HP II

Indian Hydrology Project

Technical Assistance (Implementation Support) and Management Consultancy

---

Surface Water Handbook:

Water Level, Stage-Discharge and Flow

May 2014

Surface Water Handbook: Water Level, Stage-Discharge and Flow

Issue and Revision Record

Revision	Date	Originator	Checker	Approver	Description
0	21/05/14	Helen Houghton-Carr			Version for approval
1					
2					
3					

Contents

Contents i
Glossary iv

1. Introduction 1
1.1 HIS Manual 2
1.2 Other HPI documentation 3

2. The Data Management Lifecycle in HPII 5
2.1 Use of hydrological information in policy and decision-making 5
2.2 Hydrological monitoring network design and development 6
2.3 Data sensing and recording 6
2.4 Data validation and archival storage 6
2.5 Data synthesis and analysis 7
2.6 Data dissemination and publication 8
2.7 Real-time data 9

3. Surface Water Monitoring Stations and Data 10
3.1 Types of surface water quantity monitoring station 10
3.2 Surface water monitoring networks 13
3.3 Site inspections, audits and maintenance 14
3.4 Data sensing and recording 15
3.5 Data processing 17

4. Water Level Data Processing and Analysis 19
4.1 Data entry 19
4.2 Primary validation 21
4.3 Secondary validation 24
4.4 Correction and completion 27

5. Stage-Discharge Data Processing and Analysis 30
5.1 Data entry 30
5.2 Primary validation 33
5.3 Fitting rating curves 35

6. Flow Data Processing and Analysis 41
6.1 Data computation 41
6.2 Secondary validation 41
6.3 Correction and completion 46
6.4 Compilation 49
6.5 Analysis 50

7. Data Dissemination and Publication 56
7.1 Hydrological products 56
7.2 Annual reports 56
7.3 Periodic reports 59
7.4 Special reports 59
7.5 Dissemination to hydrological data users 60

References 61

Annex I States and agencies participating in the Hydrology Project 62

Annex II **Summary of distribution of hard copy of HPI HIS Manual Surface Water** **63**

Annex III **How to specify an ADCP system** **64**
III.1 Components of an ADCP system 64
III.2 ADCP manufacturers 64
III.3 Training 64
III.4 Where to go to for support 65

Annex IV **How to measure river discharge using an ADCP** **66**
IV.1 Selecting a site and a deployment method 66
IV.2 Preparation 66
IV.3 Pre-gauging procedures 67
IV.4 Gauging procedures 68
IV.5 Post-gauging procedures 69
IV.6 Where to go to for support 69

Annex V **How to process and validate ADCP river discharge measurements** **70**
V.1 Inspecting general data 70
V.2 Inspecting transect data 71
V.3 Discharge calculation 72
V.4 Final checks 72
V.5 Where to go to for support 73

List of figures

1.1 Hydrometric information lifecycle 1
4.1 Example water level relation curve 27
5.1 Example of stage-discharge relationship or rating curve 36
5.2 Form of single power law rating curve 37
6.1 Definition sketch for double mass analysis 44
6.2 Generalised form of relationship between annual rainfall and runoff 46
6.3 Flow duration curve on a log-probability scale 52
6.4 Example of moving average of annual runoff 53
6.5 Example of residual mass analysis for reservoir design 54
6.6 Definition sketch of the threshold level approach for run-rum analysis 55
7.1 Report for stage-discharge data 58

List of tables

1.1 HPI surface water training modules 4
1.2 HPI surface water “training of trainers” modules 4
2.1 Surface water data processing timetable for data for month n 8
3.1 Where to go in the HIS Manual SW for surface water data management guidance: water level 11

3.1 cont/ Where to go in the HIS Manual SW for surface water data management guidance: stage-discharge and flow 12
3.2 Recommended observation frequency for water level measurement 16
4.1 Measurement errors for water level data 22
III.1 Main features of Sontek and Teledyne RDI ADCPs 65

Glossary

ADCP	Acoustic Doppler Current Profiler
ARG	Autographic Rain Gauge
AWS	Automatic Weather Station
BBMB	Bhakra-Beas Management Board
CGWB	Central Ground Water Board
CPCB	Central Pollution Control Board
CWC	Central Water Commission
CWPRS	Central Water and Power Research Station
Div	Division
DPC	Data Processing Centre
DSC	Data Storage Centre
DWLR	Digital Water Level Recorder
e-GEMS	Web-based Groundwater Estimation and Management System (HPII)
eHYMOS	Web-based Hydrological Modelling System (HPII)
eSWDES	Web-based Surface Water Date Entry System in e-SWIS (HPII)
e-SWIS	Web-based Surface Water Information System (HPII)
FCS	Full Climate Station
GEMS	Groundwater Estimation and Management System (HPI)
GW	Groundwater
GWDES	Ground Water Data Entry System (HPI)
GWIS	Groundwater Information System (GPI)
HDUG	Hydrological Data User Group
HIS	Hydrological Information System
HP	Hydrology project (HPI Phase I, HPII Phase II)
HYMOS	Hydrological Modelling System (HPI)
IMD	India Meteorological Department
Lab	Laboratory
MoWR	Ministry of Water Resources
NIH	National Institute of Hydrology
SRG	Standard Rain Gauge
Stat	Station
Sub-Div	Sub-Division
SW	Surface Water
SWDES	Surface Water Data Entry System (HPI)
TBR	Tipping Bucket Raingauge
ToR	Terms of Reference
WISDOM	Water Information System Data Online Management (HPI)
WQ	Water Quality

1. Introduction

This Hydrology Project Phase II (HPII) Handbook provides guidance for the management of surface water data on water levels in rivers and in dams/lakes/reservoirs, and associated river flow. The data are managed within a Hydrological Information System (HIS) that provides information on the spatial and temporal characteristics of the quantity and quality of surface water and groundwater. The information is tuned to the requirements of the policy makers, designers and researchers to provide evidence to inform decisions on long-term planning, design and management of water resources and water use systems, and for related research activities. The Indian States and Central Agencies participating in the Hydrology Project are listed in Annex I. However, this Handbook is also relevant to non-HP States.

