A Review of Stream Gauge Records for Design Flood Estimation

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Abstract

Design flood estimation remains a problem for many professionals involved in the management of rural and urban catchments. Recorded flood data provides the basis for most design flood estimation; the recorded flood data is used in application of the design flood estimation technique (FFA) or in the development of the technique (RFFE). In general, data used for design flood estimation is the peak flow of the flood hydrograph. However, the data recorded at most gauging stations is the water level in the channel (the channel stage). To convert these stages to an equivalent flood flow, a rating curve or a stage-discharge relationship is used. For most design flood problems, extrapolation of the stage-discharge relationship usually is required to enable the desired translation. There is a need to consider the magnitude of this extrapolation of the stage-discharge relationship. Furthermore, there is a need to consider the data used for development of the stage-discharge relationship and the impact of this data on the subsequent extrapolation. Presented herein will be the results of an investigation into stage-discharge relationships and their basis.

1. INTRODUCTION

Design flood estimation remains a problem for many professionals involved in the management of rural and urban catchments. Advice is required regarding design flood characteristics for many design problems including the design of culverts and bridges necessary for cross drainage of transport routes, the design of urban drainage systems, the design of flood mitigation levees and other flood mitigation structures, design of dam spillways, and many environmental flow problems.

While the flood characteristic of most importance depends on the nature of the problem under consideration, but typically it is one of the following:

- Flood flow rate – typically, it is the peak flow rate of the flood hydrograph that is the desired design flood hydrograph characteristic;
- Flood level – similar to the flood flow rate, it is the peak flood level during the flood hydrograph that is the commonly desired design flood hydrograph characteristic;
- Flood rate of rise – this design flood characteristic is a concern when planning is undertaken for operational floods;
- Flood volume – this design flood characteristic becomes a concern when the design flood volume is a major factor in the design problem. This situation occurs when storage of a significant portion of a flood hydrograph is used as part of a flood management system; or
- System failure – the usual design flood problem is located at a single point. There are a number of design problems, however, where the issue becomes one of multiple points within a system. Typical examples of these problems include urban drainage systems where the individual components of the system are not statistically independent which is a common assumption, and transportation routes with multiple cross drainage structures of one or more river systems.

While all of these flood characteristics have been noted as being of interest to flood designers, the dominant characteristic of concern has been the flood flow rate. As a result of the historical focus of flood designers, alternative approaches to design flood estimation have developed. These alternatives can be categorized as risk-based design and standards-based design. With risk-based design it is necessary to estimate both the magnitude and frequency of the flood characteristic of interest. In other words, there is a need to estimate the magnitude of the flood characteristic (for example, the peak flow of a flood hydrograph) associated with a given exceedance probability. Designing a structure to pass the 1% or 1 in 100 year AEP (Annual Exceedance probability) flood event is an example of a risk-based design. Conversely, with standards-based design, there is a need only to estimate the magnitude of the flood characteristic and it is not necessary to estimate the associated exceedance probability of the flood characteristic. Designing a structure to pass the flood of record, or a spillway to pass the flood arising from the Probable Maximum Precipitation, are examples of standards-based criteria that do not involve the specification of exceedance probabilities.

The desired flood characteristics to be used for the design must be interpreted from a statistical viewpoint. This contrasts with the analysis of the flood characteristics of a historical event where a deterministic viewpoint is appropriate. There are two alternative situations when design flood characteristics are required; these are:

- Suitable historical information is available; and
- Suitable historical information is not available.

As discussed by Ball *et al*. (2011), where suitable historical information is available, estimation of the desired flood characteristics can be undertaken using at-site flood frequency methods (see, for example, Jin and Stedinger, 1989, and Kuczera, 1999) while where suitable historical information is not available, estimation of the desired flood characteristics can be achieved through either catchment simulation techniques (commonly referred to as rainfall based techniques) or regional transformation techniques (commonly referred to as Regional Flood Frequency methods; see, for example, Rahman *et al*. 2014). Monitored data from which the catchment response to rainfall can be determined is an essential component of all three approaches to estimation of the desired flood characteristic.

Hence there is a need to consider the reliability of the gauged data in terms of flood flows. A typical gauging station, however, monitors river stages and requires a stage-discharge relationship to convert the recorded levels to an equivalent flow. For design flood estimation it is common to extrapolate this stage-discharge relationship. There is a need, therefore, to consider the impact of this extrapolation of the stage-discharge relationship on the predicted flood characteristic. Presented herein will be the results of a preliminary investigation into errors within stage-discharge relationships and the impact of these errors on estimation of design flood characteristics.

