portion of the rating curve by the cross-section areas from the plotted stage–area curve for the same stage.
2. Extend the stage-velocity curve to maximum expected flood level. Where the cross-section is fairly regular and no bank overflow occurs, the rate of increase in mean velocity decreases as stage increases. If roughness increases significantly with higher stage, the mean velocity curve may bend back.

3. At sections with no bank overflow, the mean velocity curve may be extended by calculation from hydraulic parameters. At higher stage, the term $\frac{1}{n}S^{1/2}$ in Manning's equation becomes approximately constant and the equation can be rewritten as:

   $$V = kR^{2/3}$$

   i. Select various values of V from the known portion of the stage-mean velocity curve.

   ii. Extract corresponding values of R from analysis of the cross-section.

   iii. C.ompute values of k for the range of stage in the known portion of the stage-mean velocity curve.

   iv. Plot stage versus k; the curve should tend asymptotic to the vertical and can thus be extended.

   v. Read values of k and combine with respective values of $R^{2/3}$ to extend the stage-mean velocity curve.

4. A simpler approximation to the above, described in Annex D4 of ISO 1100-2:1982 (E), is to plot $log\ R$ versus $log\ V$. The plot will form a straight line, which may be extended to the required value of R if the relation holds true over the full range of flows and the cross-section shape does not change significantly. Values for V can then be read and transferred to the stage-mean velocity curve.
5. Test the maximum mean velocity obtained is reasonable:

   i. Calculate the Froude number; it should be < 0.8 in a natural erodible channel.

   ii. Compare with other measured sites of similar size and slope.

Note: It is unusual for low gradient and/or widely bermed New Zealand rivers to exceed a mean velocity of 4 m/s. Larger rivers in a confined reach may attain a mean velocity of 5 m/s but would rarely exceed 5.5 m/s. Higher mean velocities should be carefully scrutinised and justified in the metadata.

6. For various stage heights, obtain corresponding values of mean velocity and area from the related curves and plot their product on the discharge curve, then draw the discharge curve through these points.

<u>Log-Log method</u>

This method can be used for ratings that fit the general equation and where the control shape and channel roughness remain fairly constant over the extrapolated range. It is most suited to channel controls and should not be used to extrapolate more than 1.5 times the highest measured discharge.

1. For selected points on the existing rating transform gauge height H to effective depth of flow over the control by subtracting the effective gauge height of zero flow e. To find e see Cease to Flow (CTF) below.
2. Plot the corresponding flows against the transformed depths using logarithmic scales for both axes, or calculate $log\, Q$ and $log(H - e)$ then plot using natural scales.
3. The rating should form a straight line which may be extended linearly to the required effective depth.
4. Values of Q and effective depth can then be read from the extended line and converted back to values of Q and gauge height for the rating; that is,. add $\boldsymbol{e}$ again to return effective depths to gauge heights.
5. Curves should not be extended through break points; for example, if bank overflow occurs, the rating must first be drawn to bankfull stage and from there extended to the highest stage.

Areal comparison of Mean Annual Flood

For suitable New Zealand rivers a variant of the areal peak runoff method that can be applied before a suitable event has occurred is to determine mean annual flood (MAF) by regional flood estimation (McKerchar and Pearson, 1989), and assuming MAF approximates the channel forming discharge, assign that discharge to the bankfull stage of the active cross-section.

The active cross-section is typically the wetted perimeter denuded of vegetation and usually excludes berm overflow.

$Q\ vs\ A\sqrt{d}$

The WMO *Manual on stream gaging* (2010b; vol. II, Chap. 1, Section 1.11) regards this method, described in Corbett et al. (1943), as superior to the area–velocity method. The method is applicable if extension above actual measurement is not too great and the shape of the channel is similar over the extrapolated range to that for the measured flows.

1. Measured discharge is plotted as a function of the product of cross-section area and square root of mean depth, where mean depth is area divided by top (surface) width; that is, not hydraulic radius.
2. Extend a line through the plotted points to the value of $A\sqrt{d}$ for the desired stage.
3. The corresponding value of Q can then be read from the extended line and transferred to the stage–discharge curve.

Methods recommended by Ramsbottom and Whitlow (2003), in increasing order of complexity, are briefly described below. For more information, method details and case studies, refer to the actual document.

Simple Hydraulic Techniques

Simple extension

Applies the form of the curve for the uppermost defined segment of the existing rating to higher stages. It can be used when there is no change to factors influencing flow above the known portion of the curve. It should not be used if there is any transition; for example, onset of overbank, berm or drowned flow. It does not allow for variation in the cross-section or changes in roughness.

Most, if not all, time-series software in use in New Zealand can apply simple extension of rating curves by default; however, this Standard does not permit default extension because results can be unpredictable and undesirable. If simple extension is used, it must be applied by explicit definition of the extended curve in the rating model.

Logarithmic extrapolation

This is the same as the log–log method described previously. Limitations of the method are similar to those of simple extension. The method has potential to generate very large errors and requires considerable expertise to be used successfully.

Weir equation

General weir equations may be used to extend a rating curve at sites under section control, particularly if the control is a standard structure. Methods exist for free and drowned flow, but should not be used beyond the structural limit or transition from drowned condition to channel control.

Compound weirs can be catered for using separate calculations for each weir crest then combining results.

The equations require estimation of coefficients of discharge and velocity head, and drowned flow reduction factor for the drowned condition. The drowned flow reduction factor requires knowledge of upstream and downstream water levels.

Velocity extrapolation

This is the same as the area–velocity method described previously. Its limitations are similar to simple extension.

Note: This method has often been applied beyond bankfull stage in New Zealand but Ramsbottom and Whitlow (2003) recommend against this.

Slope–area

This is a variation of the indirect measurement of discharge by slope–area methods, where water surface slopes may be estimated from paired water level readings upstream and downstream of the gauge, or approximated by the friction slope, rather than from survey of pegged and/or peak flood levels.

This is the most hydraulically correct of the simple methods for channel control situations.

Divided Channel Method (DCM)

This method extends the above simple hydraulic approaches to overbank conditions. Typically the cross-section is divided into channel and left and right berms, with each extended separately then combined to obtain a rating for the entire cross-section.

<u>Computational hydraulic modelling</u>

1-D, 2-D or 3-D hydraulic models may be used to determine water levels at the gauge site for various discharges, and thus extend the rating curve.

Modelling software is becoming more mainstream and widespread in New Zealand but the techniques, when applied to the task of extending rating curves, are data and resource intensive. Considerable modelling expertise is also required to obtain results justifiably superior to careful use of simple methods in almost all cases.

1-D models solve for steady and unsteady flow. Flow resistance and flows at structures are estimated using standard formulae. The river is represented by a series of cross-sections. Software, if available in New Zealand hydrometric agencies, is most likely to be HEC-RAS and/or MIKE 11.

2-D models solve for steady or unsteady flow. Hydraulic structures are treated as features of the topography but culverts or gates cannot be represented. The river is represented by a series of plan-view cells. Modelled water levels can vary across a flood plain, and out-of-bank flow can be quantified in previously unknown flow paths. Software, if available in New Zealand hydrometric agencies, is likely to be MIKE 21 but would rarely be used for rating extension.

3-D models solve fully for steady or unsteady flow. Hydraulic structures are treated as features of the topography and culverts and gates can be represented. The river is represented by a grid of 3-D cells. Surface roughness and interation between flood plain and main channel can be represented. It is unlikely any New Zealand hydrometric agency would use a 3-D model for rating curve extension.

Low Flow

Extension to CTF

If the curve is plotted using natural scales and the gauge height at which flow ceases can be determined (see Cease to flow (CTF) below), the lower portion of the rating can simply be extended to zero flow, provided there is no significant change in shape of the cross-section below the lowest gauged flow.

General weir formulae

Typically the low flow control will be some form of section control for which an appropriate weir formula for the geometry may be used to calculate estimates of flow for given gauge heights, which can then be used to extend the rating curve. This technique is useful to define the shape of the lower curve. Refer to Annex F – 'Structures' for more information about selection and application of the formulae.

Simple extension, as described in Ramsbottom and Whitlow (2003).

This method applies the form of the curve for the lowest defined segment of the existing rating to lower stages. It can be used when there is no change to factors influencing flow below the known portion of the curve. It should not be used if there is any transition; for example, from drowned to free flow. It does not allow for variation in the cross-section or changes in roughness.

Most, if not all, rating curve software can apply simple extension by default. This Standard does not permit default extension. If simple extension is used, it must be applied by explicit definition of the extended curve in the rating model.

Cease to Flow (CTF)

The gauge height at which flow will cease, i.e. e in the general equation, must be determined for ephemeral streams, and for others as required, to apply the general equation.

Estimate CTF by one or more of the following (in descending order of reliabilty):

1. Survey the low flow control to identify the lowest elevation in terms of gauge datum.
2. Sound maximum depth in the estimated low flow control and transfer this depth to a gauge reading below current water level at the gauge.
3. If gauged between the recorder and the control in a uniform reach, subtract maximum sounded depth during the gauging from stage for the gauging.
4. Assume various values of e and plot $log\, Q$ against $log(H - e)$ until a straight line is obtained. Use Q and H from the rating curve, not actual measurements. If e is too low the plot will curve up; too high and the plot will curve down.

5. If the lower curve segment is a parabola, plotted to natural scales with discharge on *x*-axis:

    i. Select three discharges, q_1, q_2, and q_3, in geometric series, from the known portion of curve.

    ii. Draw vertical lines up from q_1 and q_2, and horizontal lines back from q_2 and q_3 so they intersect at points A and B, respectively.

    iii. Extend a straight line through A and B and a straight line through q_1 and q_2 until they intersect; the stage at which provides the estimate of CTF (see Figure 17).

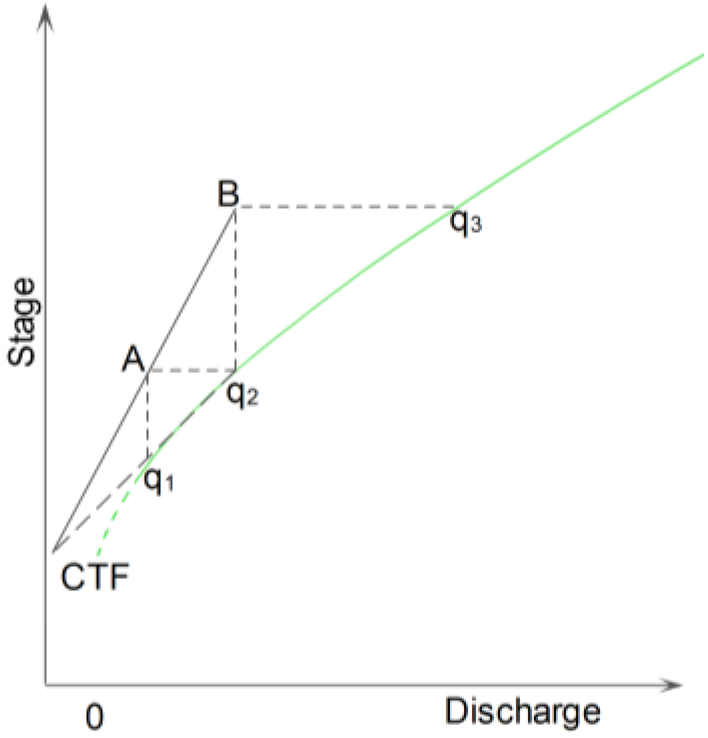


Figure 17 – Estimating cease to flow (CTF) from a partial rating curve plot

Illustration*:* Marianne Watson.
(based on an image from 'Provisional Procedure No. 4 Stage–Discharge Curves'
by W. B. Morrissey and C. Toebes (circa 1963) in *Handbook of Hydrological Procedures)*.

Annex H –Deriving an Initial Theoretical Rating: A Worked Example

This Annex provides a worked example of the derivation of an initial theoretical rating for a station on a larger river, with a combination of controls.

The example uses several, but not all, methods described in this Standard. Ultimate choice of appropriate methods will depend on the:

- immediacy of the need for a full rating curve
- hydraulic characteristics of the reach, and
- availability of any discharge measurements, suitable supporting data and information.

Note: In this example use is made of existing cross-section data, which is conveniently, but not ideally, located. Data for this example was generously provided by Horizons Regional Council.