It is important to recognise that there are two separate issues involved in managing surface water information. The first issue covers the general principles of understanding monitoring networks, of collecting, validating and archiving data, and of analysing, disseminating and publishing data. The second covers how to actually do these activities using the database systems and software available. Whilst these two issues are undeniably linked, it is the first – the general principles of data management - that is the primary concern. This is because improved data management practices will serve to raise the profile of Central/State hydrometric agencies in government and in the user community, highlight the importance of surface water data for the design of water-related schemes and for water resource planning and management, and motivate staff, both those collecting the data and those in data centres.

This Handbook aims to help HIS users locate and understand documents relevant to surface water in the library available through the Manuals page on the Hydrology Project website. The Handbook is a companion to the HIS Manuals. The Handbook makes reference to the six stages in the hydrometric information lifecycle (Figure 1.1), in which the different processes of data sensing, manipulation and use are stages in the development and flow of information. The cycle and associated HIS protocols are explored more fully in Section 2. Subsequent sections cover different stages of the cycle for different surface water variables.

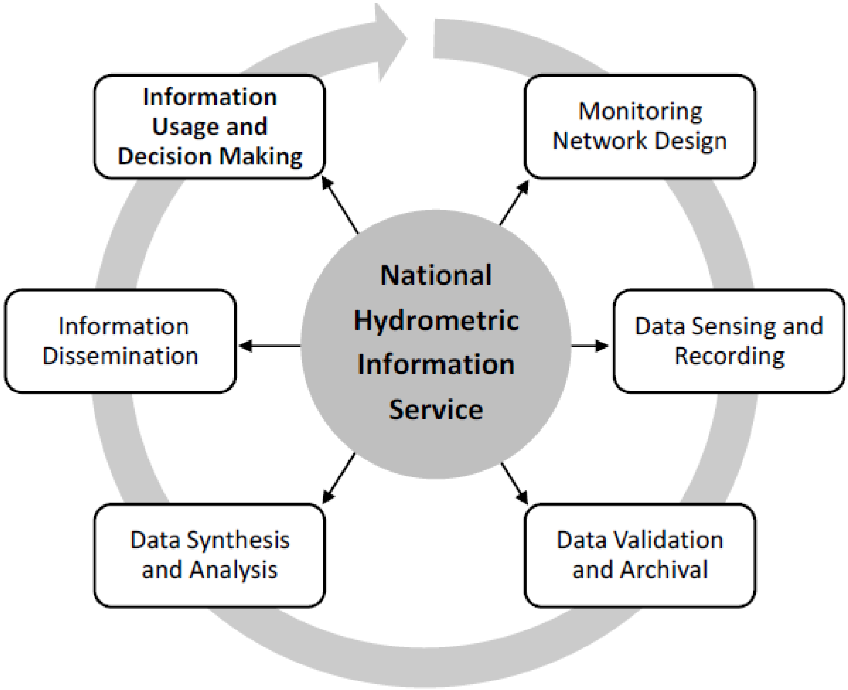


Figure 1.1 Hydrometric information lifecycle (after: Marsh, 2002)

1.1 HIS Manual

The primary reference source is the HIS Manual Surface Water (SW), one of many hundreds of documents generated during Hydrology Project Phase I (HPI) to assist staff working in observation networks, laboratories, data processing centres and data communication systems to collect, store, process and disseminate hydrometric data and related information. During HPI, special attention was paid to the standardisation of procedures for the observation of variables and the validation of information, so that it was of acceptable quality and compatible between different agencies and States, and to facilities for the proper storage, archival and dissemination of data for the system, so that it was sustainable in the long-term. Therefore, the majority of the documents produced under HPI, particularly those relating to fundamental principles, remain valid through and beyond HPII. Some parts of the guides, manuals and training material relating to HPI software systems (SWDES, HYMOS, WISDOM, GWDES, GEMS, GWIS) have been partially or wholly superseded as replacement Phase II systems (e-GEMS, e-SWIS) become active.

The HIS Manual SW describes the procedures to be used to arrive at a sound operation of the HIS in regard to surface water quantity data. The HIS Manual SW consists of 10 volumes. Each volume contains one or more of the following manuals, depending on the topic:

- Design Manual (DM) - procedures for the design activities to be carried out for the implementation and further development of the HIS.

- Field Manual (FM) or Operation Manual (OM) – detailed instructions describing the activities to be carried out in the field (station operation, maintenance and calibration), at the laboratory (analysis), and at the Data Processing Centres (data entry, validation, processing, dissemination, etc). Each Field/Operation Manual is divided into a number of parts, where each part describes a distinct activity at a particular field station, laboratory or data processing centre.

- Reference Manual (RM) - additional or background information on topics dealt with or deliberately omitted in the Design, Field and Operation Manuals.

Those HIS Manual SW volumes relevant to water level and flow are:

SW Volume 1: Hydrological Information System: a general introduction to the HIS, its structure, HIS job descriptions, Hydrological Data User Group (HDUG) organisation and user data needs assessment.

- Design Manual
- Field Manual
    - Part II: Terms of Reference for HDUG
    - Part III: Data needs assessment

SW Volume 2: Sampling Principles: units, principles of sampling in time and space and sampling error theory.

- Design Manual

SW Volume 4: Hydrometry: network design, implementation, operation and maintenance.

- Design Manual
- Field Manual
    - Part I: Network design and site selection
    - Part II: River stage observation
    - Part III: Float measurements
    - Part IV: Current meter gauging
    - Part V: Field application of ADCP

    - Part VI: Slope-area method
    - Part VII: Field inspection and audits
    - Part VIII: Maintenance and calibration
- Reference Manual

SW Volume 8: Data processing and analysis: specification of procedures for Data Processing Centres (DPCs).

- Operation Manual
    - Part I: Data entry and primary validation
    - Part II: Secondary validation
    - Part III: Final processing and analysis
    - Part IV: Data management

SW Volume 10: Surface Water protocols: outline of protocols for data collection, entry, validation and processing, communication, inter-agency validation, data storage and dissemination, HIS training and management.

