Papua New Guinea

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FLOOD ESTIMATION MANUAL

August 2018

Acknowledgment to SMEC, CEPA, NWS and Australian Bureau of Meteorology

Flood Estimation Manual Revised and
updated July 2018

Foreword

Department of Works (DoW) is a technical Government Department and is the agency responsible for implementation, approvals and delivery of infrastructure projects, particularly roads, but also other infrastructure throughout Papua New Guinea.

The previous edition of Flood Estimation Manual was published in 1990 and has been widely used throughout the country in the years since publication. This revision has totally reviewed and revised the previous edition and has applied locally collected hydrologic data from gauges throughout Papua New Guinea. When locally collected data has been sparse or lacking, international (mainly Australian) data and procedures have been adjusted for local conditions and applied. The recent publication of "Australian Rainfall and Runoff" (ARR), published by Geoscience Australia has been referenced extensively. ARR has recommended current best practice flood estimation methods for practical application. Since the publication has a Creative Commons copyright, it can be used with attribution, so the Department acknowledges the substantial contribution to this manual from ARR and Geoscience Australia.

The Flood Estimation Manual has been prepared to assist with routine flood estimation problems throughout Papua New Guinea. Routine applications include projects such as road culverts and bridges, design of drainage channels and floodplain planning. Major projects requiring flood estimates such as dam design or mine water management are considered specialist applications that, while many of the data procedures from Flood Estimation Manual can be considered as useful inputs for these will generally require more advanced analysis methods.

Proposed future amendments for consideration on the Flood Estimation Manual should be forwarded to First Assistant Secretary (Design Services Division), Department of Works, P. O. Box 1108, Boroko. National Capital District. Port Moresby. Papua New Guinea.

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List of Symbols and Abbreviations

Symbol / Abbreviation	Description
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
A	Catchment area (km^2 or ha) OR Cross-sectional area (m^2)
ADAM	Australian Data Archive of Meteorology
AEP	Annual Exceedance Probability
ALS	Aerial Laser Survey
AMS	Annual Maxima Series
A_{n2}	Gross water area in the constriction
A_p	Total projected area of the piers
ARF	Areal Reduction Factor
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
AVM	Average Variability Method
BoM	Australian Bureau of Meteorology
C	Expansion and contraction loss coefficient
C_{10}	Runoff coefficient for the 10% AEP event
CCAM	Conformal-Cubic Atmospheric Model
CEPA	Conservation and Environmental Protection Authority
CFD	Computational Fluid Dynamics
CMIP5	Coupled Model Intercomparison Project Phase 5
CSIRO	Commonwealth Scientific and Industrial Research Organisation
C_Y	Runoff coefficient for ARI of Y years
D	Maximum vertical dimension of the culvert
d_{50}	Average rock size
d_{75}	Particle diameter at 75% in the cumulative distribution
d_{84}	Particle diameter at 84% in the cumulative distribution
d_{av}	Weighted mean travel distance for flood flow in the catchment
d_c	Critical depth of flow
DIS	Duration Independent Storm
DoW	Department of Works

Symbol / Abbreviation	Description
DTM	Digital Terrain Model
Δx	Distance between cross sections
EIA	Effective Impervious Area
EY	Number of Exceedances per Year
Fr	Froude Number
FHWA	Federal Highway Administration's Hydraulics Toolbox (U.S. Department of Transportation)
F_y	Frequency Factor
g	Acceleration of gravity (9.8 m^2/s)
GCM	Global Climate Model
GEV	Generalized Extreme Value
GIS	Geospatial Information Systems
h OR hr	Hour
H	Total Head (m)
h_e	Head loss between cross sections
HEC-RAS	Hydrologic Engineering Centre - River Analysis System
IFD	Intensity-Frequency-Duration
IPWEA	Institute of Public Works Engineering Australasia
$I_{tc,Y}$	Rainfall intensity (mm/hour) for rainfall with duration t_c and ARI Y years
J	Blockage area due to piers
k_c	Catchment storage parameter
k_s	Equivalent roughness height
K_x	Values for the Log-Pearson III distribution
L	Design life (years) OR length of mainstream (km) from the outlet to the catchment divide; OR length of protection downstream of culvert outlets
m	Nonlinearity parameter
M	Bridge opening ratio parameter
MIS	Median Intensity Storm
n	Manning's value
n_e	Equivalent Manning's value
NWS	National Weather Service
P or P_w	Wetted perimeter (m)
PMP	Probable Maximum Precipitation