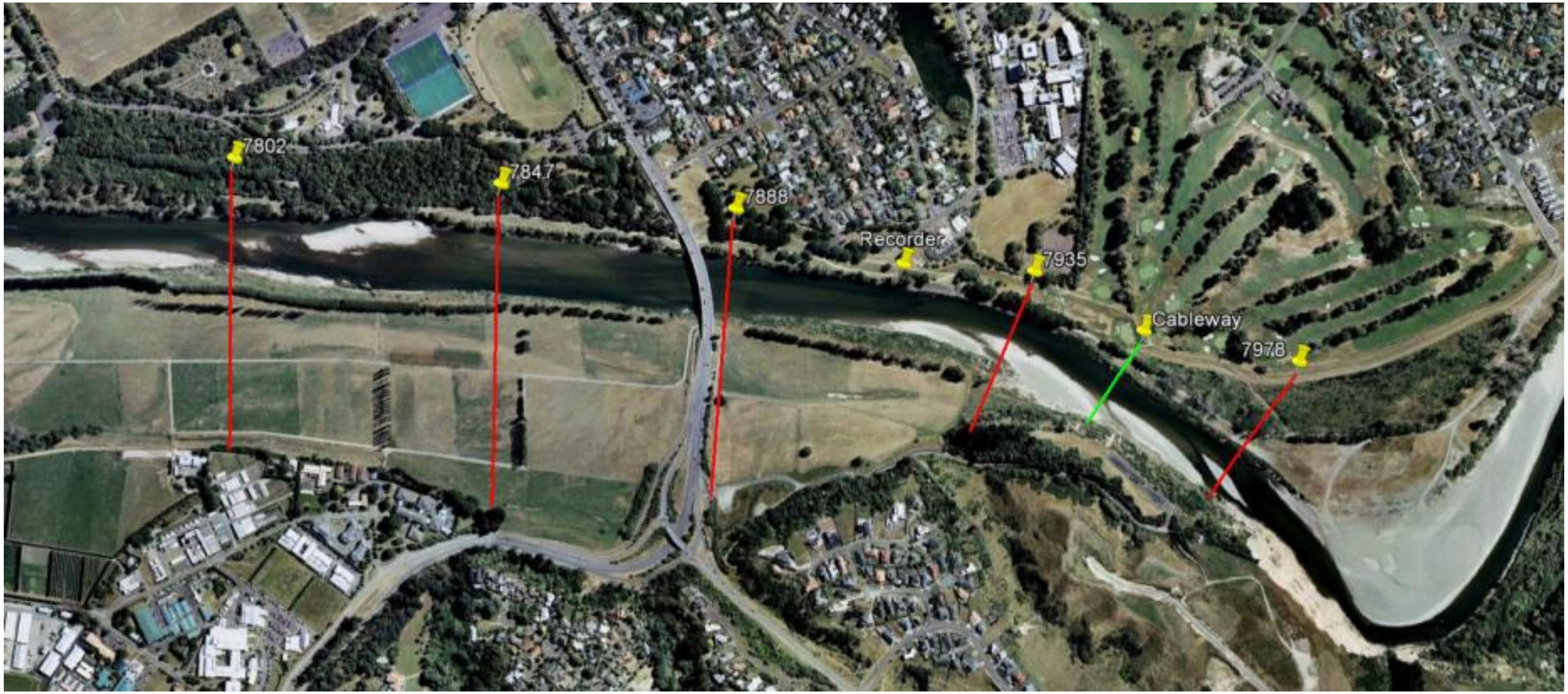


Figure 18 – Recording reach at Manawatu at Teachers College
showing location of recorder tower, gauging cableway and surveyed river cross-sections

Note: Flow is right to left.

Illustration: Marianne Watson
(based on Google Earth image (2007), and other data provided by Horizons Regional Council).

Required Data

With reference to Figure 18:

Site Controls

- Low flow section control is observed to be at the rapid at section 7802.
- Mid-stage control is channel control downstream of the recorder and governed by riparian vegetation.
- High stage control is the bridge immediately downstream of section 7888.

Other Hydraulic Characteristics

- The river is stopbanked along the true right bank. Flows may spill over the wide left bank berm. Cross-sections, as shown in Figures 18 and 19, are to the full flood extent.
- Mean annual flood rises to stopbank toe and spreads across some of the left bank berm.
- Water cannot flow under the bridge approach that crosses the left bank berm; all flow must pass under the bridge.
- The active channel is alluvial with layered willow margins. A short distance of right bank above the recorder is rock-lined. The left bank is a high cliff upstream of section 7935 as far as the sharp bend with large point bar.
- The river is too deep to wade except at very low flows.

Cross-sections

The cross-sections have been surveyed in terms of reduced level (RL) in metres with datum of mean sea level (MSL) at Moturiki.

The gauging cableway is between sections 3397978 and 3397935. The recorder is 380 m downstream of the cableway, on the right bank between sections 3397935 and 3397888. Section 3397888 is immediately above the high stage control (bridge). Sections 3397888 and downstream to 3397802 form the mid- to low-flow control reach.

The cross-sections are plotted in sequence by upstream distance in Figure 19. Section number encodes distance; for example section 3397978 is 79.78 km upstream of the river mouth.

Gauge zero at the recorder is 21.209 m MSL Moturiki.

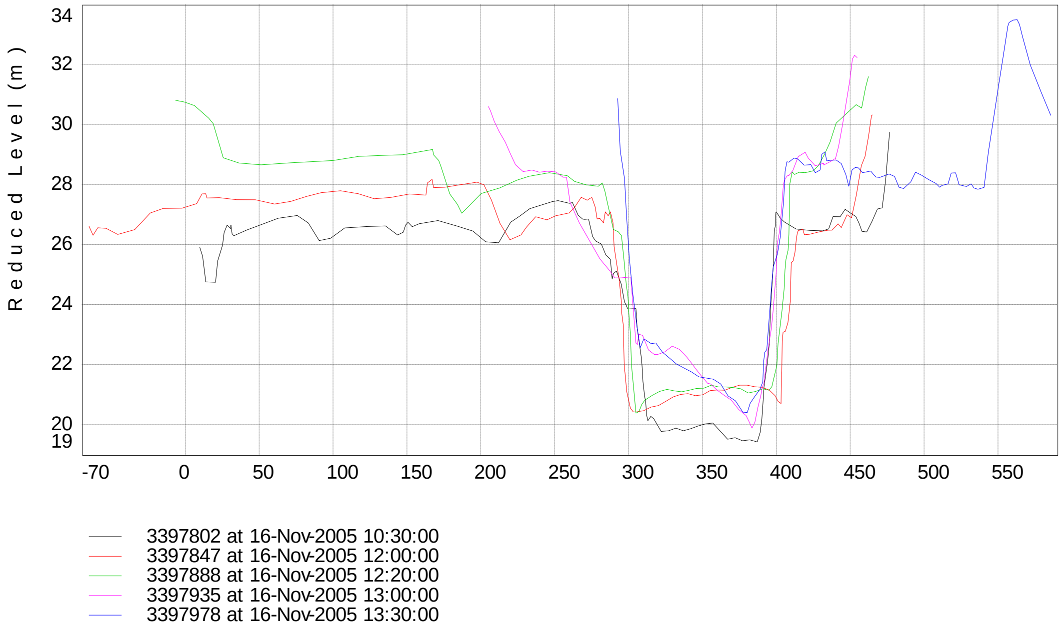


Figure 19 – Available cross-sections in the Manawatu at Teachers College reach

Note: Cross-sections have been shifted to align at the centre of the active (main) channel.

The low flow control section (Figure 20) is steep sided and rectangular up to approximately 24 m MSL Moturiki.

Channel between the recorder and low flow section control is reasonably straight and uniform, as shown in Figure 18.

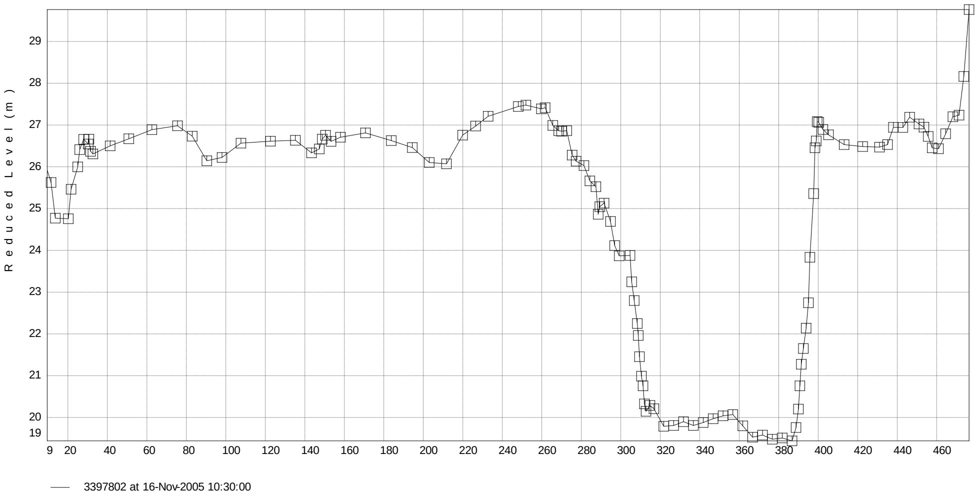


Figure 20 – Low flow section control for Manawatu at Teachers College recorder

Estimates of Water Surface Slope

Water levels were not surveyed when the cross-sections were done. Estimates of water surface slope will need to be obtained by other means.

From surveyed thalweg profile

We might assume that the channel is sufficiently uniform through the recording reach that water surface slope may be estimated from the riverbed profile. From thalweg levels of the cross-sections available along the straight reach:

Section (km)	Thalweg (m)	Fall (m)	Distance (m)	Slope	
79.35	19.91				
78.88	20.41	−0.5	470	−0.001064	
78.47	20.45	−0.04	410	−0.000098	
78.02	19.45	1	450	0.002222	
				0.000354	average
		0.46	1330	0.000346	overall

It is obvious, though, that the bridge has some local effect on thalweg, and is also, given the constriction, likely to have an effect on high flood water surface slope. We could choose to rely solely on the reach below the bridge, which gives slope of 0.002222.

From surveyed mean bed level profile

We can overcome local thalweg effects by considering mean bed level instead. Excluding banks and berms from the calculation of mean bed level we find:

Section (km)	Mean Bed Level (m)	Fall (m)	Distance (m)	Slope	
79.35	21.731				
78.88	21.146	0.585	470	0.001245	
78.47	20.996	0.15	410	0.000366	
78.02	19.844	1.152	450	0.002560	
				0.001390	average
		1.887	1330	0.001419	overall

Mean bed level at the recorder (79.18 km) is estimated to be 21.519 m by interpolation of the above results.