- Operation Manual
    - Data entry forms

In this Handbook, individual parts of the HIS Manual SW are referred to according to the nomenclature “SWvolume-manual(part)” e.g. Volume 4: “Hydrometry” Field Manual Part V: “Field application of ADCP” is referred to as SW4-FM(V), and Volume 8: “Data processing and analysis” Operation Manual Part I: “Data entry and primary processing” is referred to as SW8-OM(I).

A hard copy of the relevant manuals should be available for the locations listed in Annex II. For example, a hard copy of SW4-FM(V) should be carried with all ADCPs and also be available at all hydrometric stations where flow measurements with an ADCP take place. Similarly, SW8-OM(I) should be available at all Data Processing Centres where data entry and primary validation take place.

1.2 Other HPI documentation

Other HPI documents of relevance to surface water include:

- The e-SWIS software manual, and the SWDES and HYMOS software manuals - although SWDES and HYMOS are being superseded by e-SWIS in HPII, to promote continuity, e-SWIS contains eSWDES and eHYMOS modules.

- “Illustrations: hydrological observations” – an illustrative booklet demonstrating how to make measurements of rainfall, water level and flow at stations, and also how to carry out an inspection at those stations.

- “Surface Water O&M norms” – a maintenance guide for hydro-meteorology, stage-discharge and water quality instrumentation and equipment.

- “Surface Water Yearbook” – a template for a Surface Water Yearbook published at State level.

- “Entering SW historical data” – a paper outlining the proposed approach to the entry of historical surface water data.

- Surface water training modules – these relate to the entry, primary and secondary validation, processing, analysis and reporting of water level, stage-discharge and flow data using SWDES

Table 1.1 HPI surface water training modules

Topic	Module	Title
Stage-discharge	21	How to make data entry for water level data
	22	How to carry out primary validation of water level data
	23	How to carry out secondary validation of water level data
	24	How to correct and complete water level data
	25	MISSING – How to analyse water level data
	26	MISSING – How to report on water level data
	27	How to make data entry for flow measurement data
	28	How to carry out primary validation of stage-discharge data
	29	How to establish stage-discharge rating curve
	30	How to validate rating curve
	31	How to extrapolate rating curve
	32	How to carry out secondary validation of stage-discharge data
	33	How to report on stage-discharge data
	34	How to compute discharge data
	35	UPDATED – shifted to module 36
	36	How to carry out secondary validation of discharge data
	37	How to do hydrological data validation using regression
	38	How to do data validation using hydrological models
	39	How to correct and complete discharge data
	40	How to compile discharge data
	41	How to analyse discharge data
	42	How to report on discharge data
	43	Statistical Analysis with Reference to Rainfall & Discharge Data
	44	How to carry out correlation and spectral analysis
	45	How to review Monitoring Networks

Table 1.2 HPI surface water "training of trainers" modules

Topic	Module	Title
Stage-discharge		Demarcation & Establishment of Discharge Sites
		Understanding Stage-Discharge Relations
		How to analyse Stability of Stage-Discharge relations
		Estimation of Discharge by Area-Slope Method
		Introduction to Advanced Discharge Measurement
		Investigation & Selection of Hydrological Observation Station
		Processing of Stream Flow Data

and HYMOS (see Table 1.1). Their contents have been largely incorporated into this Handbook as the underlying principles for data validation and analysis remain valid.

- Surface water "training of trainers" modules, primarily relevant to stage-discharge topics, which may be of interest to the more advanced user (see Table 1.2).

2. The Data Management Lifecycle in HPII

Agencies and staff with responsibilities for hydrometric data have a pivotal role in the development of surface water quantity information, through interacting with data providers, analysts and policy makers, both to maximise the utility of the datasets and to act as key feedback loops between data users and those responsible for data collection. It is important that these agencies and staff understand the key stages in the hydrometric information lifecycle (Figure 1.1), from monitoring network design and data measurement, to information dissemination and reporting. These later stages of information use also provide continuous feedback influencing the overall design and structure of the hydrometric system. While hydrometric systems may vary from country to country with respect to organisation set-ups, observation methods, data management and data dissemination policies, there are also many parallels in all stages of the cycle.

2.1 Use of hydrological information in policy and decision-making

The objectives of water resource development and management in India, based on the National Water Policy and Central/State strategic plans, are: to protect human life and economic functions against flooding; to maintain ecologically-sound water systems; and to support water use functions (e.g. drinking water supply, energy production, fisheries, industrial water supply, irrigation, navigation, recreation, etc). These objectives are linked to the types of data that are needed from the HIS. SW1-DM Chapter 3.3 presents a table showing HIS data requirements for different use functions on page 19. In turn, these use functions lead to policy and decision-making uses of HIS data, such as: water policy, river basin planning, water allocation, conservation, demand management, water pricing, legislation and enforcement.

Hence, freshwater management and policy decisions across almost every sector of social, economic and environmental development are driven by the analysis of hydrometric information. Its wide-ranging utility, coupled with escalating analytical capabilities and information dissemination methods, have seen a rapid growth in the demand for hydrometric data and information over the first decades of the 21st century. Central/State hydrometric agencies and international data sharing initiatives are central to providing access to coherent, high quality hydrometric information to a wide and growing community of data users. Hydrological data users may include water managers or policymakers in Central/State government offices and departments, staff and students in academic and research institutes, NGOs and private sector organisations, and hydrology professionals. An essential feature of the HIS is that its output is demand-driven, that is, its output responds to the hydrological data needs of users.

SW1-FM(III) presents a questionnaire for use when carrying out a data needs assessment to gather information on the profile of data users, their current and proposed use of surface water, groundwater, hydro-meteorology and water quality data, their current data availability and requirements, and their future data requirements. Data users can, through Central/State hydrometric agencies, play a key role in improving hydrometric data, providing feedback highlighting important issues in relation to records, helping establish network requirements and adding to a centralised knowledge base regarding national data. By embracing this feedback from the end-user community, the overall information delivery of a system can be improved.