Symbol / Abbreviation	Description
PMF	Probable Maximum Flow
PNG	Papua New Guinea
PNGFEM	Papua New Guinea Flood Estimation Manual
PNGRIS	Papua New Guinea Resource Information System
PNGROI	Papua New Guinea Report on Investigation
PoTS	Peak over Threshold Series
PRT	Parameter Regression Technique
Q_E	Peak Discharge for flood envelop curve (m^3/s)
Q_{PMF}	Flow for a PMF event (m^3/s)
QRT	Quantile Regression Technique
Q_Y	Peak flow rate (m^3/s) for ARI Y years
R or R_h	Hydraulic radius of the cross-section (m)
Re	Reynold Number
RFFA	Regional Flood Frequency Analysis
RORB	RORB Runoff routing model
S	Longitudinal slope of the stream (m/m)
S_e	Equal area slope (m/km)
SD	Standard Deviation
S_f	Friction Slope
SLS	Serviceability Limit State
SPT	Standard Penetration Test
TBRG	Tipping Bucket Rain Gauge
t_c	Time of concentration, the time for flow to travel from the most remote point in the catchment to the outlet.
TMR	Queensland Department of Transport and Main Roads (Australia)
U	Proportion of the catchment that is urbanized OR Urbanisation Index
UD	Urban Disturbed (land with no cover and/or under development)
UF	Urban Forest (land covered by tropical forest)
UH	Urban High density (>50% impervious)
UL	Urban Low density (17% impervious)
ULS	Ultimate Limit State
UM	Urban Medium density (33% impervious)
UR	Urban Rural (rural land in urban area with good cover (default)

Symbol / Abbreviation	Description
USACE	United States Army Corps of Engineers
V	Cross-sectional averaged flow velocity (m/s)
V_x	Velocity in the x-direction
V_y	Velocity in the y-direction
WMO	World Meteorological Organisation
Y	Year
y	Water depth
y_1	Depth of flow in the approach section
y_4	Tailwater depth of flow
Z	Elevation of main channel inverts

Papua New Guinea

Chapter 2
Hydrologic Data

Chapter 2. Hydrologic Data

2.1 Introduction

Data of several different types is essential for all water resources investigations, including the flood studies which are the concern of the FEM. This chapter discusses the categories of hydrologic data required as well as the means of collection and application of the data. ARR 2016 has an overview of the data requirements for flood estimation while Cordery et al (2006) describes the value of hydrologic data for a range of applications.

Standard hydrologic data, includes formal records of rainfall and streamflow data, but this is only a portion of the total range of valuable data that can assist in estimating floods and preparing designs that are suitable for the consideration of flood risk. Alternative data collection programs can supplement the formal data collection systems.

Long records of hydrologic data are important to ensure that reliable statistics can be extracted from the data, to help ensure that extremes, especially of floods are captured and to assess the possibility of trends or other changes on the long-term flood patterns.

Considering the specific concerns for the PNGFEM, inadequate data or the lack of data leads to uncertainty in the results of the analysis and may tend to require additional freeboard allowance for example to compensate for the uncertainty.

While there are available procedures that are regional and can be implemented on ungauged catchments, there is more uncertainty in these applications and therefore an increased risk in the flood estimation application. Practitioners need to utilize as much local information as possible to reduce this risk, even if this is anecdotal and limited.

Stationarity or changes on the magnitude of flood peaks is an important factor in flood assessments and is manifested as a long-term trend or cyclic pattern in flood occurrence. These changes can mean long term changes in flood risk. Many applications of flood data assume that the data is stationary, that is there are no long-term changes. This is a reasonable assumption in many cases, since the period of record is often too short to detect changes in any case. However, if there are non-stationary effects, these may have a noticeable impact on designs that rely on flood analysis.

Non-stationarity in flood records for a particular location can result from one or several different causes. In addition to changes in climate caused by global warming, changes in flood peaks can result from catchment land use changes such as urbanization, changes in water abstraction for irrigation or water supply, construction of dams or floodplain works.

While flood data is often assumed to be stationary, it is important to consider the possibility that there are non-stationary effects, and these should be tested.

2.2 Data Sources and Categories

Data can be sourced from either formal records held by government agencies or from a range of informal and unofficial sources.

In Papua New Guinea, there are two main government agencies that collect data and maintain a data archive as a formal part of their responsibilities. These are the National Weather Service (NWS), that has a responsibility for rainfall and other meteorological data and the Conservation and Environmental Protection Authority (CEPA), which maintains streamflow records as well as some rainfall records. CEPA also archives hydrologic data collected by private organisations such as mining companies, where there is a licence requirement to monitor hydrologic conditions.

In addition to these two government agencies, there are other data sources that may be useful in specific applications. These include:

- private businesses such as mining companies, which may maintain hydrologic monitoring in and around their operations
- other government agencies such as those with responsibility for roads or agriculture
- local councils with an interest on flood damage and planning

- individual residents in rural or urban areas who may have written records, photographs or recollections of flood events.

When a flood investigation is underway, all relevant organisations or individuals that may have useful data should be consulted to obtain information to assist in ensuring that the flood study uses all available information and to ensure that the results are consistent with historical observations.