2. STAGE-DISCHARGE RELATIONSHIPS

Rating curves, or stage-discharge relationships, describe the relationship between the water surface level (stage) and discharge at a gauging site. Once established, they are used to translate a continuous record of stage to an observed flow and provide a foundation for subsequent analyses. To develop a stage-discharge relationship, individual points on the relationship are determined by field measurement. Typically, these measurements involve measuring the stream stage and flow velocity at one or more points in a sub-section of the stream. The appropriate discharge is then calculated by multiplying the flow velocity by the measured cross-sectional area of the section. The paired stage-discharge measurements are plotted and fitted with a power-law relationship; the result being the stage-discharge relationship for that gauging station.

An example of the development of a stage discharge relationship using measured stage and velocities in sub-sections is presented by Tilley et al. (1999). Shown in Figure 1 are the calculated sub-section stage-discharge relationships and the stage-discharge relationship for the total section determined by Tilley *et al*. (1999).

It is common to assume stage-discharge relationships are error free in the interpolation zone of the relationship; as presented by Kuczera (1999), the interpolation zone of the stage-discharge curve occurs below the highest recorded level for which a discharge has been measured (i.e. the highest gauging). Since the interpolation zone of the stage-discharge relationship is used to inform the

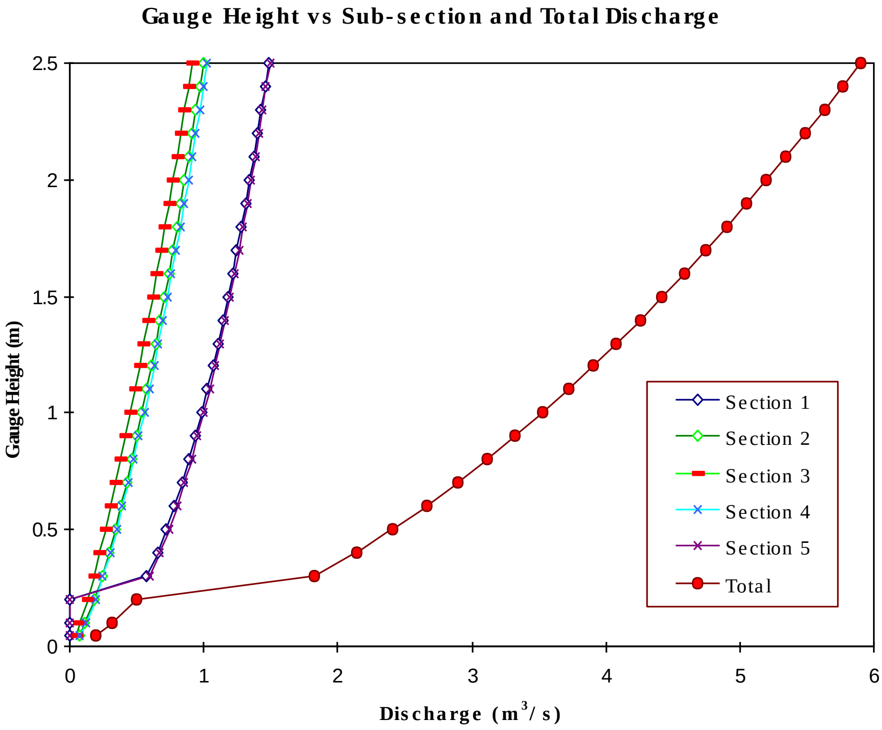

Figure 1 Powells Creek Stage Discharge Relationship (after Tilley et al. 1999)

extrapolation zone (i.e. the region of the relationship where the measured stage is higher than the highest gauging), there is a need to assess the sources and magnitudes of errors in the interpolation zone of stage-discharge relationships.

Within the interpolation zone, uncertainty in the stage-discharge relationship is the result of both random and systemic errors. The random errors include instrument accuracy while systemic errors include estimation of the stream cross-section or sub-sections characteristics, estimation of the section velocity, and deviation of the flow conditions from the assumed steady flow conditions (i.e. hysteresis in the relationship).