A key activity within HPII was a move towards greater use of the HIS data assembled under HPI. Two examples of the use of HIS data include the Purpose-Driven Studies (PDS) and the Decision Support Systems (DSS) components of HPII. See the Hydrology Project website for more information about DSS and PDS, and access to PDS reports.

The 38 PDS, which were designed, prepared and implemented by each of the Central/State hydrometric agencies, are small applied research projects to investigate and address a wide range of real-world problems and cover surface water, groundwater, hydro-meteorology and water quality topics. Some examples of projects include optimisation of the river gauging station and raingauge networks in Maharashtra (PDS number SW-MH-1), and a water availability study including supply-demand analysis in Chhattisgarh (PDS number SW-CH-2). The PDS utilise hydrometric data and products developed under HPI, supplemented with new data collected during HPII.

Two separate DSS programmes were set up under HPII. One, for all participating implementing agencies, called DSS Planning (DSS-P), has established water resource allocation models for each State to assist them to manage their surface and groundwater resources more effectively. The other, called DSS Real-Time (DSS-RT) was specifically for the Bhakra-Beas Management Board (BBMB), although a similar DSS-RT study has also now been initiated on the Bhima River in Maharashtra. The DSS programmes have been able to utilise hydrological data assembled under the Hydrology Project to guide operational decisions for water resource management.

2.2 Hydrological monitoring network design and development

Section 3.2 of this Handbook outlines the design and development of surface water monitoring networks. Networks are planned, established, upgraded and evolved to meet a range of needs of data users and objectives, most commonly water resources assessment and hydrological hazard mitigation (e.g. flood forecasting). It is important to ensure that the hydro-meteorological, surface water, groundwater and water quality monitoring networks of different agencies are integrated as far as possible to avoid unnecessary duplication. In particular, a raingauge network should have sufficient spatial coverage that all flow monitoring stations are adequately covered. Integration of networks implies that networks are complimentary and that regular exchange of data takes place to produce high quality validated datasets. Responsibility for maintenance of Central/State hydrometric networks is frequently devolved to a regional (Divisional) or sub-regional (Sub-Divisional) level.

2.3 Data sensing and recording

Sections 3.1 to 3.4 of this Handbook review water level and flow monitoring networks and stations, maintenance requirements and measurement techniques. Responsibility for operation of Central/State water level and flow monitoring stations is frequently devolved to a regional (Divisional) or sub-regional (Sub-Divisional) level. However, it is important that regular liaison is maintained between sub-regions and the Central/State agencies through a combination of field site visits, written guidance, collaborative projects and reporting, in order to ensure consistency in data collection and initial data processing methods across different sub-regions, maintain strong working relationships, provide feedback and influence day-to-day working practice. Hence, the Central/State agencies are constantly required to maintain a balance of knowledge between a broad-scale overview and regional/sub-region surface water quantity awareness. Operational procedures should be developed in line with appropriate national and international (e.g. Indian, ISO, WMO) standards (e.g. WMO Report 168 “Guide to Hydrological Practices”).

For the Hydrology Project, field data from observational stations are required to be received at Sub-Divisional office level by the 5th working day of the following month (SW10-OM Protocols and Procedures).

2.4 Data validation and archival storage

The quality control and long-term archiving of surface water quantity data represent a central function of Central/State hydrometric agencies. This should take a user-focused approach to improving the information content of datasets, placing strong emphasis on maximising the final utility of data e.g. through efforts to improve completeness and fitness-for-purpose of Centrally/State archived data. Section 3.5 of this Handbook summarises the stages in the processing of hydrometric data. Sections 4 to 6 of this Handbook cover the process from data entry through primary and secondary validation to correction and completion of data, and also compilation and analysis of data (Section 2.5), for water level, stage-discharge and flow data, respectively.

During all levels of validation, staff should be able to consult station metadata records detailing the history of the site and its hydrometric performance, along with topographical and climate maps and previous quality control logs. Numerical and visual tools available at different phases of the data validation process, such as versatile hydrograph plotting and manipulation software to enable comparisons between different near-neighbour or analogue flow measurement sites, assessment of basin rainfall input hyetographs and assessment of time series statistics greatly facilitate validation. High-level appraisal by Central/State staff, examining the data in a broader spatial context, can provide significant benefits to final information products. It also enables evaluation of the performance of sub-regional data providers, individual stations or groups of stations, which can focus attention on underperforming sub-regions and encourage improvements in data quality.

A standardised data assessment and improvement procedure safeguards against reduced quality, unvalidated and/or unapproved data reaching the final data archive from where they can be disseminated. However, Marsh (2002) warns of the danger of data quality appraisal systems that operate too mechanistically, concentrating on the separate indices of data quality rather than the overall information delivery function.

For the Hydrology Project, the timetable for data processing is set out in SW10-OM Protocols and Procedures, and summarised in Table 2.1 of this Handbook. Data entry and primary validation of field data from observational stations is required to be completed at Sub-Divisional/Divisional office level by the 10th working day of the following month (e.g. for June data by 10th working day in July), ready for secondary validation by State offices. Initial secondary validation, in State DPCs for State data, and CWC local offices for CWC data, should be completed by the end of that month (e.g. for June data by 31st July). Some secondary validation will not be possible until the end of the hydrological year when the entire year’s data can be reviewed in a long-term context, and compared with CWC data, so data should be regarded as provisional approved data until then (e.g. for June data by the end of the hydrological year plus 3 months), after which data should be formally approved and made available for dissemination to external users. At certain times of year (e.g. during the monsoon season), the data processing plan outlined above may need to be compressed, so that validated hydrometric data are available sooner.