While much of the data applied in flood studies will be time series of rainfall, flood discharges or water levels, observations or measurements from major historical flood events are extremely valuable. Where major floods have occurred, even if these occurrences were in the distant past, having a good understanding of this history can assist in the effective and reliable flood estimation processes and results.

This historical information is particularly important for most projects and can often provide a significant improvement in the quality of the analysis. While data on historical floods may be difficult to obtain at times, efforts expended in finding and analyzing this data is extremely valuable.

There are three types of historical observational data referred to here. These are:

- Significant events: If a major event occurs, it is important for government agencies to collect as much relevant information as possible soon after the event and publish this, even if only in an internal report. Because major events occur rarely and unexpectedly, it is often difficult to mobilise the resources in time and appropriately. As well it may not always be obvious that this data will be useful, so there may not be an immediate interest in the data collection, so collected data should be cataloged, reported and stored for possible future application.
- Historical events: Where especially significant events have occurred in the past, there are often historical records. These records may be in reports by relevant government agencies, but often there may be useful information in newspaper reports, historical societies or museums, or information can be gathered from long term residents.
- "Routine" flood data: As well as the major events noted above, data on more routine (though still large) events can be sourced from discussions with residents and other stakeholders. This data is usually descriptive, but often actual flood levels can be surveyed based on the data held by residents and flood marks on buildings and elsewhere. This data is especially useful if there has been a major flood in reasonably recent times, and local residents can recall details. Photos or videos can sometimes be obtained as part of these programs.

The accuracy of this type of data may be extremely variable and careful review and checking is essential. Usually this type of data is of variable quality, but with careful collection and checking, is almost always very valuable in implementation of projects.

As well as "numerical data", other less formal data can be collected for historical events. These can include photos or videos taken during the flood or eye witness descriptions and accounts. While this type of information may not be directly applicable for detailed model calibration, it is invaluable in many applications to ensure that the model is representing the general flow conditions and distribution. This type of data is often sourced from local residents during consultation programs.

2.3 Data Management

A key part of the application of data to flood studies is the importance of making the data available to government agencies, private organisations, consultants or individuals who may use the data to assist in the flood investigations.

The components of managing hydrologic data is critical and the following processes are required:

- Collection: In this component the data is sourced, from the official government agencies noted above, other public or private agencies or individuals.
- Editing: An important aspect of data is knowledge of its accuracy (sometimes referred to as its uncertainty) and original source. Prior to insertion into a database, it is necessary to define these parameters. Meta-data and other descriptive information is needed as well as descriptions of the data collection processes and estimated uncertainty.

- Storage: The storage of the data is critical. The data must be stored in an appropriate secure location and in a format where it can be retrieved and applied when required. This storage is likely to be computer based, but this is not essential.
- Analysis: It is possible that some analysis of data may be required. This analysis could include statistical analysis or reviews of rating curves for streamflow data for example, though this analysis should be distinct from the analysis required for the flood study itself.
- Presentation and distribution: The final conceptual component is the presentation or distribution component, where the data is made available to the practitioner who will apply the data to a specific application.

No matter how comprehensive the data collection process may be, the data has limited value unless it can be made available to and used by practitioners who are carrying out flood related projects.

2.4 Hydrologic Data

The data types generally required for flood applications are as follows:

- rainfall
- other precipitation types
- water levels
- streamflow
- catchment data, including topography, survey, digital terrain, land use, soils, geology and planning data
- other hydrologic data, including tidal information, meteorological, sediment movement and deposition and water quality.

2.5 Rainfall Data

2.5.1 Overview

Rainfall is a primary data input for almost all water resources projects, and rainfall data forms the basic input to the development of design rainfall estimates in Chapter 3 of this manual.

The NWS is the primary agency responsible for collection of rainfall data in Papua New Guinea. Daily rainfall data for Papua New Guinea has been archived by the Australian BoM from pre-independence years as well as more recent periods, and additional data is available on international databases such as the World Meteorological Organisation (WMO) from where data can be downloaded.

In many major flood events, it is often valuable to look for unofficial rain gauges where data has been collected by members of the public or local businesses.

The types of rainfall data that may be useful include:

- daily rainfall records
- pluviograph (or sub-daily) records.

2.5.2 Rainfall Observations

The standard instrument for manual measurement of rainfall is the 203 mm rain gauge (see Figure 2.1). In essence, this instrument is a circular funnel, with a diameter of 203 mm and the top located 0.3 m above the ground surface, that collects the rain into a graduated and calibrated cylinder. Any excess precipitation is captured in the outer metal cylinder. Most manually read gauges are used for daily observations.

Daily rainfall is nominally measured each day. Very few stations have a complete unbroken record of rainfall information. Missed observations may be due to observer illness or equipment failure. If, for some reason, an observation is unable to be made, the next observation is recorded as an accumulation, since the rainfall has been accumulating in the rain gauge since the last reading.