3. INTERPOLATION ZONE ERRORS IN STAGE-DISCHARGE RELATIONSHIPS

The primary sources of uncertainty in the stage-discharge relationship are
- Measurement error arising from instrument resolution;
- Cross-section determination;
- Estimation of the average velocity in the cross-section or sub-section;
- Hysteresis effects; and
- Flow variations during the measurement (i.e. unsteady flow effects).

Each of these errors will be considered in the following sections.

3.1. Measurement Errors

The first source of uncertainty arises from instrument resolution. Consequently, this uncertainty is not stationary but rather will vary with time. This is a particular problem at long-established gauging stations where early gaugings were undertaken using less precise instruments and less reliable approaches.

Di Baldassare and Montanari (2009) claim the errors in measurement of the stage are similar in magnitude as topographic errors. WMO (2010) suggest that accuracy in stage measurement should be taken as 0.003m or 0.2% of the effective stage. Nonetheless, indicative resolutions for different measuring techniques are:

- Staff gauges – typically half the smallest marked division (usually 5mm);
- Float gauges – Venetis (1970) claims a resolution of ±6mm should be expected;
- Pressure transducers – Venetis (1970) claims their resolution to be ±1.4 to 4mm; and
- Local oscillations in the water surface – a variation of ±20mm was suggested by Dottori et al. (2009) as a reasonable estimate of surface variability. This suggested value may be higher in steeper streams.

It is worth noting that human error in the reading (recording of stage), particularly during gaugings, should not be discounted. Types of human errors that need consideration include differences between individual hydrographers, lighting conditions (shade, poor light, etc.), and differences in gauging technique.

3.2. Estimation of Cross-Section Characteristics and Velocities

Uncertainty due to estimation of the cross-section characteristics and the average velocities within the sub-sections will be considered concurrently as it is the integration of these two factors that ultimately leads to the estimation of the discharge for a given stage.

There are two issues that impact on the errors associated with estimation of the cross section properties. The first of these issues is how representative the selected cross section is of the channel reach while the second issue is the determination of the cross section properties for the selected cross section.

The representativeness of a particular cross section cannot be assessed without recourse to the survey of a number of cross sections in close proximity. An estimate of the variability of stream cross-sections can be obtained from Burnham and Davis (1986) who undertook a detailed stream survey in assessing the uncertainty of flood profile determination using HEC-2.

Cross-section characteristics usually are determined by partitioning the cross section and determining the characteristics for the individual sub-sections. Implicit in this approach is the assumption of linear variation between the vertical partitions. Hence, a large number of vertical partitions per unit width of cross-section will result in greater the validity of this assumption.

The likely magnitude of the errors in determination of the cross section characteristics is dependent on the variability of individual channels and the number of vertical partitions. The more variable the cross section, the greater the likely error in cross section characteristics for a given number of vertical partitions per unit width of channel.

In most instances, the stream velocity is not measured over the complete flow profile but rather is measured at a number of points in the vertical profile. Typically, these depths are 0.2, 06, and 0.8 of the flow depth. If the velocity is measured at only one point, it is usual to measure the velocity at 0.6 of the flow depth. Implicit in the selection of these depths is the assumption of a logarithmic variation of velocity with depth (i.e. a logarithmic velocity profile); the validity of this assumption should be considered in the estimation of the sub-section average velocity and its uncertainty.

3.3. Hysteresis Errors

Hysteresis occurs commonly during flood periods when the stage and flows are changing rapidly. As the flood wave approaches the gauge site, the stream velocities ahead of the flood wave will increase due to the increased energy gradient. Conversely, after the flood wave has passed, the stream velocities will be reduced due a decreased energy gradient. Consequently, for a given stage, the flood flow will be higher during periods of rising stage than during periods of falling stage. This effect is illustrated in Figure 2.