2.5 Data synthesis and analysis

Central/State hydrometric agencies play a key role in the delivery of large-scale assessments of surface water quantity data and other hydrological data. Through their long-term situation monitoring, they are often well placed to conduct or inform scientific analysis at a State, National or International level, and act as a source of advice on data use and guidance on interpretation of river flow patterns. This is especially true in the active monitoring of the State or National situation or the assessment of conditions at times of extreme events (e.g. monsoonal rains, droughts) where agencies may be asked to provide input to scientific reports and research, as well as informing policy decisions, media briefings, and increasing public understanding of the state of the water environment. Sections 4 to 6 of this Handbook cover compilation and analysis of data, as well as the process from data entry through primary and secondary validation to correction and completion of data (Section 2.4), for water level, stage-discharge and flow data, respectively.

Table 2.1 Surface water data processing timetable for data for month n

Activity	**Responsibility**	**Deadline**
Water level data		
Data receipt	Sub-Divisional office	5th working day of month n+1
Data entry	Sub-Divisional/Divisional office	10th working day of month n+1
Primary validation	Sub-Divisional/Divisional office	10th working day of month n+1
Secondary validation	State DPC	Initial - end of month n+1
	State DPC	Final – end of hydrological year + 3 months
Correction and completion	State DPC	Initial - end of month n+1
	State DPC	Final – end of hydrological year + 3 months
Stage-discharge data		
Data receipt	Sub-Divisional office	5th working day of month n+1
Data entry	Sub-Divisional/Divisional office	10th working day of month n+1
Primary validation	Sub-Divisional/Divisional office	10th working day of month n+1
Fitting rating curves	State DPC	Annually
Reporting	State DPC	At least annually
Flow data		
Data computation	State DPC	10th working day of month n+2
Secondary validation	State DPC	Initial - end of month n+2
	State DPC	Final – end of hydrological year + 3 months
Correction and completion	State DPC	Initial - end of month n+2
	State DPC	Final – end of hydrological year + 3 months
Compilation	State DPC	As required
Analysis	State DPC	As required
Reporting	State DPC	At least annually
Data requests	State DPC	95% - within 5 working days 5% - within 20 working days
Interagency validation	CWC	At least 20% of State stations, on rolling programme, by end of hydrological year + 6 months

2.6 Data dissemination and publication

One of the primary functions of Central/State hydrometric agencies is to provide comprehensive access to information at a scale and resolution appropriate for a wide range of end-users. However, improved access to data should be balanced with a promotion of responsible data use by also maintaining end-user access to important contextual information. Thus, the dissemination of user guidance information, such as composite summaries that draw users' attention to key information and record caveats (e.g. monitoring limitations, high levels of uncertainty regarding specific flood event accuracy, major changes in hydrometric setup), is a key stewardship role for Central/State hydrometric agencies, as described in Section 7 of this Handbook.

For large parts of the 20th century the primary data dissemination route for hydrometric data was via annual hardcopy publications of data tables i.e. yearbooks. However, the last decade or so has seen a shift towards more dynamic web-based data dissemination to meet the requirement for shorter lag-time between observation and data publication and ease of data re-use. Like many countries, India now uses an online web-portal as a key dissemination route for hydrometric data and associated metadata which provides users with dynamic access to a wide range of information to allow selection of stations. At least 95% of data requests from users should be processed within 5 working days. More complex data requests should be processed within 20 working days.

2.7 Real-time data

During HPII many implementing agencies developed low cost real-time data acquisition systems, feeding into bespoke databases and available on agency websites. Such systems often utilise short time interval recording of data e.g. 5 minutes, 15 minutes, etc. In some instances, agencies are taking advantage of the telemetry aspect of real-time systems as a cost-effective way of acquiring data from remote locations. However, for some operational purposes (e.g. real-time flood forecasting, reservoir operation, etc), real-time data may need to be used immediately.

Real-time data should go through some automated, relatively simple data validation process before being input to real-time models e.g. checking that each incoming data value is within pre-set limits for the station, and that the change from preceding values is not too large. Where data fall outside of these limits, they should generally still be stored, but flagged as suspect, and a warning message displayed to the model operators. Where suspect data have been identified, a number of options are available to any real-time forecasting or decision support model being run, and the choice will depend upon the modelling requirements. Whilst suspect data could be accepted and the model run as normal, it is more common to treat suspect data as missing or to substitute them with some form of back-up, interpolated or extrapolated data. This is necessary for hydrometric agencies to undertake some of their day-to-day functions and, in such circumstances, all the data should be thoroughly validated as soon as possible, according to the same processing timetable and protocols as other surface water data.

Real-time data should also be regularly transferred to the e-SWIS database system, through appropriate interfaces, in order to ensure that all hydrological data are stored in a single location and provide additional back-up for the real-time data, but also to provide access to the data validation tools available through the eSWDES and eHYMOS modules of e-SWIS.

3. Surface Water Monitoring Stations and Data

3.1 Types of surface water quantity monitoring station

Table 3.1 (two parts) lists the relevant section in the HIS Manual SW for detailed information, for different types of surface water monitoring station and instrument, on design and installation, maintenance, measurement, data entry, primary and secondary validation, correction and completion of data, compilation and analysis of data, and reporting.

Water level (stage) is the elevation of water surface above an established datum. SW4-DM Chapter 6.1 includes a comparison table of different methods of water level measurement on pages 67-68. Records of water level are used with a stage-discharge relationship in computing the record of river flow (discharge). The reliability of the flow record depends on the reliability of the water level record, and of the stage discharge relationship. Stage is also used to characterise the state of a water body for management purposes like the filling of reservoirs, navigation depths, flood inundation, etc. Water level is usually expressed in metres. Water level monitoring instruments include:

- ***Staff gauges*** – manually-read water level gauges, the most common of which is the vertical staff gauge which is simple, robust and easily understood. Other types include inclined/ramp staff gauges, crest staff gauges for maximum water level, and electric tape gauges.

- ***AWLR*** – a water level recorder with autographic recording by means of a chart or shaft encoder. The instrument is usually a float in a stilling well or a gas bubbler system. A staff gauge will also be present.

- ***DWLR*** – a water level recorder with digital recording to a data logger. The instrument is usually a float-operated shaft-encoder or pressure transducer, but other types are becoming more common e.g. radar, ultrasonic, etc. A staff gauge will also be present.