Figure 2.1 Standard Rain Gauge (Source: BoM and ARR 2016)

An alternative to the manual measurement is to use a continuous recording rain gauge resulting in either an analogue chart record or a digital record. Older recordings are taken on chart recorders, but the more common form of continuous rain gauges is the Tipping Bucket Rain Gauge (TBRG) (see Figure 2.2). Like the manual rain gauge, the aperture of the funnel for a TBRG is 203 mm.

Figure 2.2 Tipping Bucket Rain Gauge (Source: BoM and ARR 2016)

Advantages of the TBRG include unattended, automatic operation and the ability to record the rate at which the rain is falling. Operation of a TBRG is based on the generation of an electronic pulse when the water volume collected in the bucket results in bucket tipping with varying bucket sizes used in different locations.

2.5.3 Review of Rainfall Data

Quality reviews of rainfall data include:

- values that extend beyond what is considered realistic

- inconsistent observations (for example, high rainfall combined with clear skies)
- discontinuous or abrupt changes in values over a short period of time.

While rainfall data is frequently regarded as reliable and accurate, there are some issues with the accuracy and consistency of rainfall data that should be considered when applying data to practical applications. Issues often encountered are:

- Accumulated records: Rainfall data, especially from daily read gauges may have missing days of record. In some cases, these missing days are simply not recorded while on other occasions, the total for a number of days is accumulated. This occurs since the rainfall is collected in the rain gauge and several days' record are recorded on a single day at the end of the accumulated period. These records need to be reviewed in conjunction with records from neighbouring gauges and adjustments made as necessary. Accumulated records may give an excessively high daily record for the day where the records are accumulated.
- Missing data: In some cases, for both daily read and continuous gauges, there may be missing periods of record. In this case, the record should be reviewed carefully in conjunction with records from neighbouring catchments and appropriate adjustments made.
- Gauge quality: The quality of recordings should be considered. Where records for gauges appear inconsistent with nearby stations, the siting of the gauge needs consideration and it may be necessary to remove the gauge from the analysis.

2.5.4 Rainfall Databases

Rainfall data for daily read gauges and pluviography in Papua New Guinea can be obtained on request from the NWS or the CEPA. Some data can be downloaded from international databases available on-line.

When applying rainfall data to projects, meta-data should be included with the data supplied. This meta-data should include:

- rainfall station name and number
- rainfall station location in latitude and longitude
- rainfall station elevation
- details of the current instrumentation.

Other useful meta-data includes:

- maps showing location of rainfall station
- schematic of rainfall station layout
- photos of rainfall station
- photos for each of the four main compass points showing siting, clearance and proximity to trees, buildings and other factors likely to influence measurement of rainfall
- history of instrumentation installed at site
- record of dates of site visits, maintenance undertaken, problems identified and resolution adopted.

2.5.5 Application of Rainfall Data for Flood Estimation

Rainfall data is a critical input to the development of the PNGFEM and is also essential in many flood applications, with two principle applications:

- Extensive statistical analysis of rainfall data has been carried out to prepare the Intensity Frequency Duration (IFD) input applied to many assessments as described in the manual.
- Rainfall data is applied for analysis of historical events for flood analysis, and in this application, recorded rainfall data is required for these historical events.

2.6 Other Precipitation Types

Other sources of precipitation include snow, hail or dew. These are usually a relatively minor component of the water balance in Papua New Guinea, but there are some locations and occasions where this data may be of interest or value for particular projects.

Because of the relatively minor contribution to flood issues in PNG, there is no comment on these precipitation types here, but for unusual situations where this may be needed, specialist advice is required.

2.7 Water Levels

2.7.1 Overview

Water level data is a critically important type of data required for flood estimation and is used for calibration of hydraulic models as well as to calculate streamflow data.

Formal stream gauging stations (discussed further below) record water level data, which are then used to calculate stream discharge by the application of a rating curve, which is a stage-discharge relationship.

While many stream gauging stations convert water levels into discharges, there are some stations where the discharge is not calculated, especially where determination of a rating curve is difficult.

Water level data may be in the form of continuous records monitored by an automatic recorder or as manually read records. Because of the rapid response of many streams, the manually read records may not provide the peak levels and may even totally miss short duration flood events.

Manually read records are usually a better representation of flow for large slowly responding streams and this data can be used with confidence, but smaller catchments may be significantly in error. Manually read records frequently show smaller flood peaks and lower discharges than automatic recorders. Data from manually read stations may be the only available record and must be used, but careful consideration is needed to make sure the records are interpreted correctly.

In addition to the formal water level records, informal records can also be obtained usually following a major flood event. These records can be obtained from one of several possible stakeholders who survey flood marks to indicate the maximum water levels reached. This data provides an indication of the variation of water levels across the floodplain and an indication of the flow patterns. The quality of this data may sometimes be questionable, and the records need to be carefully checked. These checks can include checking for consistency and reasonableness as well as a review of the reliability of the agency or person who has collected the data. When this type of data is collected, it is important that the records include careful descriptions of the circumstances of the collection and an indication of the expected accuracy.