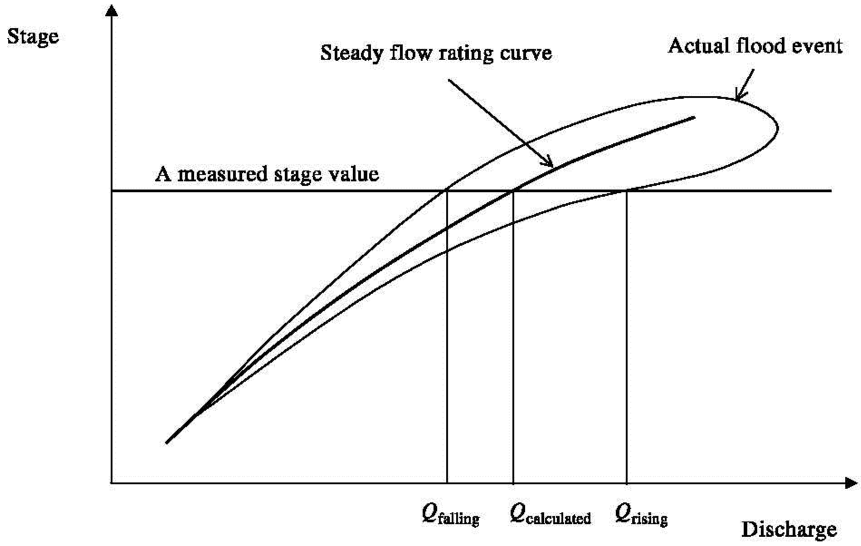

Figure 2 Looped Rating Curve (after Fenton and Keller, 2001)

Fenton and Keller (2001) investigated the problem of hysteresis in the stage-discharge relationship. To correct the systematic error introduced through the assumption of a singular relationship, they recommended the use of a modified Jones formula for development of a suitable relationship for transformation of the recorded stage to discharge.

The deviation of the loop from the singular relationship is not a function only of the gauging station characteristics. The flood wave characteristics also influence the magnitude of the loop with the more dynamic flood waves demonstrating the greatest loops. Nonetheless, consideration of the examples presented by Fenton and Keller (2001) suggest ±10% variations could occur due to the presence of hysteresis.

3.4. Unsteady Flow Errors

In addition to the hysteresis effect, unsteady flows introduce an additional problem during a gauging. This problem is the definition of the stage at which the discharge measurement has been made; as the stage varies during the time taken to obtain the discharge estimate, it is likely that the stage at the start of the measurement will differ from that at the end of the measurement. While it is common to assume a linear variation in stage with time, this assumption needs to be validated for each gauging event and particularly for those gaugings at the peak of a flood event. Tilley et al. (1999) present a methodology to minimise the systematic error associated with temporally variations during gauging events.

4. GAUGED DATA AND FLOOD FREQUENCY ANALYSIS

Flood frequency analysis refers to procedures that use recorded and related flood data to select and fit a probability model of flood peaks at a particular location in the catchment. For valid frequency analysis, the data used should constitute a random sample of independent values, ideally from a homogeneous population. Streamflow data are collected usually as a continuous record with discrete values extracted from this record as the events to be analysed.

The most common method of selecting the discrete values from the continuous record is the Annual Maxima Series (AMS); the series comprises the highest instantaneous rate of discharge in each year of record. This was the approach adopted for extraction of the flood flows to be considered in this analysis of gauged flow uncertainty.

Analysis of the extracted flows considered the following attributes:

- Missing data;
- Highest gauged flow;
- Whether the highest gauged flow was an in-bank or an out-of-bank flow;
- Proportion of the AMS above the highest gauged flow; and
- Gauging Ratio for the extrapolated flows (defined by Q/Q_{max} gauged).

To obtain these attributes, the NSW Office of Water database (distributed as PINNEENA) was interrogated. Approximately 1300 gauging station sites were considered. However, a considerable number of these stations had incomplete attribute data (for example, no cross section provided) or inadequate length of record. After filtering the stations, a total of 477 remained.

Station 201001 (Oxley River at Eungella) will be used as an example to illustrate the analysis undertaken. Monitoring of flows occurred at this gauging station from 1957 to 2005; hence, the record length is 47 years. During this period, 19% of the data is missing; reasons for the missing data were not explored although it was noted that the majority of the missing records occurred early in the record. The maximum gauged flow at this gauging station is 246m3/s. This gauging was categorised as being within the channel; in other words, potential changes in the cross section characteristics are not considered when flow on the adjacent floodplains occurs. The Gauging Ratio for the maximum recorded flow is 6.46.

Extraction of the AMS resulted in 38 data points. For the other 9 years, it was not possible to confirm heuristically if the available records contained the maximum flow for that year. Shown in Figure 3 is the resultant AMS. Also shown in that figure is the maximum gauged flow. Finally, as shown in Figure 3, 24 data points in the AMS are above the highest gauged flow; this is 63% of the AMS data.