SW4-DM Chapter 6.1 includes a comparison table for different methods of flow (discharge) measurement on pages 131-133. Flow measurement methods include:

- ***Current metering*** – the rotating element (impeller or cup-type) meter is the most commonly used method of velocity measurement in India, and a proven, if relatively slow, method for generating data for stage-discharge relationships and checking the performance of structures and other methods of flow measurement. Flow is derived from the mean velocity and cross-sectional area. Additional information quantifies the error in flow measured by current metering which demonstrates that the more verticals and the more sampling points in each vertical, the smaller the error, ultimately leading to the continuous profile approach used by ADCPs. Current meters are deployed by wading, from bridges and from boats, and less often from cableways (cableways are being phased out due to both health and safety considerations and development of other flow gauging techniques). Current meters should be serviced and calibrated regularly, ideally every 300 hours or 90 working days of use, and at least once a year. Electromagnetic current meters also exist.

- ***Float methods*** – the simplest, cheapest and earliest form of flow measurement, though less accurate than other methods. The technique involves the timing of floats over a measured length of uniform river reach. Flow is derived from the mean surface water velocity and cross-sectional area. Floats are not as accurate (+/-20%) as current meters and ADCPs.

Table 3.1 Where to go in the HIS Manual SW for surface water data management guidance: water level

Instrument / Variable	Design & Installation	Maintenance	Measurement	Data entry	Primary Validation	Secondary Validation	Correction & Completion	Compilation	Analysis	Reporting
Staff gauge	SW4-DM 6.1.2-6.1.5, 8.1 SW4-FM(I) 2.3	SW4-FM(VII) SW4-FM(VIII) 2.1, 4.1.1	SW4-DM 5.2 SW4-FM(II) 2	SW8-OM(I) 8.3	SW8-OM(I) 9.2.1, 9.3-9.5	SW8-OM(II) 7	SW8-OM(II) 8			
AWLR	SW4-DM 6.1.6, 8.1 SW4-RM 2, 3	SW4-FM(VII) SW4-FM(VIII) 2.2	SW4-DM 5.2 SW4-FM(II) 3	SW8-OM(I) 8.3, 8.4	SW8-OM(I) 9.2.2, 9.3-9.5	SW8-OM(II) 7	SW8-OM(II) 8			
DWLR	SW4-DM 6.1.7-6.1.9, 8.1 SW4-RM 5	SW4-FM(VII) SW4-FM(VIII) 2.3, 4.1.2	SW4-DM 5.2 SW4-FM(II) 4	SW8-OM(I) 8.3, 8.4	SW8-OM(I) 9.2.3, 9.3-9.5	SW8-OM(II) 7	SW8-OM(II) 8			

Table 3.1 Where to go in the HIS Manual SW for surface water data management guidance: stage-discharge and flow

Instrument / Variable	Design & Installation	Maintenance	Measurement	Data entry	Primary Validation	Secondary Validation	Correction & Completion	Compilation	Analysis	Reporting
Current metering	SW4-DM 6.2, 6.4, 8.2 SW4-FM(I) 2.4.1	SW4-FM(VIII) 3.1, 4.3	SW4-DM 5.3 SW4-FM(IV) SW4-RM 7	SW8-OM(I) 10.4.2, 10.4.5	SW8-OM(I) 11					
Floats	SW4-DM 6.3 SW4-FM(I) 2.4.2		SW4-FM(III)	SW8-OM(I) 10.4.3, 10.4.5	SW8-OM(I) 11					
ADCP	SW4-DM 6.2, 6.5 SW4-FM(I) 2.4.3 Handbook Annex III	SW4-FM(VIII) 3.2, 4.2	SW4-DM 6.5.4, 6.5.5 SW4-FM(V) SW4-RM 9.4, 9.5 Handbook Annex IV, V	SW4-DM 6.5.6 SW4-RM 9.6	SW8-OM(I) 11					
Slope-area	SW4-DM 6.6 SW4-FM(I) 2.4.4		SW4-FM(VI)	SW8-OM(I) 10.4.4, 10.4.5	SW8-OM(I) 11					
Artificial control (structure)	SW4-FM(I) 2.4.6 SW4-RM 6	SW4-RM 6.14.7	SW4-RM 6.14							
Rating curves	SW4-FM(I) 2.4.5				SW8-OM(II) 10	SW8-OM(II) 12			SW8-OM(II) 9, 11	SW8-OM(III) 11
Flow / discharge				SW8-OM(II) 13		SW8-OM(II) 14 SW8-OM(III) 2, 3	SW8-OM(II) 15	SW8-OM(II) 16	SW8-OM(III) 3, 7	SW8-OM(III) 12

- ***ADCPs (Acoustic Doppler Current Profiler)*** – a rapid, accurate (+/-10%) and increasingly used method of direct flow measurement in India, which also generates data for stage-discharge relationships, and can be used to check the performance of structures and to survey the bed of the river channel or other water body. The velocity throughout the water column is measured by a method based on the Doppler effect of sound waves scattered on particles suspended in the water, and combined with measurements of depth and ADCP movement. ADCPs are deployed by wading, ropes, from bridges and from boats, and on remote-controlled floats. ADCPs have a high capital cost and require a skilled operator to make the measurements and process the data. The recommended ADCPs are manufactured by Sontek and Teledyne RDI.

- ***Slope-area methods*** – a method based on open channel formulae for estimating velocity using surface water slope and channel geometry e.g. Manning's formula, traditionally used to estimate peak discharges when it is not possible to make flow measurements by the other means listed above. Flow is derived from the mean velocity and cross-sectional area. Slope-area methods are not as accurate (+/-25%) as current meters and ADCPs.

- ***Artificial structures*** - different flow measuring structures include thin plate weirs, broad-crested weirs, triangular profile weirs, compound weirs, flumes, and reservoir spillways, sluice gates and other control structures. Structures have a high capital cost, but are highly accurate (+/-5%) providing the flow is within the modular range of the structure.