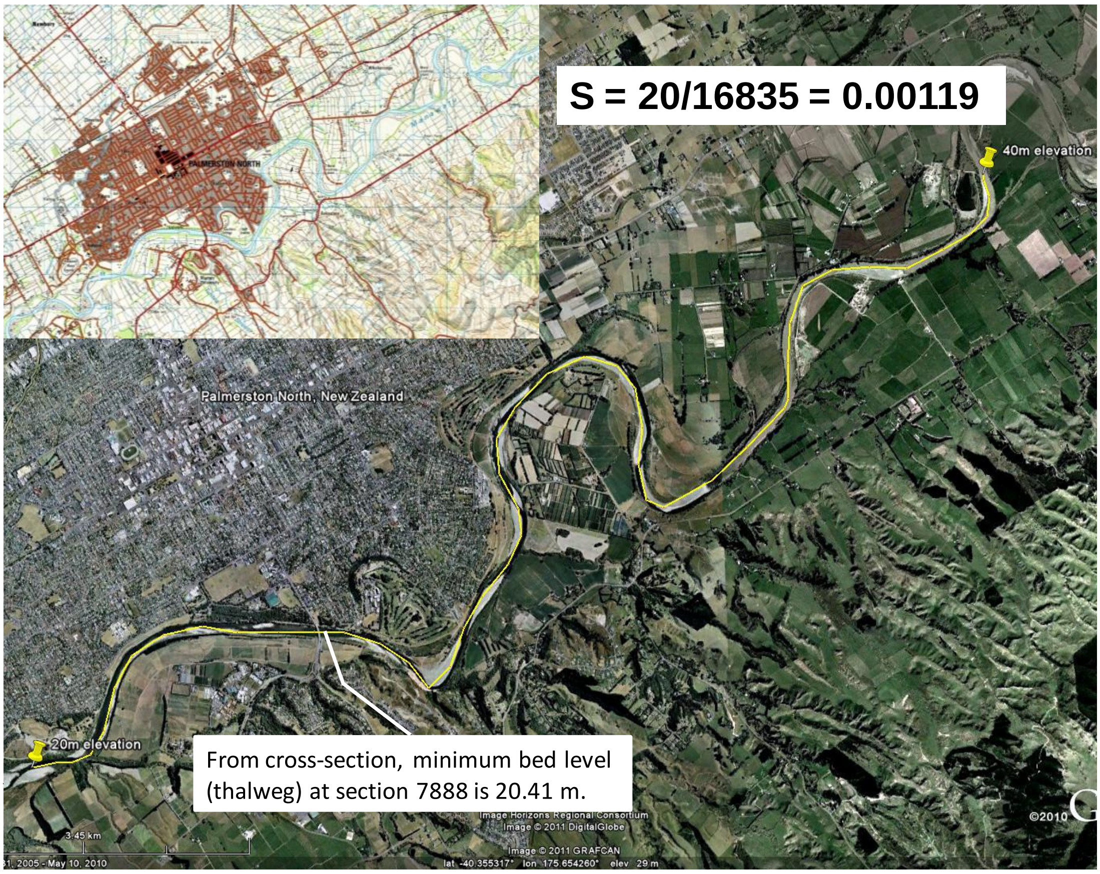
From estimated channel slope using mapped topographical data

We might average out the effect of the bridge by considering a much longer reach. For larger rivers we can make use of topographical maps and Google Earth; see Figure 21.

The mapped 40-m and 20-m contours, upstream and downstream of the site respectively, are 16.835 km apart, so average channel slope through the recording reach is:

$$20/16835 = 0.00119.$$

We can assess this approximation by plotting known surveyed bed levels on the map. Bed levels are much lower in the vicinity of the recorder and bridge than the average slope estimated in this way would suggest (see Figure 21).



S = 20/16835 = 0.00119

From cross-section, minimum bed level (thalweg) at section 7888 is 20.41 m.

Figure 21 – Estimating channel slope of the Manawatu River near Palmerston North from topographical maps

Source: Google Earth image, 2010.

From surrogate information

A study in the Hutt River related median particle size to channel slope. When median particle size was 40 to 50 mm, channel slope was about 0.0015 to 0.0017.

The Manawatu River is mined upstream of the recorder site, which distorts the particle-size distribution, but observation suggests a median particle size of 40 to 50 mm for the Teachers College reach is reasonable, and channel slope here might reasonably be assumed to also be in the range 0.0015 to 0.0017.

From historic site files

A search of historic paper files located slope-area measurements for the historic recorder 250 m downstream of the present tower. These measurements estimated water surface slope as 0.00105 at high flow. Twice since, the bridge has been replaced (with narrowed waterway each time) and stopbanks raised. The active channel is now much more confined and considerably deeper than it was. These changes do reduce the relevance of the early measurements.

Conclusion

It seems reasonable to try a range of water surface slopes between 0.0011 and 0.0015, with a preference for the higher slope at lower flows (parallel with bed slope) and the lower slope at higher flows (influenced by the several factors that provide greater flow resistance).

Estimates of Manning's *n*

A 'typical' value for a 'typical' New Zealand river is 0.03, and the lower Manawatu is quite typical.

We can check this assumption using Hicks and Mason (1991), which indicates that something in the range 0.03 to 0.04 is probably reasonable.

Discussion with local river engineers reveals adoption of a value of 0.034 when designing river works.

A formula derived by Gary Williams for application to rivers with gravel beds, from estimates of slope, is:[4]

$$n = 0.104\, S^{0.178}$$

which gives a range of:

$$n = 0.104\, (0.0011)^{0.178} = 0.031$$

to $$n = 0.104\, (0.0015)^{0.178} = 0.033$$

The river banks are thickly lined with layered willow and flow must pass through substantial plantings beyond bankfull. From Hicks and Mason (1991), an *n* value approaching 0.045 may be more appropriate for berm flow.

Cease to Flow

CTF is the lowest point of the low flow section control and can therefore be obtained from section 7802 as 19.45 m MSL Moturiki.

However, when the thalweg profile is plotted for the whole recording reach, it is clear that the bar formed below the bridge would become the low flow control if flow tended toward zero (in almost 100 years of record at this station, flow has not dropped below 8 $\mathrm{m^3/s}$).

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[4] P. Blackwood, Design Engineer, Horizons Regional Council, personal communication.

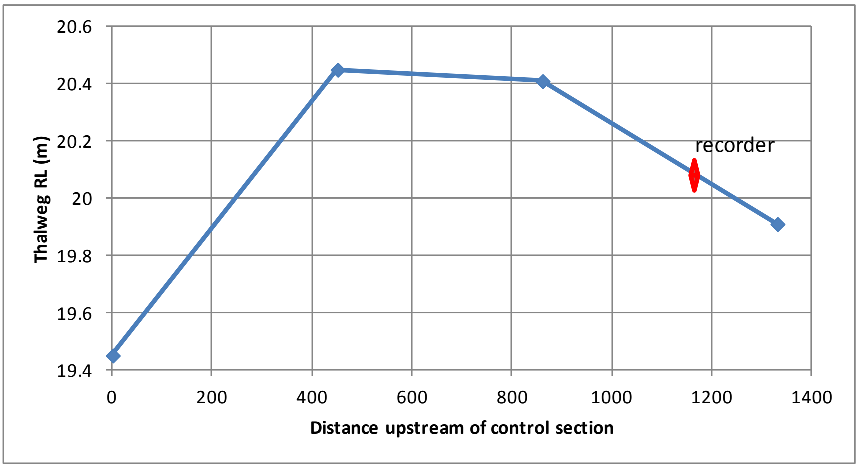


Figure 22 – Thalweg profile of Manawatu at Teachers College gauging station reach (16 Nov 2005)

Thus CTF is 20.45 m MSL Moturiki from the thalweg of section 7847, which is 710 m downstream of the recorder. We don't need to allow for water surface slope because thalweg at the recorder is lower and water would therefore pool to this level.

Recorder gauge datum is 21.209 m MSL Moturiki, so:

CTF = 20.45 - 21.209

CTF = -0.759 m on gauge.

General Rating Equation

We can use the general rating equation reasonably reliably up to the onset of berm flow.

From equation (4) in Annex E:

$$Q = C_d y^m$$

where: $C_d = kb$, and

$$\mathrm{k} = \sqrt{\mathrm{S}}/_{\mathrm{n}}$$

with $b = 80$ m at section 7802 we can obtain a range of values for k and thus C_d, depending on our choice of n and S, as follows:

S	n	C_d
0.0011	0.031	85.59
0.0011	0.033	80.40
0.0015	0.031	99.95
0.0015	0.033	93.89

For a rectangular channel, exponent m may be taken as 1.67, and thus Q can be calculated for a range of depths y over the control section. We must then relate these depths to equivalent gauge heights at the recorder. The control section is 1160 m downstream of the recorder, so fall between gauge and control is significant and must be taken into account.

We've assumed a rectangular channel so we can begin with $y = 0$ being mean bed level at the control section to convert the depths y to reduced water levels. If the channel and flow is uniform, we can assume constant slope between recorder and control. Using the slope S and distance between the control and recorder, we can calculate the fall between them and then add that to the reduced water levels at the control to obtain estimates of reduced water levels at the recorder. Finally we subtract gauge zero from each reduced water level at the recorder to obtain gauge heights corresponding to the discharges calculated.

We can obtain four estimates of a rating from our four estimates of C_d as follows:

			Q (m^3/s)			Q (m^3/s)				
Gauge	RL (m)		S_f=0.0011			S_f=0.0015		RL (m)		Gauge
Height	gauge	control	C_d=85.59	C_d=80.40	y (m)	C_d=99.95	C_d=93.89	control	gauge	Height
-0.089	21.12	19.844	0.00	0.00	0	0.00	0.00	19.844	21.584	0.375
0.011	21.22	19.944	1.83	1.72	0.1	2.14	2.01	19.944	21.684	0.475
0.111	21.32	20.044	5.82	5.47	0.2	6.80	6.39	20.044	21.784	0.575
0.411	21.62	20.344	26.90	25.27	0.5	31.41	29.51	20.344	22.084	0.875
0.911	22.12	20.844	85.59	80.40	1	99.95	93.89	20.844	22.584	1.375
1.161	22.37	21.094	124.24	116.71	1.25	145.08	136.29	21.094	22.834	1.625
1.411	22.62	21.344	168.46	158.25	1.5	196.72	184.80	21.344	23.084	1.875
1.661	22.87	21.594	217.92	204.71	1.75	254.48	239.05	21.594	23.334	2.125
1.911	23.12	21.844	272.36	255.85	2	318.05	298.77	21.844	23.584	2.375
2.161	23.37	22.094	331.57	311.47	2.25	387.19	363.72	22.094	23.834	2.625
2.411	23.62	22.344	395.35	371.39	2.5	461.67	433.69	22.344	24.084	2.875
2.661	23.87	22.594	463.56	435.47	2.75	541.33	508.52	22.594	24.334	3.125
2.911	24.12	22.844	536.06	503.58	3	625.99	588.05	22.844	24.584	3.375
3.161	24.37	23.094	612.73	575.60	3.25	715.52	672.15	23.094	24.834	3.625
3.411	24.62	23.344	693.45	651.43	3.5	809.78	760.70	23.344	25.084	3.875
3.661	24.87	23.594	778.14	730.98	3.75	908.67	853.60	23.594	25.334	4.125
3.911	25.12	23.844	866.69	814.17	4	1012.08	950.74	23.844	25.584	4.375
4.161	25.37	24.094	959.03	900.91	4.25	1119.91	1052.04	24.094	25.834	4.625
4.411	25.62	24.344	1055.09	991.15	4.5	1232.08	1157.41	24.344	26.084	4.875
4.661	25.87	24.594	1154.79	1084.80	4.75	1348.50	1266.78	24.594	26.334	5.125
4.911	26.12	24.844	1258.07	1181.82	5	1469.11	1380.07	24.844	26.584	5.375
5.161	26.37	25.094	1364.87	1282.15	5.25	1593.82	1497.23	25.094	26.834	5.625
5.411	26.62	25.344	1475.13	1385.73	5.5	1722.58	1618.18	25.344	27.084	5.875
5.661	26.87	25.594	1588.80	1492.51	5.75	1855.32	1742.88	25.594	27.334	6.125

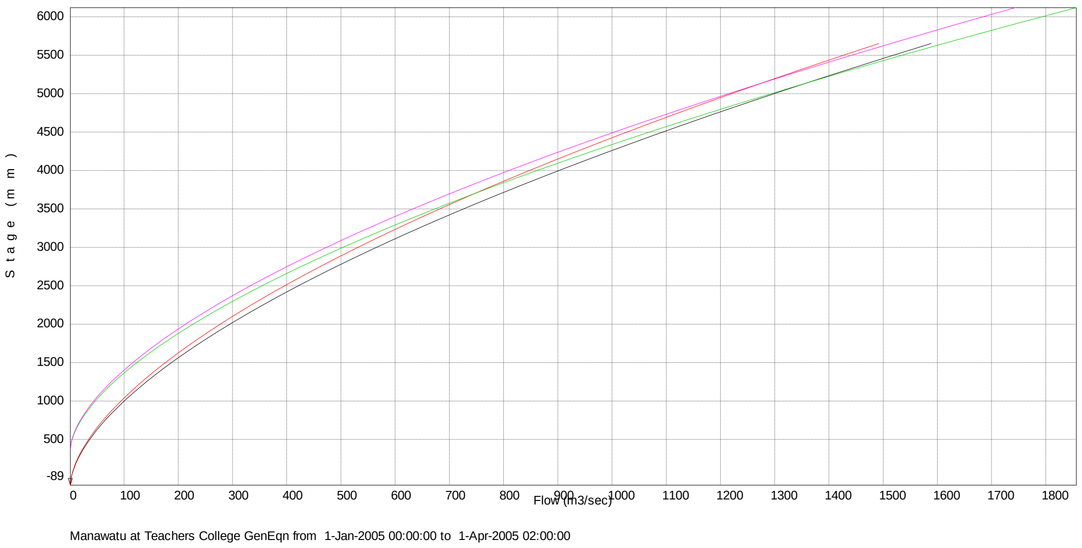


Figure 23 – Estimated theoretical rating for Manawatu at Teachers College from general rating equation

Rating for Low Flow Section Control

If we consider that the section control for very low flows appears to be section 7847 rather than section 7802, we may be able to improve the bottom end of the rating by considering the low flow section control to be a triangular profile flat-V weir.