Common concerns with this data is the level of observed debris marks, whether the water levels have been collected at the peak level of the flood and the source of the water level, either local drainage or backwater for example. Therefore, while very useful data can be obtained, it must be carefully reviewed otherwise the data may lead to incorrect conclusions in the resulting analysis.

However, water levels are often only used as the source of streamflow or discharge data, as discussed below, and while water levels are useful in many applications, streamflow data is usually of far greater value for many water resources studies.

2.7.2 Historical Flood Level Data

Continuous Water Level Recorders

Continuous water level recorders measure water levels at nominated intervals and, where a rating curve (stage-discharge relationship) exists, these can be converted to discharge. Flow is derived from stage using a stage-discharge relationship and it is critical that the maximum gauged flow is known so that the extent of extrapolation underlying the ‘recorded’ flow is clear. These records are very important as, if intact, they will show the complete hydrograph (i.e. the rise, peak and fall of the flood). It is important to confirm the datum for these records. In the case of large events, these recorders can fail and the data needs to be inspected for 'flat' areas, which may indicate failure of the gauge or they may rise steeply in case of occurrence of a landslip. Typically, each stage record has an accuracy code assigned and these should be noted before use.

Maximum Height Gauges

Maximum height gauges simply record the peak flood level reached during a particular event. Failure of these gauges is difficult to detect as they are simply recording the peak level, and if the gauge fails before the peak of an event, it may still provide a 'peak level' value, which will refer the flood level reached prior to the peak at the time of gauge failure.

Peak Level Records

If the flood event has been of a significant nature, it is likely that stakeholders or residents have been able to collect some actual flood levels at a variety of locations. Residents often also record peak flood levels, particularly if the flood has inundated any buildings on their property. Post event flood levels can be collected from residents by a questionnaire and survey of reliable marks. An assessment as to the reliability of these levels can be made after viewing the marks themselves and noting the care with which the recording has been made and comparing the consistency of the recording with other nearby measurements.

Some points to be considered are as follows:

- Have different event dates been recorded by the resident or is the resident relying on memory to determine one event from another?
- Has the location of the marks changed in any way since the record was made? For example, if the marks are made near the front door, has the house been raised at any time since?
- Detailed discussions with the resident can often unearth important details otherwise unknown.

Debris Marks

Debris marks are a typical means of measuring the maximum flood level and are best observed and measured as soon as possible after the event, when the debris or scum line is still fresh. This ensures that the mark is attributable to the event of interest and has not been subsequently degraded.

Debris marks can be inaccurate for a number of reasons. They can be influenced by dynamic hydraulic effects such as waves, eddies, pressure surges, bores or transient effects, which may not be accounted for in a hydraulic model. For example, if the debris mark is located within a region of fast flowing floodwater it is possible that the floodwater has pushed the debris up against an obstacle, lodging it at a higher level than the surrounding flood level. More common though is the fact that debris often lodges at a level lower than the peak flood level. The reason for this is that for debris to be deposited it needs to have somewhere to lodge and this elevation is not always at the peak flood level.

Anecdotal Information

Anecdotal information is usually qualitative in nature but can be very valuable in determining flow behaviour and subsequently verifying that the flood analysis represents these observations in the hydraulic modelling undertaken. Photograph and video evidence can also be beneficial in this regard and can often assist long-term residents in recalling details of historical floods long past. The flood modeller will need to be mindful of the fact that memories can sometimes fade or be skewed by other events that have occurred particularly when several floods occur close together. In addition, information providers may not be able to provide unbiased information due to a vested interest (e.g. pride or financial gain etc.) in the level to which an historic event reached. Again, detailed discussions with residents and stakeholders can provide the modeller with a general feel for the reliability of all anecdotal evidence. Inconsistent facts must be identified and discarded and discrepancies have to be studied and explained.

Application of Water Level Data in Analysis

The principle application of observed water level data in flood projects is in the calibration of hydraulic models and to ensure that the models represent reality.

2.8 Streamflow Data

2.8.1 Overview

Streamflow data is one of the most important data requirements for individual projects and for development of regional procedures. As noted above, streamflow data is calculated from records of water levels, usually collected by major water authorities. The water levels are used to calculate streamflow data by the application of a stage-discharge relationship (rating curve) developed for the station. Continuous records of streamflow can be calculated from the continuous records of water levels. The stage-discharge relationship is often uncertain and application is one of the major sources of uncertainly in the data.

Streamflow data has been applied extensively in the preparation of this manual for the development of the regional flood estimation procedures.

Streamflow data can be obtained on request from the CEPA. In addition to CEPA, some mining companies and other major businesses also collect localised streamflow data and this may be obtained from these organisations or their consultants.