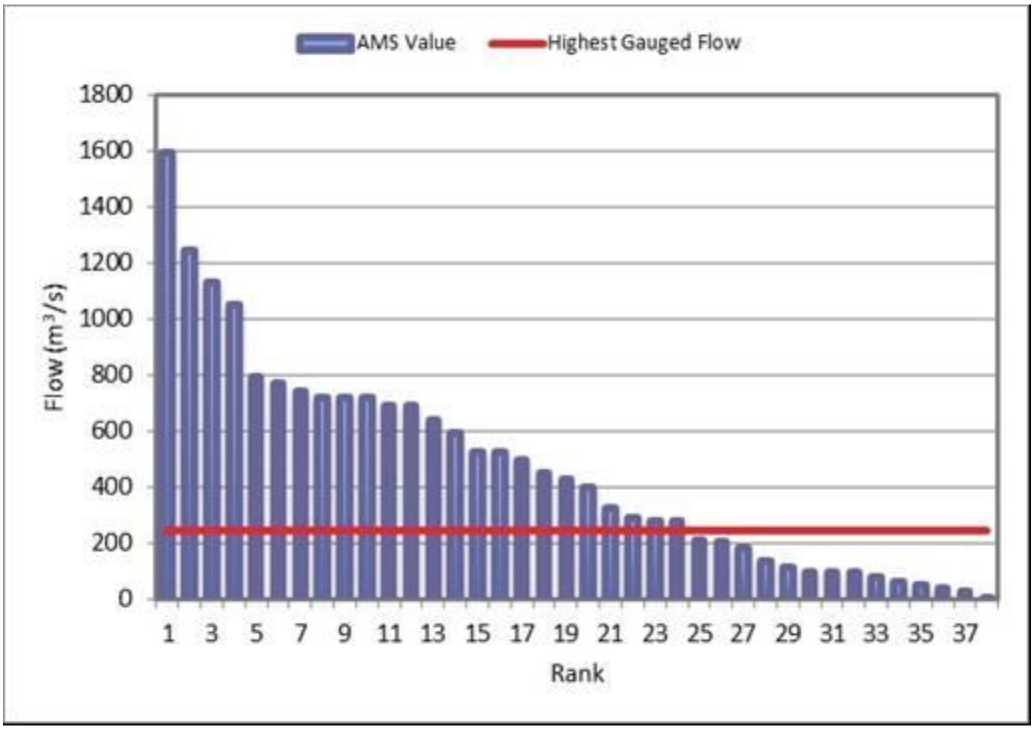

Figure 3 AMS for Gauging Station 201001

Similar data was obtained from each of the gauging stations considered to have suitable data and attribute data. Shown in Figure 4 is the summary of missing data; as shown in that figure, 76% of the stations have less than 25% missing data. In a similar manner, a summary of the gauging ratios is shown in Figure 5. As shown in Figure 5, 16% of the gauging stations had ratios above 10 of the highest recorded flow to the highest gauged flow. It is worth noting that the ratios are indicative only as they are based on the assumption that the extrapolation zone of the stage-discharge curve is accurate. A summary of the location of the highest gauging is provided in Table 1. As shown in that table, 58% of the total number of gauging stations (76% of the gauging stations where the location of the highest gauging was able to be defined) had the highest gauging within the channel. Extrapolation of the stage-discharge relationship above the highest gauging, therefore, should be viewed with care as potential changes in the cross section characteristics may not be reflected in the extrapolation.