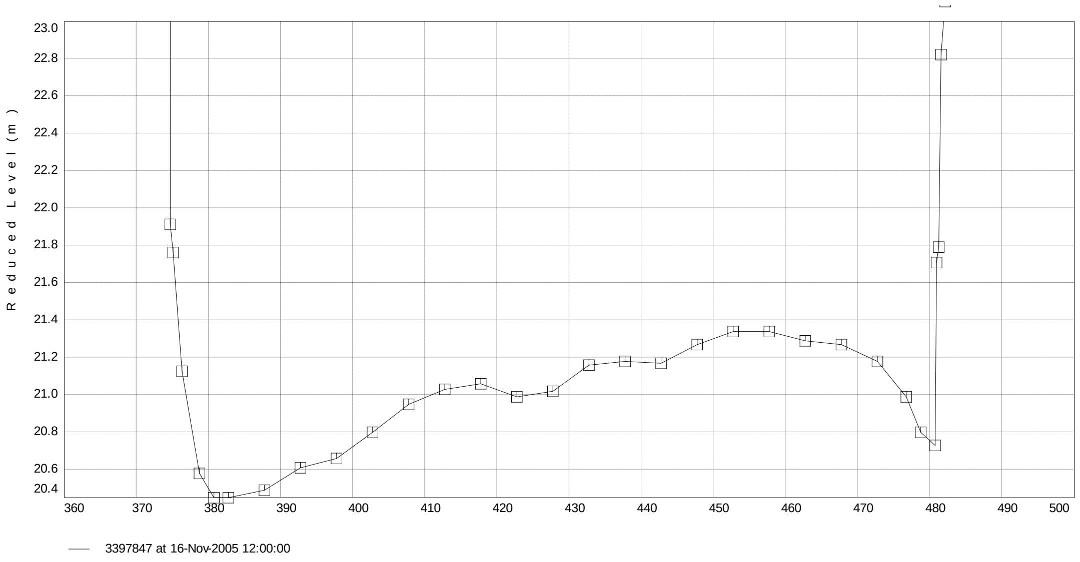


Figure 24 – Control cross-section for very low flows, 450 metres upstream of adopted low flow section control

Crest slope across the width is estimated from the surveyed bed levels as 0.89/70 m, or approximately 1 in 80.

Referring to WMO-1044-v1, the equation for a triangular flat-V weir, when flow is within the notch, is:

$$Q = \frac{4}{5} C_d \sqrt{g} n H^{5/2} \tag{14}$$

where: $n = 80$ from the above estimate of crest cross-slope

C_d = 0.63 if we assume the required 1:2/1:5 profile applies, and

H is the total head at the cross-section.

We are now presented with two problems:

We need to:

1. estimate velocity head in order to determine gauge head at this section, and
2. relate gauge head at this section to gauge height 710 m upstream at the recorder.

In the absence of velocity measurements we require good estimates of water surface slope but, as flows reduce, water levels become more confined to the deepest part of the channel which is neither straight nor of uniform bed slope. Water surface slope upstream of section 7847 will likely lessen as flows decline. Figure 25 illustrates the problem.

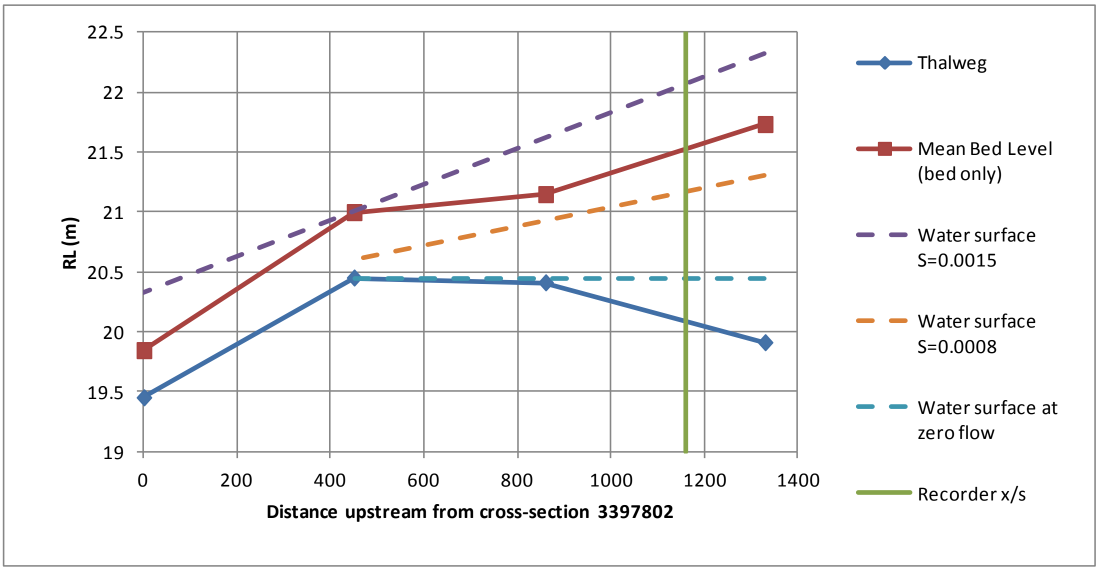


Figure 25 – Illustration of possible variation in water surface slope past the recorder under declining flows

Given the crest cross-slope is so flat, the best we may achieve is to assume a uniform reach of uniform slope with rectangular cross-sections having zero head at mean bed level (active bed only), and make use of the much simpler triangular profile (Crump) flat weir calculation instead.

The general broad-crested weir equation is:

$$Q = C_v C_d \left(\frac{2}{3}\right)^{3/2} \sqrt{g} \,.\, b.\, H_u^{3/2}$$

With crest width b =105 m from cross-section 7847 the above reduces to:

$$Q = C_v C_d 1.7049 * 105 {H_u}^{3/2}$$

which further reduces to:

$$Q = C_v C_d 179 {H_u}^{3/2}$$

where: C_v accounts for velocity head, so the head term is gauge head H_u.

For a flat Crump weir unaffected by tail-water, and gauge head H_u > 0.1 m, C_d can be taken as a constant 0.633. C_v is a correction for approach velocity and from Table 1.7.4 of WMO-1044 a value of 1.1 seems reasonable. We will also assume the control drowns if H_u > 1 m.

Results, beginning from mean bed level (MBL) because we've assumed a flat weir, and allowing for fall of 0.523 m, being the difference between MBL estimated at the recorder and that calculated for section 7847, are:

H_u (m)	Q (m^3/s)	Reduced Level (RL) (m) control	gauge	Gauge height
0.0	0.00	20.996	21.519	0.31
0.1	3.94	21.096	21.619	0.41
0.2	11.15	21.196	21.719	0.51
0.5	44.07	21.496	22.019	0.81
0.8	89.19	21.796	22.319	1.11
1.0	124.65	21.996	22.519	1.31

We know that calculated CTF is -0.76 m gauge height and the overall cross-section shape tends more triangular at very low flows, so the lower end of the rating probably curves more steeply than the above table implies.

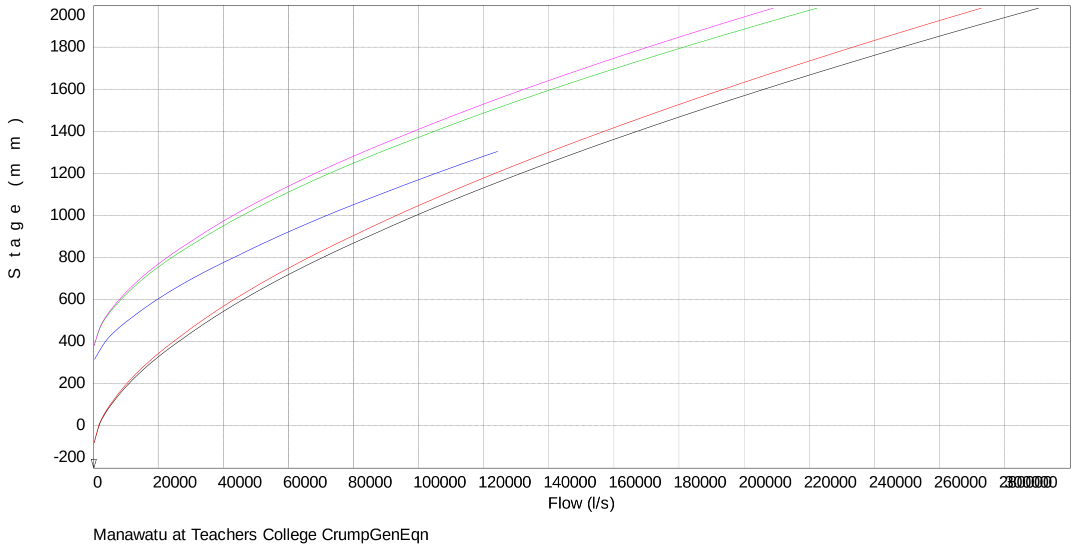


Figure 26 – Estimated low flow rating for Manawatu at Teachers College from crump flat weir equation, shown with results from the previous general rating equation calculation

High Flow Rating

We should use two different methods. In this example we will use the conveyance-slope method, and a modification of the log-log method in which the cross-section is divided into left and right berm and main channel, with general equations fitted to each part, then discharges from each part summed to give total discharge for the rating.

The rating curve must extend to a gauge height of 9 m to cover highest anticipated flood. Control at this height is the constriction at the bridge. Berm width increases downstream towards the bridge but all flow must pass under the bridge, which extends from 270 m to 450 m equivalent on section 7888.

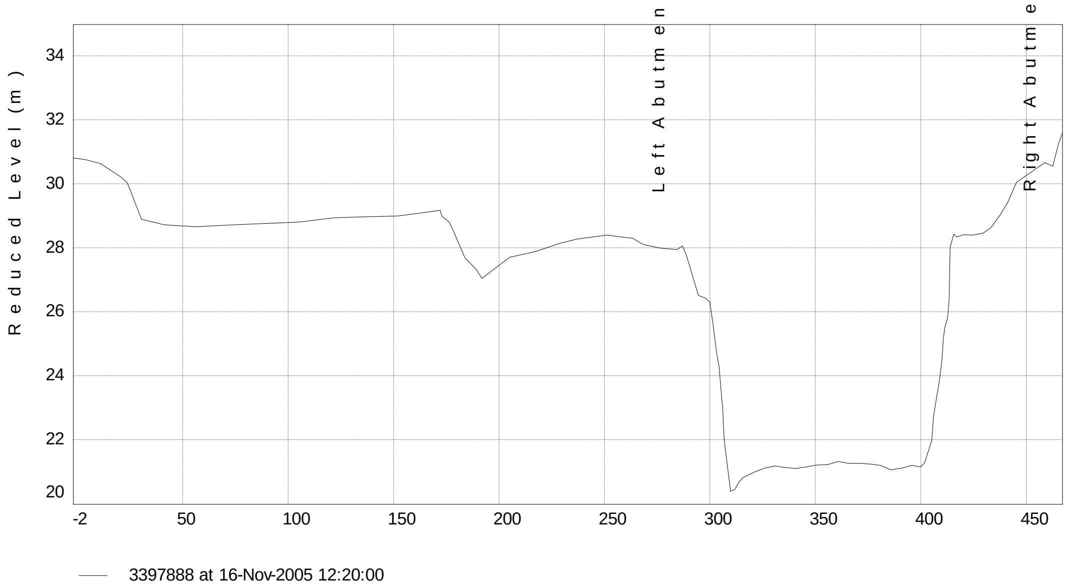


Figure 27 – Control cross-section for high flows, upstream side of road bridge, 300 metres downstream of gauge