A set of specifications for surface water equipment was compiled under HPI and updated under HPII. The specifications, which are downloadable from the Hydrology Project website, provide a guideline for procurement, some technical guidance for which is offered in SW4-DM Chapter 7 (with examples of some procurement templates and documents also on the Hydrology Project website).

3.2 Surface water monitoring networks

Monitoring networks should be considered to be dynamic entities. It is important that the current utility of well-established monitoring networks is periodically assessed to ensure that they continue to meet changing requirements and to optimise the information they deliver. Network reviews should be done in collaboration with other agencies. SW4-FM(I) Chapter 1 describes network design and optimisation for monitoring water levels in rivers and in dams/lakes/reservoirs, and associated river flow. This is a multi-step process comprising:

1. Identification of hydrological data users and their data needs to understand what data are required and at what frequency.

2. Definition of the purposes and objectives of the network in order to fulfill the hydrological data need, and evaluation of the consequences of not meeting those targets, to inform a prioritisation of objectives in case of budget constraints.

3. Evaluation of the existing network to assess how well it meets the purposes and objectives, as well as the adequacy of existing equipment and operational procedures, and possible improvements to existing network. Helpful tables are provided in SW4-FM(I) Chapters 1.4 and 1.5 to guide users through this step and steps 4 to 6. These may involve the development of regionalisation and network optimisation techniques (e.g. Institute of Hydrology, 1999; Hannaford *et al.*, 2013).

4. Review of existing data to assess catchment behaviour and variability.

5. Identification of gaps (need for new stations) and over-design (redundancy) in the existing network e.g. locations where the States and CWC, or two States, have river gauging stations very close together. This may require the collection of maps and background information to inform the revised network design.

6. Prioritisation of gauging stations using, for example, some simple form of classification system.

7. Estimation of overall costs of installing, operating and maintaining the network and the different types of monitoring station making up the network.

8. Evaluation of revised network in relation to purposes and objectives, ideal network, available budgets and overall benefits to assess sustainability which is of paramount importance. Achieving an optimum network design may involve an iterative process, repeating some or all of steps 3 to 7, until a satisfactory outcome is reached.

9. Preparation of phased implementation plan for optimum network that is prioritised, realistic and achievable in the time scales allowed.

10. Selection of sites and site surveys. SW4-FM(I) devotes Chapter 2 to this topic, which may involve selecting sites for water level monitoring only, or for water level and flow measurement by a variety of methods. SW4-FM(I) Annex 2.1 provides a useful checklist of all the factors that should be taken into consideration in selecting a site and the type of monitoring station to ensure long-term reliable data. A site survey comprises four phases: a desk study, a reconnaissance survey, a topographic survey and other surveys e.g. trial flow gauging. The site survey, which should be carried out in collaboration with CWC, may reveal that the desired location is unsuitable, and an alternative site or flow measurement technique may need to be considered.

11. Establishment of a framework for periodic network reviews (e.g. after 3 years or sooner if new data needs develop) i.e. starting this process again from step 1.

A good example of a monitoring network review under HPII is the Purpose Driven Study (PDS) on optimisation of the river gauging station and raingauge networks in Maharashtra (PDS number SW-MH-1).

For more detailed information see: SW2-DM Chapter 7 which provides some generic guidance on types of network and the steps in network design; SW2-DM Chapters 3.2.1 to 3.2.6 which describe classification of stations and offer some examples of types of network; and Surface Water Training Module 45 “How to review monitoring networks”.

3.3 Site inspections, audits and maintenance

Regular maintenance of equipment, together with periodic inspections and audits, ensures collection of good quality data and provides information that may assist in future data validation queries. Table 3.1 lists the relevant section in the HIS Manual SW for maintenance of the different types of surface water stations and instruments. Whilst this topic is largely covered in different chapters of SW4-FM(VII) for field inspections and audits, and SW4-FM(VIII) for routine maintenance and calibration of equipment, information is collated together in the document “Surface Water O&M norms” which is a maintenance guide for hydro-meteorology, stage-discharge and water quality instrumentation and equipment.

Maintenance and calibration requirements depend to a large extent of the type of station, instruments and equipment so are often site-specific. A supply of appropriate spare parts should be kept on site and/or taken on station visits in case they are needed. SW4-FM(VIII) Annex II lists maintenance norms for flow monitoring stations, including maintenance of civil works, maintenance of equipment, costs of consumable items and payments to staff (where the costs should be regarded as out of date).

The approach becoming the standard for checking ADCP performance is “regatta” testing whereby every 2 years (typically) an ADCP is tested against other ADCPs and against a discharge accurately measured by a non-ADCP method. Despite the logistical issues and financial investment of holding regattas, it is highly recommended that this approach is implemented, perhaps holding several regattas in different regional locations every year, involving CWC, State governments and independent agencies operating ADCPs.

Inspections of water level and flow monitoring stations are carried out every day that somebody is on site as set out in SW4-FM(VII) Chapter 3, with station log sheets in the SW4-FM(VII) Annex. Formal inspections cum audits are carried out at a frequency dependent on the importance of the station, the type of station and the time of year and will typically vary between monthly and annually as set out in SW4-FM(VII) Chapter 2, with a comprehensive audit checklist in the SW4-FM(VII) Annex. Activities may include: checking the performance of and motivating the field staff; identifying existing or potential problems with the site, instruments, equipment and observation procedures at an early stage so they can be rectified; and undertaking independent measurement checks.