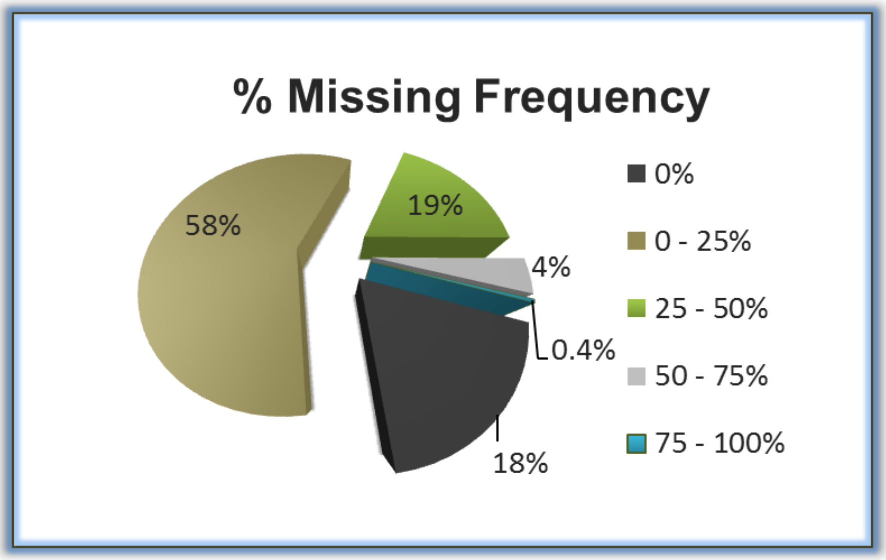

Figure 4 Missing Data Summary

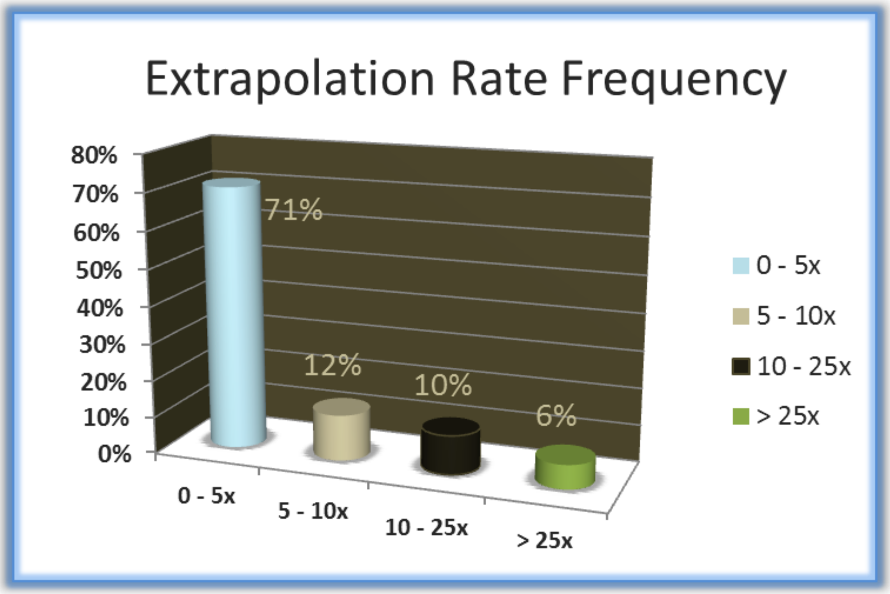

Figure 5 Gauging Ratio Summary

Table 1 Locations of Highest Gauging

Location	Occurrence	Percentage
Channel	279	58%
Overbank	87	18%
Unknown	111	23%

The final statistic computed was the proportion of the AMS within the extrapolation zone of the stage-discharge relationship. As shown in Table 2, 19% of the extracted AMS had more than 50% of the data points in the extrapolation zone of the stage-discharge relationship. This will result in a significant influence on the reliability of the predicted design flows.

Table 2. Proportion of AMS in Extrapolation Zone

Category	Occurrence	Percentage
0 - 25%	287	60%
25 – 50%	100	21%
50 – 75%	68	14%
75 – 100%	22	5%

5. CONCLUSIONS

Design flood estimation remains a problem for many catchment managers. Fundamental to the estimation of design flood magnitudes, is the use of monitored data. This monitored data is obtained from gauging stations. Typically, the data collected at a gauging station comprises the stage which is converted to a discharge using a stage-discharge relationship. Uncertainty in the stage measurement was determined to be of the order of ±20mm arising from local water surface oscillations. Other uncertainties influencing the recording of the stage include potential errors from the use of staff gauges ±5mm, float gauges ±6mm, and pressure transducers up to ±4mm.

One of the larger sources of uncertainty is the stage-discharge relationship itself. There are two zones within a stage-discharge relationship; these zones being an interpolation zone and an extrapolation zone. Within the interpolation zone, it was found that uncertainty of at least 10% could occur due to hysteresis effects during flood events.

Analysing the AMS extracted from records at 477 gauging stations in NSW, it was found that:

- The extrapolation required to convert recorded stages to flows at 16% of the gauging stations exceeded an order of magnitude;
- At 19% of the gauging stations, over 50% of the AMS data points were in the extrapolation zone of the stage-discharge relationship; and
- The extrapolation for out-of-bank flows at 76% of the gauging stations was based on gauging data collected only for channel flows.

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