Conveyance-slope

Manning's equation can be rewritten as:

$$Q = KS^{1/2}$$

where: K is conveyance, calculated from

$$K = \frac{1}{n} A\, R^{2/3}$$

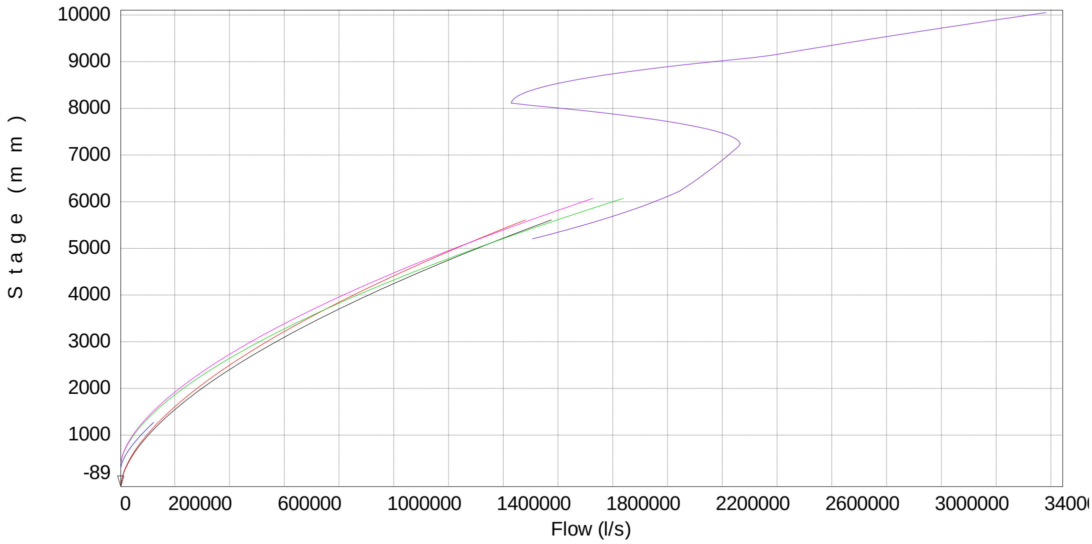
We must calculate the hydraulic parameters, area A and hydraulic radius R, from the cross-section for a range of water levels above 5 m gauge height, equivalent to a reduced level (RL) of 25.8 m at section 7888 (300 m downstream of the recorder) while allowing for an average of 0.4 m fall. We can then calculate K for the range of stage values, provided we know n.

We believe n varies with stage and could range between 0.034 at lesser flood flows up to bankfull, and 0.045 when flow extends over the berms; that is, above RL = 28 m at section 7888 or about 7 m gauge height.

We have also surmised that slope may be closer to 0.0015 when flow is confined to the main channel but reduces to 0.0011 when berm flow occurs. The effect of the bridge may reduce slope even more as water heads up due to the constriction. Given the underside bridge beam level, heading up is expected to occur from about 8.5 m gauge height.

Our estimated rating then is:

RL (m)		Gauge	A (m²)	R	n	K (m³/s)	S	Q (m³/s)
control	gauge	Height						
26	26.45	5.24	500	4.342	0.034	39170	0.0015	1517
27	27.45	6.24	615	4.943	0.034	52670	0.0015	2040
28	28.45	7.24	760	4.259	0.034	58440	0.0015	2263
29	29.33	8.12	1010	2.652	0.045	43010	0.0011	1426
30	30.33	9.12	1420	3.341	0.045	70630	0.0011	2343
31	31.33	10.12	1870	3.959	0.045	103730	0.0011	3440



Manawatu at Teachers College TopEnd from 1-Jan-2005 00:00:00 to 1-Jun-2005 00:00:00

Figure 28 – Estimated high flow rating for Manawatu at Teachers College from conveyance-slope calculation, shown with results from the previous low flow and general rating equation calculations

This gives us some idea of where the rating needs to go but the combination of large berm and bridge constriction obviously creates complex hydraulic conditions for which our simple assumptions of the variability of n and S with stage are a bit coarse.

Log-Log Variant: Fitting General Equations to a Partitioned Control Section

We use the general equation as before; that is, equation (4) in Annex E.

$$Q = C_d y^m \text{ where } C_d = kb \text{ and } \mathrm{k} = \sqrt{\mathrm{S}}/_{\mathrm{n}}$$

Main channel

For the main channel at cross-section 7888 we will use $b = 115$ m, $n = 0.04$ and S =0.0011, hence C_d = 95.35, and m = 1.67 as before. A larger value for n is justified because the slower berm flow will provide more resistance to flow in the main channel.

Other variables are a mean bed level of 21.146 m from which to calculate depth y, and reach distance of 300 m between recorder and section 7888, from which to calculate fall so we can relate reduced water levels at section 7888 to the gauge upstream.

Note: We could derive better estimates of depth y by calculating, from the cross-section data, section area for various water levels then dividing each area by the corresponding surface width, but the accuracy is not warranted given other assumptions we need to make.

		RL (m)		Gauge
y (m)	Q (m^3/s)	control	gauge	Height
0		21.146		
5	1402	26.146	26.476	5.267
6	1900	27.146	27.476	6.267
7	2458	28.146	28.476	7.267
8	3072	29.146	29.476	8.267
9	3740	30.146	30.476	9.267

Left Berm

The left berm is approximately a rectangular section of width $b = 265$ m with mean bed level RL = 28.55 m from which to calculate depth y, and with $n = 0.045$ and S =0.0011, hence C_d = 195.31, and m = 1.67 as before, then:

		RL (m)		Gauge
y (m)	Q (m^3/s)	control	gauge	Height
0		28.55	28.88	7.671
0.5	61	29.05	29.38	8.171
1	195	29.55	29.88	8.671
1.5	384	30.05	30.38	9.171

Right Berm

The right berm is more of a U shape of width $b = 20$ m with mean bed level RL = 28.67 m from which to calculate depth y, and with $n = 0.045$ and S =0.0011, hence C_d = 14.74, and m = 1.92 for a shallow U-shape, then:

		RL (m)		Gauge
y (m)	Q (m^3/s)	control	gauge	Height
0		28.67	29	7.791
0.5	4	29.17	29.5	8.291
1	15	29.67	30	8.791
1.5	32	30.17	30.5	9.291

Total Discharge

If we graph the curves for all three partitions we can then add them together to derive the overall high flow rating curve.

We should expect this rating to overestimate flow because the left berm flow in particular is likely an overestimate due to the barrier to discharge presented by the bridge approach.

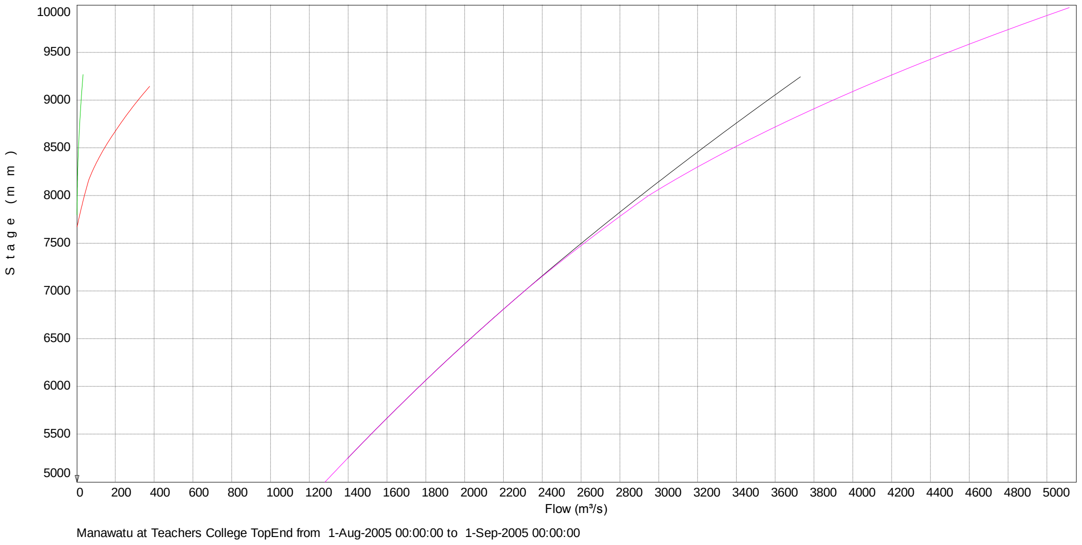


Figure 29 – Estimated high flow rating for Manawatu at Teachers College from general rating equations applied to berm and main channel partitions

Deciding the Final Curve

Ultimately our curve should be smooth, with break points only at levels aligned with changes in the physical features of the channel. The low flow segment refinement suggests then that the lower pair of initial general equation curves is a better option for merging into the mid-range flows (see Figure 26), which leaves us with:

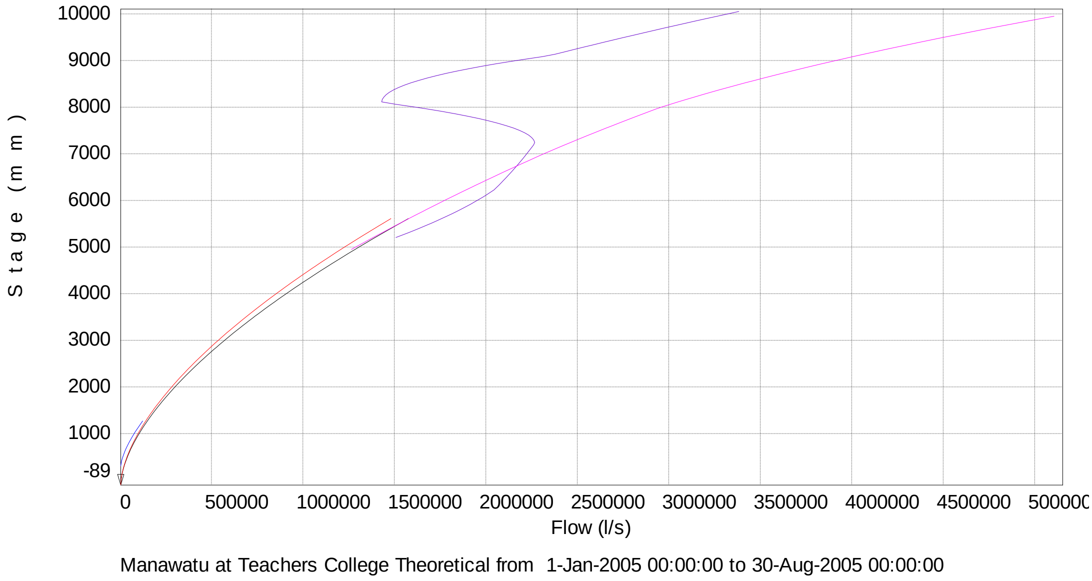


Figure 30 – Theoretical rating segments for Manawatu at Teachers College for low, mid-range and high flows

It remains then to decide where the top end should be. Results from the partitioned approach are more reliable given the complex nature of the channel; however, taking into account results from the conveyance calculation, it seems prudent to pull the curve back a little at around 8 m.

When the low, mid-range and top end estimates are combined, joins smoothed out, and the top end steepened a little as described above, a final theoretical rating is obtained.

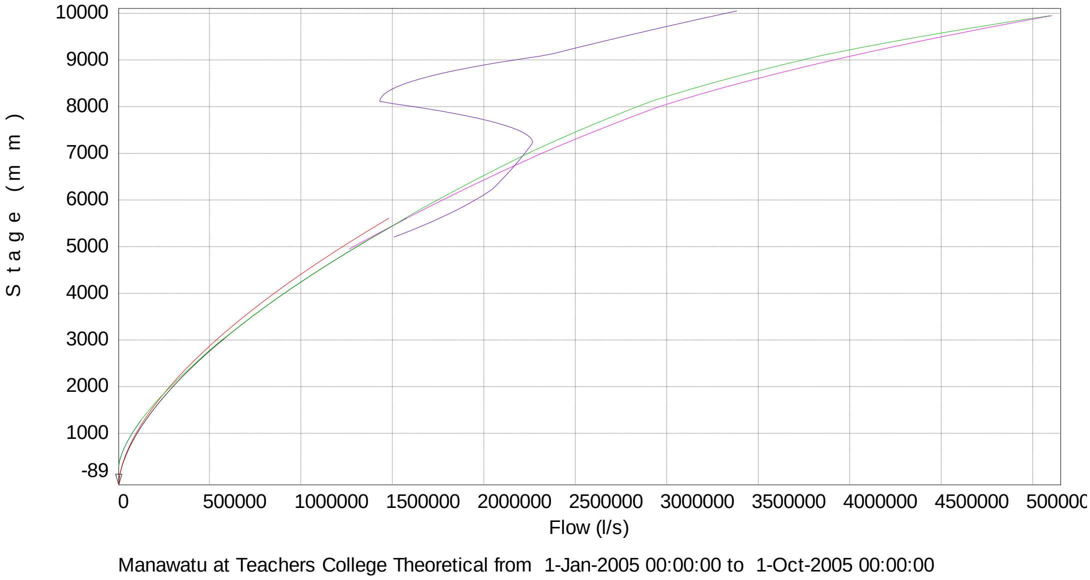


Figure 31 – Final theoretical rating curve (green) for Manawatu at Teachers College shown with the estimated low, mid-range and high flow segments from Figure 30

The litmus test, of course, is gaugings.