The accuracy and reliability of streamflow data must be checked as part of the application of the data to flood investigations. There are many checks needed when analysing streamflow data. The principle check is on the accuracy and completeness of the stage-discharge relationship. This can be checked by assessment of the number of discharge measurements that have been taken and the maximum discharge (as compared to the maximum recorded water level). As well the variability in the stage-discharge curve indicates that the relationship has changed over time and therefore may be less reliable for particular events. The stage-discharge relationship may be poor for the lower flows because of regular changes in low flow controls. As well it may also be poor at higher flows because of the lack of discharge measurements at higher flows. There are difficulties in extrapolation of the relationships, where there is a change in conditions, for example where the river overtops the banks.

Different gauges in the same catchment can be compared to test for consistency by analysing the water balance between gauges. As well there is a range of other checks that can be carried out. Having more than one gauge in a catchment though is not particularly common.

Poor quality streamflow data may mean poor quality model calibration, so a high standard for checks of data is important. However, it is noted that in many situations it is very difficult to check the accuracy of the discharge records for a station, and poor-quality data may be accepted.

2.8.2 General Stream Gauging Procedures

Gauging stations are installed where the need for streamflow records at a site has been recognised. A gauging station will comprise of instruments for measuring the river stage. The gauging station location should be selected to take advantage of the best locally available conditions for measuring levels and to allow discharge measurement to develop a stable stage-discharge relationship. While there are instruments that simultaneously monitor river stage and discharge, the more common instrumentation requires the use of a stage-discharge relationship to convert the monitored river stage into an equivalent river discharge rate. Artificial controls such as low weirs or flumes are constructed at some stations to stabilise the stage-discharge relationships in the low discharge range. These control structures are calibrated either theoretically or by stage and discharge measurements in the field.

Selection of the gauging station site and the development of the stage-discharge relationship are important components in the management of a gauging station and hence the discussion herein will focus on these aspects of management of a gauging station. While there are many other aspects important in management of a gauging station, these two aspects have the most significant impact on prediction of design flood characteristics.

2.8.3 Data Collected at a Gauging Station

There are many different approaches to collection of data at a stream gauging station and flood investigations are not necessarily the principle objective of any particular gauging station, which may be used for water resources assessment or river management for example. The purpose of a gauging station is to collect data about the time history of discharge at that point in the catchment drainage network. In general, the data collected consists of the gauge heights or the river stage. These gauge heights are used in a stage-discharge relationship to estimate the discharge at that point in time. Reliability of the discharge record is dependent on the accuracy and precision of the gauge-height record as well as the accuracy and precision of the stage-discharge relationship.

New technology, especially in the field of electronics and computer based management of field data, has led to innovations in sensing, recording and transmitting gauge height data. Gauging stations can use floats in stilling wells as the primary method of sensing gauge height or submersible or non-submersible pressure transducers which do not require a stilling well.

2.8.4 Stage-Discharge Relationships

The conversion of a record of gauge-height to a record of discharge is through use of a stage-discharge relationship. The physical element or combination of elements in the stream channel or floodplain that maintains the relation is known as a control and the gauging station location should be selected where there is a single relationship between water level and flow. The two attributes of a satisfactory control are stability and sensitivity. If the control is stable the stage-discharge relationship will be stable. If the control is subject to change, the stage-discharge relationship will be subject to change and frequent discharge measurements will be required for the continual re-calibration of the stage-discharge relationship, which increases the uncertainty of streamflow records extracted from the database.

The traditional way in which a stage-discharge relationship is derived for a particular gauging station is the measurement of discharge at convenient times. Traditionally, this measurement is undertaken with a current meter measuring the discharge velocity at enough points over the river cross-section so that the discharge rate can be obtained for that individual stage. By taking such measurements for a number of different stages and corresponding discharges over a period of time, a number of points can be plotted on a stage-discharge diagram, and a curve drawn through those points, giving what is hoped to be a unique relationship between stage and discharge, the stage-discharge relationship.

There are several factors which might cause the rating curve not to give the actual discharge, some of which will vary with time. Some factors affecting the rating curve include:

- the channel and hydraulic control changing because of modification due to dredging, bridge construction, or vegetation growth
- sediment transport - where the bed is in motion, which can have an effect over a single flood event, because the effective bed roughness can change during the event
- backwater effects - changes in the conditions downstream such as the construction of a dam or flooding in a tributary waterway downstream
- unsteadiness - in general the discharge will change rapidly during a flood, and the slope of the water surface will be different from that for a constant stage, depending on whether the discharge is increasing or decreasing
- variable channel storage - where the stream overflows onto floodplains during high discharges, giving rise to different slopes and to unsteadiness effects
- vegetation - changing the roughness and hence changing the stage-discharge relationship.