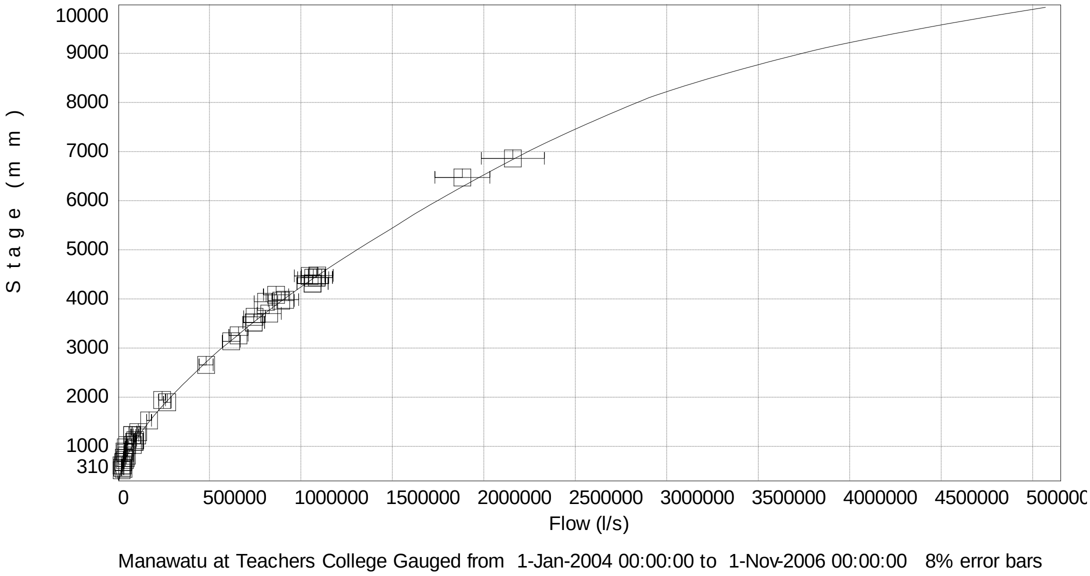


Figure 32a – Final theoretical full-range rating curve for Manawatu at Teachers College, shown with actual discharge measurements within the period of stable control during which the cross-sections used to derive the rating curve were surveyed

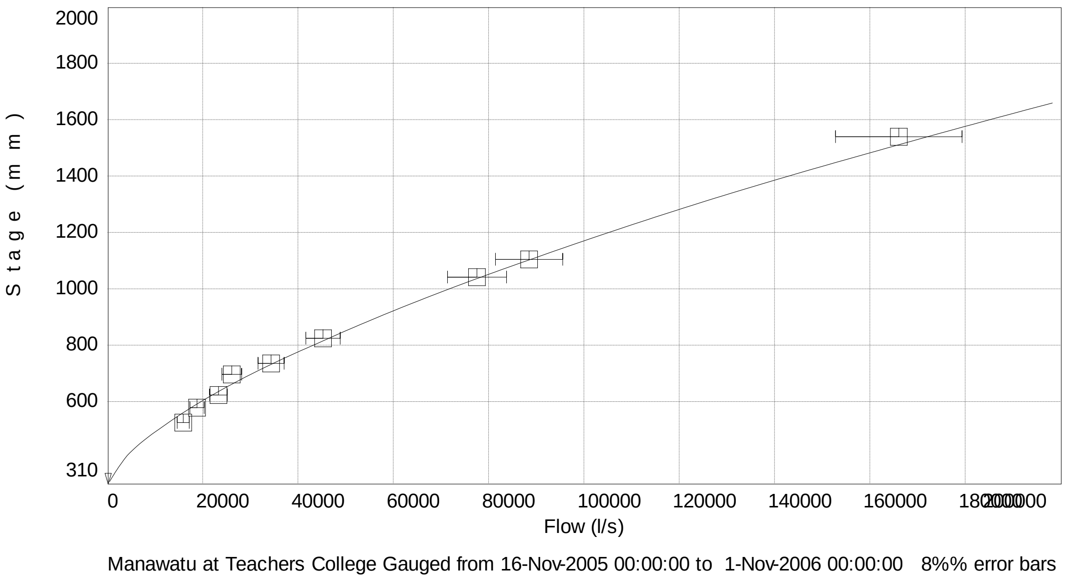


Figure 32b – Final theoretical bottom-end rating curve for Manawatu at Teachers College, shown with actual discharge measurements within the period of stable control during which the cross-sections used to derive the rating curve were surveyed

Annex I – Assessing Gauging Frequency

The frequency of river gauging has a dominant effect upon flow accuracy (determined from the stage–discharge rating and measured stage record) and should be carried out at an interval that ensures accurate determination of the discharge rating curves and detection of all rating changes.

The flow series quality assurance test of "95% of the simultaneous rated flows shall be within ±8% of the measured discharges" may be more easily achieved with fewer gaugings, but fewer gaugings risks inadequate definition of rating shape and failure to detect all shifts. This Standard therefore sets minimum frequencies for all sites, and recommends a range of gauging frequencies for various types of sites commensurate with the probability of rating shift or change.

Ibbitt and Pearson (1987) found that omission of one rating for the Rakaia River at the Gorge caused an error in the mean flow of about 6%, and 8% for the flow exceeded 95% of the time. They concluded these errors were at least five times larger than errors derived from stage measurement or incorrect rating curve shape.

Graphical Method

This method is an assessment of trend in a plot of rating changes detected each year versus the number of gaugings done in each of those years.

Figure 33 is an example using the Rakaia River at Fighting Hill, which has a continually changing alluvial channel. The period from 1989 to 2003 includes a period of funding reductions that resulted in fewer gaugings.

Up to 10 rating changes have been detected in any 1 year and, while the number of rating changes varies from year to year, there is a positive trend between the number of gaugings per year and the number of rating changes detected.

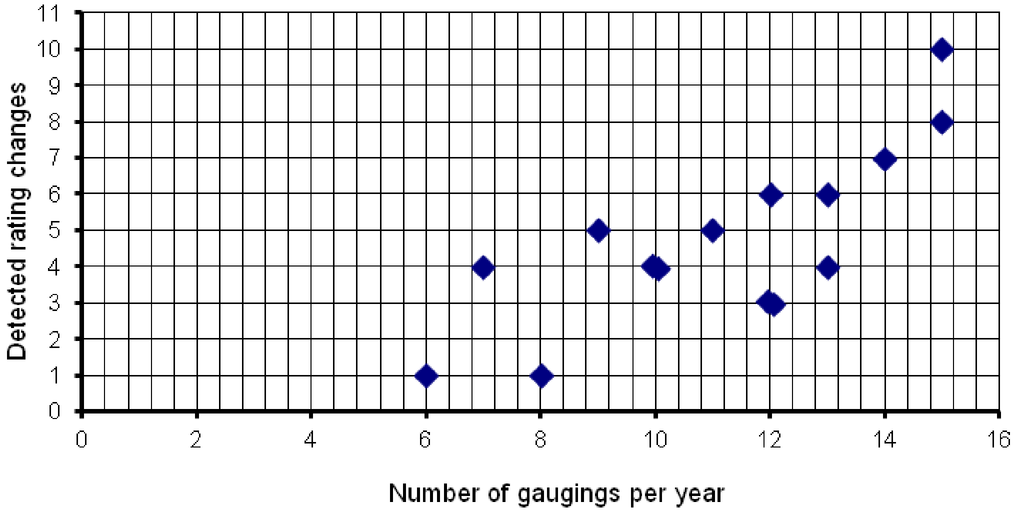


Figure 33 – Rakaia River at Fighting Hill (1989–2003), comparison between the number of gaugings per year and the number of detected rating changes per year

To understand if there is any justification for more than 15 gaugings per year, the incidence of FRE3 events was counted for each year (research has shown that FRE3 is typically the threshold for mobilisation of substrate in alluvial channels). In essence the more FRE3 events, the more gaugings should be completed.

Figure 34 shows that during the first six years gauging frequency was similar to the number of FRE3 events but subsequently was considerably less, and therefore likely inadequate to detect new ratings.

Variation in FRE3 frequency indicates the degree to which gauging frequency should also be flexible to effectively track the bed-changing events.

The FRE3 frequency trace in Figure 34 supports the notion that 13 to 15 gaugings per year would be a minimum gauging frequency at this site for most years, and some years would require more.

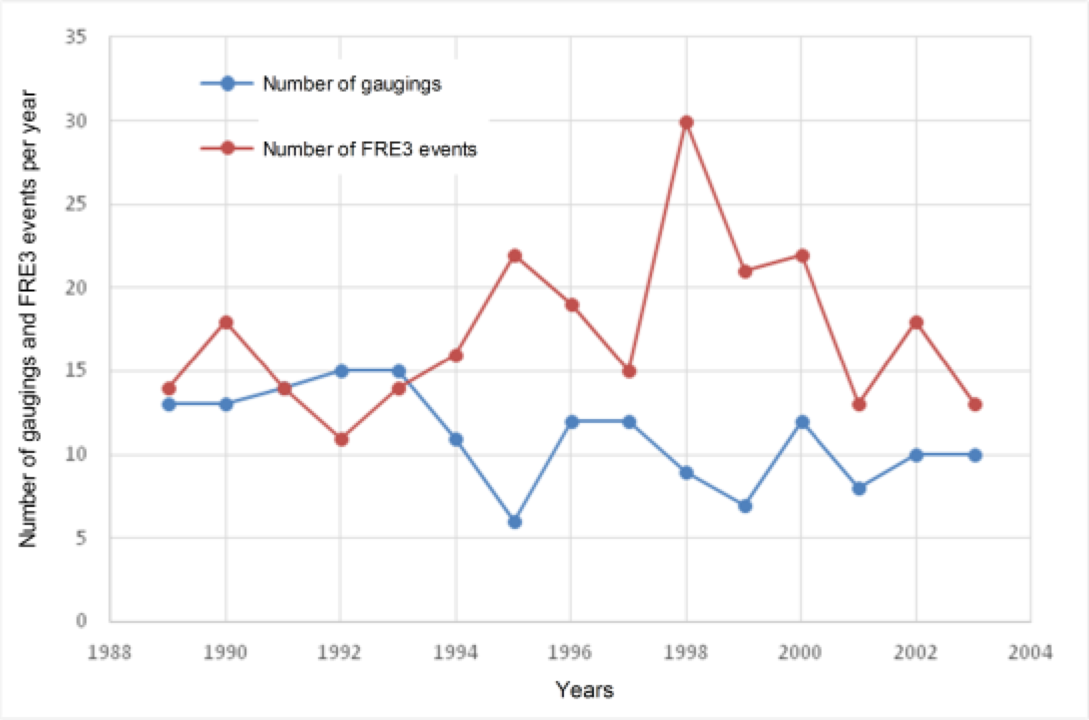


Figure 34 – Rakaia River at Fighting Hill (1989–2003), number of gaugings and fre3 events per year

Ibbitt and Pearson (1987)

This paper describes statistical analysis of gauging and rating change frequency that can be used to:

- estimate probable errors in existing flow records
- assess the confidence that can be placed on the accuracy of flow records when frequent rating changes occur, and
- control future gauging operations.

The method has been tried since publication with varying success and is not in widespread use; however, it is recommended reading as one of very few papers on the matter pertinent to New Zealand methods of rating curve construction.