In addition to these generic problems associated with the use of rating curves, there are several problems associated with the use of rating curves for prediction of a design flood characteristic. These include the following:

- The assumption of a unique relationship between stage and discharge, in general, is not totally correct, though it is a reasonable approximation.
- Discharge is rarely measured during a flood, and the quality of data at the high discharge end of the curve typically is quite poor because there are usually few velocity measurements at high flow. As a result, estimation of the peak discharge of a flood event usually involves extrapolation of the stage-discharge relationship beyond the recorded data points.
- The relationship is usually a line of best fit through the data points defining the stage-discharge relationship.
- It should describe a range of variation from no discharge through small but typical discharges to very large extreme flood events.

As highlighted in the previous discussion, the unsteadiness of the discharge during a flood event (i.e. the variation of discharge with time) and its influence on a discharge estimate is ignored in the traditional application of a rating curve. In a flood event, the slope of the water surface for a given stage will be different from that for the same stage during steady flow conditions; this difference will depend on whether the discharge is increasing or decreasing. As the flood increases, the surface slope in the river is greater than the slope for steady flow at the same stage, and hence, according to conventional hydraulic theory more water is flowing down the river than the rating curve would suggest. When the water level is falling, the slope and, hence, the discharge inferred is less. The effects might be important - the peak discharge could be significantly underestimated during highly dynamic floods, and since the maximum discharge and maximum stage do not coincide, the arrival time of the peak discharge could be in error and may influence flood warning predictions. Finally, the use of a discharge hydrograph derived inaccurately by using a single-valued rating relationship may distort estimates for resistance coefficients during calibration of an unsteady flow model.

2.8.5 Extrapolation of Stage-Discharge Relationships

The stage-discharge relationship can be considered to consist of two zones. These zones are:

- An interpolation zone where the relationship is within the range of the stage measurements used to develop the relationship.
- An extrapolation zone where the relationship is not defined by gauging taken to develop the relationship.

It is rare to obtain a flow velocity measurement at high discharges since access is often difficult during flood periods. As well it is often difficult to reach the gauging station before the flood level has begun to decline or the flood has completely finished since this may require the anticipation of a flood event so that staff can be on site during the flood.

While it is preferable that all stage measurements are within the interpolation zone, the nature of the data needed for design flood estimation and for flood prediction in general, the reliability of data from measurements within the extrapolation zone will require consideration of the extrapolation methodology. Extrapolation is needed where the rating ratio (the rating ratio is the ratio of the recorded discharge to the highest gauging used to develop the stage-discharge relationship) is larger than 1, which will be the case for most of the larger floods recorded.

There are several alternative techniques for development of the extrapolation zone of the stage-discharge relationship, with a logarithmic extrapolation being often recommended. This approach however may not be applicable because in many cases, the extrapolation may extend from a confined channel into a floodplain.

An alternative approach is the use of a hydraulic model to develop the extrapolation zone of the stage-discharge relationship. Similar to the application of a logarithmic technique, the suitability of this approach needs to be confirmed prior to its application. Of particular concern is the modelling of the energy losses associated with flow in the channel and adjacent floodplains where it is necessary to assume that the parameter values obtained during calibration are suitable for the larger discharges being simulated in the extrapolation zone of the stage-discharge relationship.

The important point in this discussion, however, is a recognition that the values of the data extracted from a discharge record for fitting of a statistical model will contain values where the conversion of the recorded level to an equivalent discharge occurred through extrapolation of the stage-discharge relationship.

2.9 Catchment Data

2.9.1 General

Catchment data is an essential component for estimation of design flood characteristics and there are various types of catchment data required. Furthermore, data is available from different sources and with a range of accuracies. Generally, it is advisable that practitioners seek the most suitable data in each instance and assess the required accuracy of that data in respect of the desired accuracy of the outputs.

There are many alternative types and forms of catchment data relevant to estimation of design flood characteristics, such as:

- topographic and infrastructure data including culverts, bridges, and pipe networks
- land use information
- vegetation data
- soil data.

2.9.2 Topographic and Infrastructure Data

Topographic data is an important component of any design flood investigation. Proper scoping of topographic and infrastructure data collection can have a significant impact on the cost-effective delivery of flood investigations. The scope of the required topographic and infrastructure data is driven by the nature of flood behaviour for a given area. The desired elements of topographic and infrastructure data include:

- catchment extent
- catchment slope
- drainage topology (i.e. the drainage flow paths and network of channels)
- channel cross-sections
- waterway structures (weirs, levees, regulators, dams, culverts and bridges etc.)
- overland flow path definition
- infrastructure (bridges, culverts, pits, pipes etc.).

Topographic data can be obtained by using one or more of the following approaches.

- field survey
- airborne techniques
- available spatial mapping.

2.9.3 Bathymetric (Underwater) Techniques

Many methods for generating surface data are not applicable for collecting bathymetric data (ground data below the water surface) in permanent or semi-permanent water bodies. Where a water body has not been surveyed adequately, a specific survey will be required to supplement the ground surface data.