The full paper is downloadable without fee from http://www.tandfonline.com/toc/thsj20/32/1#.VB-s6ZSvWA8

The method provides for:

- quantifying level of confidence in the assumption that all detectable rating changes are accounted for in an existing rated flow series
- assessing the probability of missing a future rating change that would lead to an error in the flow series larger than some stated tolerance, given a particular gauging interval
- choosing a gauging interval so that desired probability of missing a detectable change is not exceeded, and
- choosing a gauging interval so that desired probability of missing a rating change that might produce an error in the flow series larger than some stated tolerance is not exceeded.

Parameters required or estimated are:

- slope of the rating curve at mean flow
- average time between detectable rating changes
- average time between gaugings
- characteristic size of rating change, and
- minimum detectable rating change.

The paper makes a number of assumptions, all of which would need to be valid for the analysis results to be reliable. Assumptions inherent in the method are:

- ratings conform to type curves; that is, those applicable to sites with steep-sided stable banks and alluvial beds that scour and fill uniformly
- rating shape is determined from a comprehensively gauged single hydrograph shortly after commencement of recording, with subsequent change in bed level tracked by periodic gauging
- percentage change in flow for a fixed change in stage is constant
- an exponential distribution for the stage shift at mean flow due to rating change
- rating changes are caused by floods
- flow statistics of interest are temporal averages
- three sources of error in a flow series:
  - errors in water levels that are relatively small and random, tend to cancel out when averaged over time, and therefore are not significant
  - errors of rating curve shape that can be treated as the estimation of the standard error of estimate for a non-linear regression (see Ibbitt, (1975)), are semi-systematic but relatively small when extracting instantaneous flow values, except when flow is changing significantly, and therefore unlikely to cause detectable errors in annual flows
  - systematic error that is most significant and caused by failing to detect a change in rating, and
- increased gauging frequency will not reduce error in any instantaneous flow value extracted but will shorten the period over which error persists and therefore improve accuracy of mean statistics.

Annex J – Calculation of Uncertainty in the Stage–Discharge Relationship

To estimate the uncertainty associated with discharge predicted from a rating curve for a given value of stage, the conventional approach (Herschy, 1999; Schmidt & Yen, 2008) is to model the rating using a simple power law or type curve defined by the general rating equation, which is a straight line when expressed in terms of logarithmic coordinates.

$$Q = k(h - e)^m \tag{15}$$

where: Q is the discharge

h is the stage height

e is the stage height at zero flow, and

k and m are constants.

Expanded Uncertainty

The expanded uncertainty in the calculated value of $\ln Q_r$ at stage height h, is given by:[5]

$$U[\ln Q_r(h)] = \pm\, t\, S_e \left\{ \frac{1}{N} + \frac{\left[\ln(h-e) - \overline{\ln(h-e)}\right]^2}{\sum\left[\ln(h-e) - \overline{\ln(h-e)}\right]^2} \right\}^{0.5} \tag{16}$$

where: bars in equation (16) denote averages

Q_r is rated discharge

t is Students t-correction that, for 95% level of confidence, may be taken as:

t = 2 for number of gaugings $N \geq 20$
t = 2.2 for N =10
t = 2.6 for N =5

S_e is the standard error of the estimate, from:

$$S_e = \left[\frac{\sum\left(\ln Q_g - \ln Q_r\right)^2}{(N-p)} \right]^{0.5}$$

where: Q_g is gauged discharge, and

p is the number of general rating equation parameters (e, k and m) adjusted to make the rating curve fit the gauging data.

Equation (16) assumes errors in stage are small compared with the errors in discharge.

Equation (16) provides two parallel straight lines in logarithmic units, one on each side of the rating relation and each distant by $2S_e$ from it.

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[5] ISO 1100-2:2010(E), section 7.

The more gaugings available to define the type curve, the more reliable the statistical estimates of $U[\ln Q_r(h)]$.

The quantity $\pm U[\ln Q_r(h)]$ is also referred to as the 95% confidence limits or the 'standard error of the mean relation' and $100.U[\ln Q_r(h)]$ is the percentage error.

If a rating curve comprises more than one segment, and therefore is described by more than one equation of the general form, S_e and $\pm U[\ln Q_r(h)]$ should be determined for each segment using the appropriate numbers of degrees of freedom $(N - p)$ for each segment.

Uncertainty Intervals

By taking anti-logarithms of equation (16), the uncertainty interval for discharges may be expressed as:

$$Q_r(h)e^{\pm U[\ln Q_r(h)]} \approx Q_r(h)\big[1 \pm U[\ln Q_r(h)]\big] \qquad (17)$$

if $U[\ln Q_r(h)]$ is small enough that the linear approximation holds.

Uncertainty in Predicted Discharge

Finally, uncertainty in a predicted value of discharge for a nominated value of stage, $u\big[\ln Q_p(h)\big]$, may be estimated by root-sum-squares (RSS) combination:

$$u\big[\ln Q_p(h)\big] = \left\{m^2 u[\ln(h-e)]^2 + S_e + u\big[\ln\big(Q_r(h)\big)\big]^2\right\}^{0.5} \qquad (18)$$

where: $u[\ln(h-e)]$ is the uncertainty in effective depth $(h - e)$.

Expanded prediction uncertainty can be then calculated from:

$$U\big[\ln Q_p(h)\big] = \pm\, t \cdot u\big[\ln Q_p(h)\big]$$

Application to Unstable Sites with Multiple Rating Curves

The above equations apply when the rating curve is fixed, which occurs only under stable hydraulic conditions.

At sites with unstable controls, uncertainty may become significant and biased. The rating becomes invalid and must be replaced by another corresponding to the new hydraulic regime.

The new rating, possibly defined by only one or a few gaugings, might be assumed to have the same type curve as the previous well-established rating, simply reflecting a vertical shift of the type curve or a swivel if it is assumed that the top or high discharge end of the rating is reasonably stable (Ibbitt and Pearson, 1987). In either case, in the absence of other information, the uncertainty in a predicted value of discharge may still be estimated using equation (18) applied to the earlier well-established rating.

Annex K – Example Filed Comments

Rating Coverage Comment

dd-mm-yyyy hh:mm:ss

RATING COVERAGE COMMENT as at 1-Jan-2009

Maximum gauged flow is	35.2 m^3/s at stage 2.468 m on 24-09-1995
Maximum recorded flow is	71.1 m^3/s at stage 3.119 m on 12-07-2006
Minimum gauged flow is	1.25 m^3/s at stage 0.745 m on 15-04-2003
Minimum recorded flow is	1.05 m^3/s at stage 0.680 m on 25-04-2003
Maximum gauged stage is	2.504 m on 25-08-1978
Maximum recorded stage is	3.226 m on 23-08-1978
Minimum gauged stage is	0.725 m on 13-03-2008
Minimum recorded stage is	0.613 m on 22-04-2008

Mean velocity at maximum recorded flow = 2.8 m/s

Rating Model Comment

dd-mm-yyyy hh:mm:ss

RATING MODEL COMMENT

Ratings are stored, managed and applied using XYZ software. Curves are drawn in natural space and tested for fit using simple deviations. Curves are represented by stage–discharge pairs and rendered by spline interpolation. Rating shifts and changes are explicitly defined as new curves. Transitions between curves are smoothed over a specified period of time indicative of the event causing the change.

dd-mm-yyyy hh:mm:ss

RATING MODEL COMMENT

Ratings are stored, managed and applied using the ABC system. Curves are constructed in the application by mathematical curve fitting in logarithmic space and tested for fit using Student's *t*-test. Curves are segmented, each segment described and rendered by equation. Rating shifts are implemented by stage-shift. Rating change is implemented as a new curve with a defined period of applicability. Transitions are phased in over the applicability period of rating shift. Changes of rating are effective from the start of the relevant applicability period.

Note: The above are examples of suitable wording only and do not necessarily describe best practice with respect to ratings' development and application.

Gauging Deviation Comment

dd-mm-yyyy hh:mm:ss

GAUGING DEVIATION COMMENT

Gauging ##### on dd-mm-yyyy hh:mm:ss deviates –15.8% from the rating curve. When compared with other gaugings on the same cross-section, the mean velocity is lower than expected. Significant problems with floating weed were experienced while gauging and it is suspected the meter remained weed-bound despite attempts to keep clear.

dd-mm-yyyy hh:mm:ss

GAUGING DEVIATION COMMENT

Gauging ##### on dd-mm-yyyy hh:mm:ss deviates +10.2% from the rating curve. When plotted on the stage–area curve, area is greater than expected. Accurate sounding was difficult and vertical angles severe. A rating change occurred on the event that prevented useful resurvey of the section after the event.

dd-mm-yyyy hh:mm:ss

GAUGING DEVIATION COMMENT

Gauging ##### on dd-mm-yyyy hh:mm:ss deviates –9.4% from the rating curve. Analysis of the ADCP gauging data indicates problems with a moving bed, causing velocities to be under-recorded.

Synthetic Rating Comment

dd-mm-yyyy hh:mm:ss

SYNTHETIC RATING COMMENT

The rating applied between dd-mm-yyyy hh:mm:ss and dd-mm-yyyy hh:mm:ss is not supported by gauging. The curve has been derived from the theoretical equation for a rectangular sharp-crested weir (HRS variant) using measurements of the actual structure at site. Free-fall is achieved at all flows but approach velocities are variable. Discharge coefficient was obtained from published tables. Low flows are expected to be useable within approximately 15% of actual; high flows are more uncertain.

dd-mm-yyyy hh:mm:ss

SYNTHETIC RATING COMMENT

The rating applied between dd-mm-yyyy hh:mm:ss and dd-mm-yyyy hh:mm:ss is not supported by gauging. The curve has been derived by shifting the previous curve –140 mm, having assumed a type curve and inspection of the stage series plot indicating 140 mm of bed scour between the bounding high flow events with no change in channel geometry subsequently observed. Flows are expected to be within 10% of actual over the recession period.

Gap Rating Comment

dd-mm-yyyy hh:mm:ss

GAP RATING COMMENT

A rating is not able to be determined for the period dd-mm-yyyy hh:mm:ss to dd-mm-yyyy hh:mm:ss. Derived flows indicate a substantial change in the control occurred that was not measured before the subsequent flood event reshaped the control again.

Annex L – Example Tests for Quality and Accuracy

Gauging Distribution

The table below may be used to assess the quality of individual ratings. It lists the number of gaugings supporting each rating and compares the stage range recorded with the stage range gauged during each rating period of applicability.

Table 5 – Per rating number of gaugings and coverage

PERIOD OF RATING	NUMBER OF GAUGINGS SUPPORTING RATING	HIGHEST RECORDED STAGE (m)	HIGHEST GAUGED STAGE (m)	LOWEST RECORDED STAGE (m)	LOWEST GAUGED STAGE (m)
20041222 to 20050318	1	1.426	1.137	0.946	1.137
20050318 to 20050402	0	1.342	—	0.957	—
20050329 to 20050904	3	1.342	0.969	0.883	0.905
20050903 to 20060210	7	1.868	1.657	0.846	0.861
20060209 to 20061130	12	1.868	1.557	0.778	0.792
20061130 to 20061230	1	1.882	1.076	1.022	1.076
20061230 to 20080212	17	1.882	1.143	0.727	0.749
20080211 to 20080703	11	1.599	1.049	0.766	0.781
20080703 to 20080826	3	1.672	1.074	0.889	0.894
20080825 to 20090517	13	1.945	1.184	0.829	0.847
20090517 to 20090609	2	1.945	1.071	0.929	0.929
20090609 to 20090706	0	1.415	-	0.875	-
20090705 to 20100108	7	1.681	1.124	0.861	0.898
20100107 to 20100224	1	1.661	0.962	0.853	0.962
20100224 to 20100604	5	2.380	1.131	0.825	0.843
20100604 to 20110811*	17	1.978	1.218	0.902	0.913

* Note: end of audit period, not end of rating period

The graph below displays gauging coverage partitioned over the rated flow range and may be used to identify degree of measurement support for shape of rating curve segments and flow range(s) for which other evidence of shape is required.