If the water body is shallow or small, then a traditional surface survey technique may be suitable. For deeper, larger water bodies, a specialised bathymetric survey may be required. Instruments such as echo sounders, side scan sonar systems and Acoustic Doppler Profilers may be used for this purpose.

In most cases, the bathymetric survey will need to be merged with ground surface data.

2.9.4 Aerial Photographs

Aerial photographs are an important source of qualitative data and can be collected during an aerial survey and geo-referenced (or ortho-rectified) aerial photos can be supplied as part of a photogrammetric survey. In ortho-rectifying the image, the image is scaled, rotated and stretched so that various reference locations move to their correct coordinate locations in order to remove any distortions as a result of the image collection process.

When historical aerial photography is available, it is useful in assessing catchment development or sourcing information on the floodplain development when historical events occurred.

2.9.5 Historical Topography and Infrastructure

Most data collection methods are concerned with present day catchment conditions. However, when catchment modelling systems are used for design flood estimation, calibration to historical events is required and the catchment and floodplain conditions at the time of the historical event need to be considered particularly as these conditions may not be the same as present day conditions. In addition, if several historical events are to be used for calibration, changes to catchment conditions may occur between events.

2.9.6 Land Use Information

Land use data is important for several aspects of projects, and can be obtained from land use maps, field observations or consultation with local authorities, land managers or property owners.

Land use data is used in hydrology models to determine suitable parameters to calculate runoff and is also used in hydraulic models to assist in the determination of channel and floodplain roughness.

2.9.7 Vegetation Data

Information on vegetation type can be used in the hydrologic model to determine runoff characteristics or in hydraulic models to inform hydraulic roughness values (Manning's n). This data may be sourced from:

- vegetation maps
- field inspections
- inferred from aerial photographs.

Care needs to be taken with vegetation maps as, in general, the maps are based on limited sampling and inferring the survey results to be the representative of a larger area. Additionally, the representation of individual species within an area designated as vegetation types may vary.

2.9.8 Soil Data

Some hydrologic models require information on the catchment soil properties (for example, information on the A and B horizon depths and their water holding capacity, or the soil type) to estimate losses from the rainfall.

While it is possible to estimate land subject to inundation by floods through consideration of the soils and geomorphology, this does not provide any guidance on the likelihood of the flood hazard and therefore can be misleading. Furthermore, there is a need to ensure that the soil and geomorphic data is obtained at a fine scale to ensure spatial variations over short distances are adequately recognised when using soil information to assess potential flood hazard.

2.9.9 Property Data

In order to assess the magnitude of the flood hazard to people and property, property data (including building type, condition and floor level) typically are required, including:

- street address
- representative ground level
- habitable floor levels
- building construction type (e.g. brick veneer, timber, slab on ground, on piers)
- building age
- single/double storey
- house size.

Commercial and industrial properties require similar information, but also require information on the type of business undertaken at the site as this can have a significant bearing on the value of flood damages from business to business.

2.10 Other Hydrological Data

- Tidal data: In many coastal areas, ocean and tidal data can be an important component of the design flood estimation process. Tidal data may be collected by manual observations or by automatic recorders and needs to include astronomical tides as well as storm surge and long-term trends in sea levels. In some circumstances, wave data may also be relevant, particularly when associated with storm surge.

- Meteorological data: As well as rainfall and other precipitation, other meteorological data is used in water resources studies. This data is used to assess soil moisture and evapotranspiration for example. Relevant climate data includes pan evaporation, temperature, humidity, wind speed and other parameters.
- Sediment movement and deposition: Sediment movement, including scour and deposition, is one of the most important water quality impacts of drainage systems. Both natural and man-made waterways can cause environmental problems in downstream receiving waters as well as damage and disruption to drainage systems. Data collection on sediment movement is particularly difficult and there is only limited available data. Therefore, application of sediment movement and deposition data is difficult and needs considerable skill to interpret and apply. Where this is an important aspect of a project, efforts should be exerted to find and use the data.
- Water quality: As well as sediment, there are many other water quality parameters that are relevant to water resources and drainage programmes. The water quality parameters that can be monitored cover a wide range from the relatively routine such as nutrients and salinity to quite specialised contaminants.

2.11 Acknowledgements

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2.12 References

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) (2016) Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia). http://arr.ga.gov.au/arr-guideline.

Ball J, Weeks W, Smith G, Ling F, Retallick M and Green J, (2016) 2016 Data, Book 1, Chapter 4 in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia.

Cordery, I., Weeks, B., Loy, A., Daniell, T., Knee, R., Minchin, S. and Wilson, D, (2006), 'Water Resources Data Collection and Water Accounting', Australian Journal of Water Resources, Vol 11, No 2, pp.257 - 266.