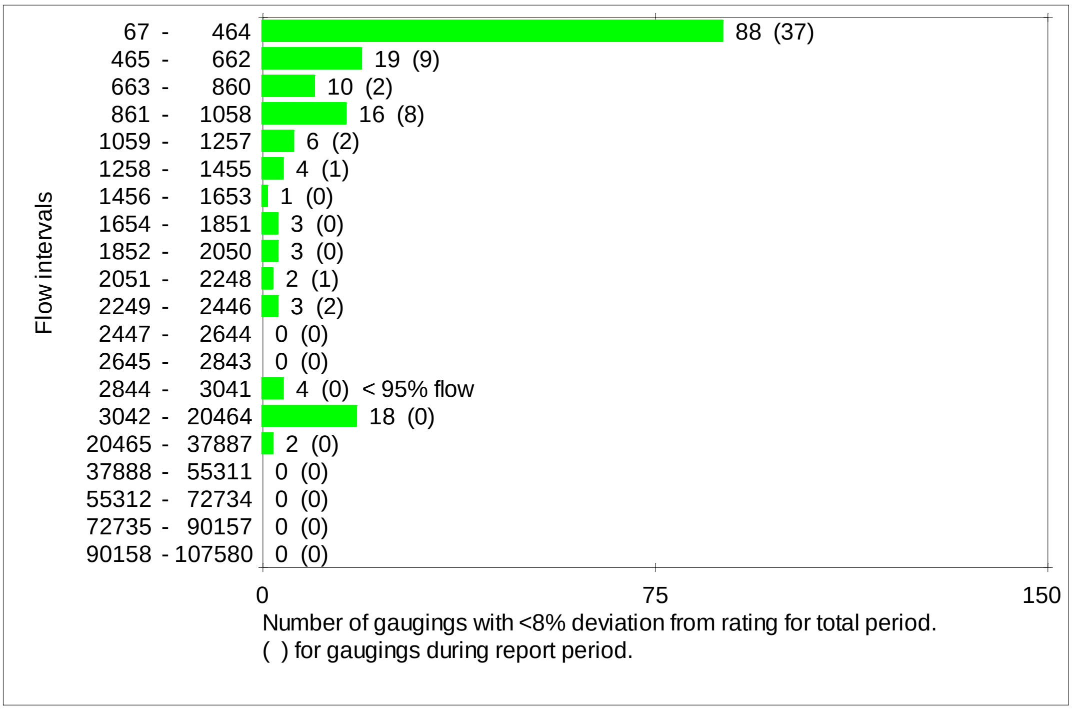

Figure 35 – Distribution of gaugings (full flow range) for data period 1968–2014, report period 1994–2014.

Source: TIDEDA Rating Quality Standards Report.

Curve Fit

Extracts of summary and individual curve statistical reports testing % flow deviations for bias and trend.

Table 6 – TIDEDA rating quality statistics

```
Standard Rating Statistics
**************************

Overall Statistics
==================

Number of gaugings     244      | Positive deviations  125
                                | Negative deviations  111
Number of runs         111
Maximum deviation     37.3 % on day 29-Feb-1968
Standard Deviation     7.8 %
Overall Bias  (+/-)  -0.36 % which is not significant at the
95% level.

Run statistics indicate a random distribution of gaugings
about rating at the 95% significance level.
--------------------------------------------------------------


Individual Ratings
==================

Rating  7-Feb-1968  7-Feb-1968
------------------------------
Number of gaugings      21      | Positive deviations   10
                                | Negative deviations   11
Number of runs          13
Standard Deviation    12.4 %
Overall Bias  (+/-)   2.43 % which is not significant at the
95% level.

Run statistics indicate a random distribution of gaugings
about rating at the 95% significance level.
--------------------------------------------------------------

Rating  4-Mar-1970  4-Mar-1970
------------------------------
Number of gaugings       4      | Positive deviations    3
                                | Negative deviations    1
Number of runs           2
Standard Deviation     2.0 %
Overall Bias  (+/-)  -2.30 % which is significant at the 95%
level.


Run statistics cannot be calculated.
```

Table 7 – Hilltop hydro gauging statistics

```
Deviation from the Gaugings: (Qr-Qg)/Qg
Qr computed from the Recorder Stage

Stage     Flow     Qr       Date         Deviation
    #      l/s      l/s                    #         %
 Rating                   18-Nov-2009     (18-Nov-2009)
  479      730      690   20-Nov-2009   -4.474      -5.5
  427      264      264   13-Jan-2010    0.04216     0.1
  416      185      212   15-Apr-2010    6.441      14.6
  441      318      336   13-Jul-2010    4.101       5.7

 Rating                   06-Sep-2010     (06-Sep-2010)
  493      997      954   13-Oct-2010   -3.162      -4.3
  408      184      183   02-Dec-2010   -0.3171     -0.8
  405      169      169   07-Dec-2010    0.1149      0.3
  405      166      169   07-Dec-2010    0.8413      2.1
  405      162      169   07-Dec-2010    1.834       4.6
  396      149      142   04-Apr-2011   -3.614      -4.5
etc.

    Rating   Gaugings   Runs  +ve Dev  -ve Dev
07-Feb-1968      21       13       10       11
04-Mar-1970       4        2        3        1
23-Jun-1970      15        7        8        7
06-Apr-1972      32       15       20       12
28-Aug-1975      84       32       48       36
10-Apr-1988      38       15       16       22
23-May-2002       4        3        2        2
28-Sep-2004       9        7        4        5
15-Jan-2008       0        0        0        0
23-Jan-2008       0        0        0        0
01-Feb-2008       9        5        4        5
23-Jul-2009       3        3        1        2
18-Nov-2009       4        2        3        1
06-Sep-2010      21       11       11       10
All Gaugings    244      113      130      114

 71% of the gaugings are within 8% of the rating

Sorted Gaugings
Stage     Flow     Qr       Date         Deviation
    #      l/s      l/s                      #      %
   1144     28242    29915    03-Jul-1974   19.66       5.9
   1049     27254    27291    29-Jun-1976     0.6321    0.1
   1029     20375    20948    10-Mar-1990    8.339      2.8
    832     19935    20328    07-May-1969    6.725      2.0
    977     18759    17615    21-Nov-1993  -19.07      -6.1
    999     17808    18939    10-Mar-1990   18.74       6.3
    825     13458    12122    30-Apr-1976  -24.04      -9.9
    824     10532     9956    09-Oct-1974  -13.70      -5.5
    808      8927     9326    16-Jun-1975    9.978      4.5
etc.
```

A bed plot gives a visual indication of curve fit to gaugings, using deviations in terms of mm of stage.

If combined with deviations calculated using only the initial rating, a 'before and after' bed plot is obtained that demonstrates both the extent of rating shifts over time and integrity of the final result when all shifts have been identified and addressed.

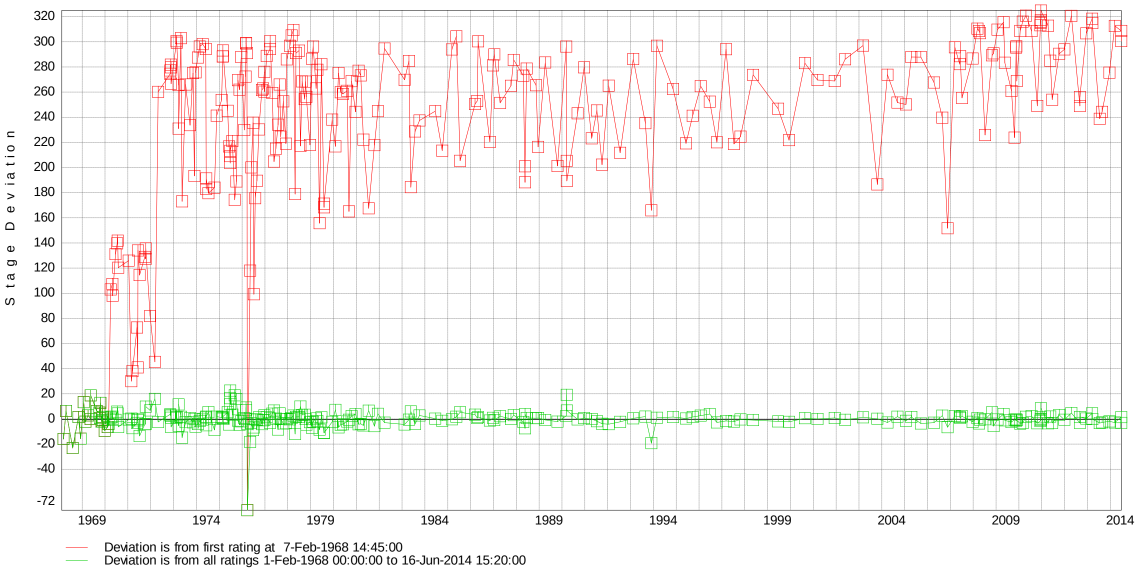

Figure 36 – 'Before and after' bed plot

Source: Hilltop hydro graphs bed plot.

Stationarity

Double mass plots provide a visual means of comparing data between sites for change in trend that may be caused by some systematic shift or error introduced at one or other site; that is, a loss of stationarity.

The test site is plotted on the *y*-axis, the comparison site on the *x*-axis.

Flows may be tested against other flows or against rainfall from records within the same catchment or a neighbouring one. If rainfall used is representative of the catchment mean above the flow site, slope of the double mass curve should be less than 1:1 because of losses to storage and evapotranspiration.

A thorough test against at least two other sites is preferable, and comparisons between the other comparison sites.

The plot below is interrupted by the period of no ratings at one site; however, the straight line thereafter indicates flow records remain consistent between sites.

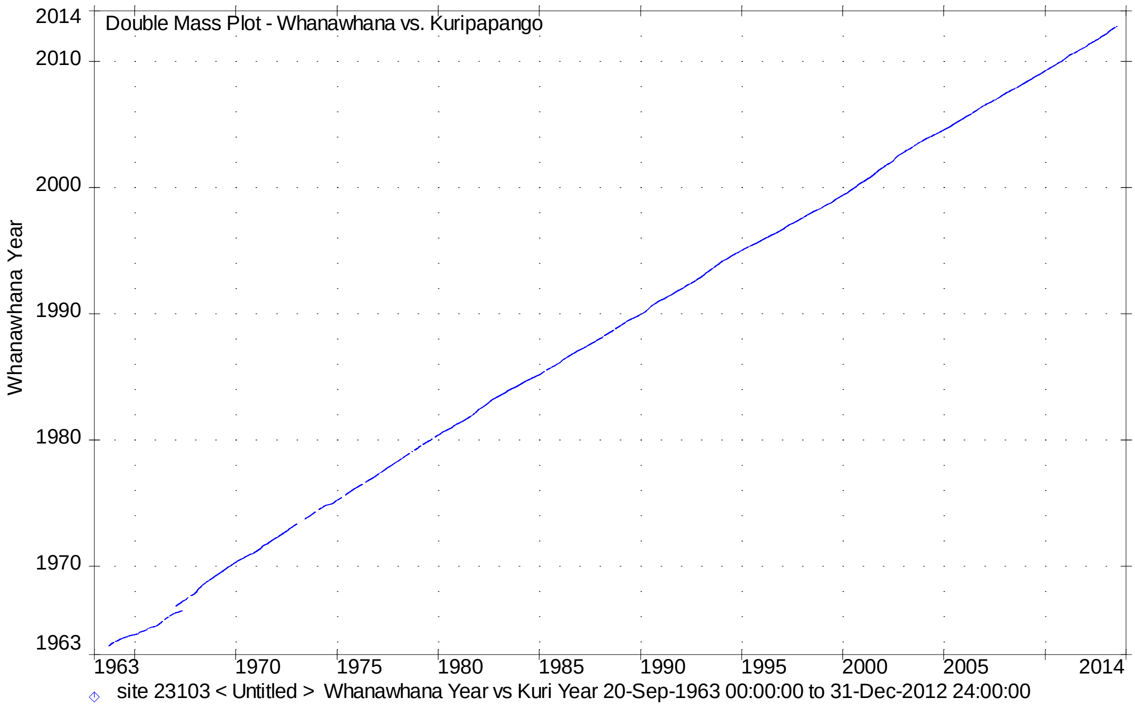

Figure 37 – Double mass flow plot

Source: TIDEDA graph special double mass curve.

Note: Double mass curves are not useful for identifying outliers or spurious errors. Tabulating extremes, and inspecting graphs of the flow series over time, are much more useful tools for this.


NEMS