3.4 Data sensing and recording

Table 3.1 lists the relevant section in the HIS Manual SW for operational instructions on the measurement of water level and flow at surface water stations. Note that there is some overlap between SW4-DM, SW4-FM and SW4-RM, and between the network design and site selection topic (covered in Section 3.2 of this Handbook) and data measurement. See also the document “Illustrations: hydrological observations” which demonstrates how to make measurements of rainfall, water level and flow at stations, and also how to carry out an inspection at those stations. The frequency at which water level measurements and flow gaugings are taken depends on:

- The function of the data – the measurement frequency should meet the requirements of the uses planned for the data. More frequent observation may be required for peak flows and/or small basins.
- The target accuracy of the data – the accuracy of hydrological data depends on the sampling density, the frequency of measurement and the accuracy of measurement. There should be a balance between the value of increased accuracy of data and the increased cost of providing that increased accuracy, within a notional upper limit of accuracy outside which the data quality would be unacceptable for its intended uses.
- The accuracy of the observation method – when observations are subject to random measurement errors, a larger number of observations are needed to meet a target accuracy where the measurement error is large.
- The time variability of the water level or flow – fewer measurements are needed to characterise a variable that is uniform or changing very slowly, than for a rapidly fluctuating variable. For example, small steep basins need more frequent measurements than large flat basins, to achieve the same accuracy and to have a sufficient number of points to adequately describe the hydrograph of an event.
- The seasonality of the water level or flow – flow in rivers is highly seasonal and, during the monsoon, changes in water level and discharge may be large and rapid. Typically, a higher frequency of measurement is required during the monsoon season (hourly) than outside it (hourly only during the day), which has additional costs in manpower.
- The marginal cost/benefit of improved accuracy – accuracy can be improved by increasing the frequency of measurement or increasing the accuracy of measurement. For example, increasing the frequency (and accuracy) of water level measurement is cheaper for a DWLR

than a manually-read staff gauge, and increasing the frequency (and accuracy) of flow gauging is quicker for an ADCP than for a current meter; however, the increasing the accuracy may require the site to be upgraded which has capital costs.

- The benefits of standardisation - it is quicker to process records in the same format and at the same frequency of observation. Data processing staff become familiar with handling standardised data, and the records where some aspect is unusual tend to get left until the end.

For all surface water stations, water level (stage) measurement will take place throughout the year, and a “no flow” condition should be recorded if a river dries up, to clearly distinguish from missing data. Different practice is adopted depending on whether water level measurement is by staff gauge, AWLR or DWLR, and on the time of year, as summarised in Table 3.2.

For staff gauges only, observations are generally made up to three times a day outside the monsoon season, and at multiple times a day during flood times. For flashy rivers, staff gauges may even be read at hourly intervals during the monsoon season. An AWLR gives a continuous record of water level in time, and levels are extracted manually from these autographic records, normally at an hourly time interval. A DWLR may be set to record data at any time interval e.g. hourly, 15-minute, etc.

The purpose of flow (discharge) gauging is to take a sufficient number of stage-discharge readings to fit a good stage-discharge relationship (rating curve) which can be used to estimate flow from water level only. The required number of flow measurements, by current meter and/or ADCP, at a gauging station depends primarily on the stability of the control section, as this determines how frequently gauging are required to achieve a target accuracy. A precise interval between gauging cannot be specified as the need to gauge may depend on the occurrence of flow in a particular range, with the aim to capture data for a wide a range of events (low flow, medium flow and high flow) as possible. Daily gauging is common in India, with more frequent gauging to obtain data for high flow events (particularly during the monsoon), and weekly or monthly gauging outside the monsoon season. Whilst some key gauging stations will have static field teams, mobile field teams, touring gauging stations with relative stable ratings, make efficient use of limited, skilled manpower and expensive equipment.

Flow gauging by ADCP, including preparatory activities and data recording, is covered in SW4-DM Chapter 6.5, SW4-FM(V) and SW4-RM Chapter 9. These three chapters are supplemented by three guidance notes “How to specify an ADCP system”, “How to measure river discharge using an ADCP” and “How to process and validate ADCP river discharge measurements” which are included in Annexes III to V of this Handbook. Several different ADCPs from different manufacturers are in operation in India, so the guidance notes present a generic approach to deployment of ADCPs for determining a single instantaneous measurement of discharge.

The observer should become familiar with the expected flow patterns of individual rivers (e.g. knowing how quickly the river typically rises and falls after a rainfall event), in order to be able to spot potentially anomalous behaviour.

Table 3.2 Recommended observation frequency for water level measurement

Instrumentation	Frequency	Notes
Staff gauge only	Hourly 1-3 per day	Monsoon season Non-monsoon times of year
AWLR	Hourly	Depends on scale of chart – more frequent readings could readily be extracted from some charts
DWLR	Hourly/15 minute	Depends on the size of basin and purpose of data

The observer should always note any occurrences which may influence the water level or flow measurements as observed by the instruments. These may include: damage to the equipment for a specified reason; extraction of sand/gravel, scouring or other lowering of the river bed level at the gauges or control; any downstream activities or blockage of the channel by floating debris which may have artificially raised the water level; presence of significant weed growth in the channel or on the instruments and its subsequent removal. The observer should also note any maintenance activities carried out at the monitoring site (e.g. change batteries, clean sensor, etc).

The observer should double-check that that any manual reading is taken correctly, and transcribed correctly (e.g. decimal point in right place). If the reading is later transferred to another document (e.g. hand copied or typed in, or abstracted from a chart), the observer should always check that this has been done correctly. An experienced and suitably qualified observer should compare measurements with equivalent ones from earlier that day or from the day before, if available, as an additional form of checking. However, the observer should not, under any circumstances, retrospectively alter earlier readings or adjust current readings, but should simply add an appropriate comment.

Data collected in the field are delivered to a Data Processing Centre (DPC) on a variety of media, including handwritten forms and notebooks, charts and digital data.

3.5 Data processing

SW8-OM(IV) Chapter 2 sets out the steps in processing of surface water quantity data, which starts with preliminary checking in the field, as described in Section 3.4 of this Handbook, through receipt of raw field data at a DPC, through successively higher levels of validation in State and Central DPCs, before data are fully validated and approved in the National database. Validation ensures that the data stored are as complete and of the highest quality as possible by: identifying errors and sources of errors to mitigate them occurring again, correcting errors where possible, and assessing the reliability of data. It is important for staff to be aware of the different errors that may occur as described in SW8-OM(IV) Chapter 2.5.1.

Data validation is split into two principal stages: primary and secondary, with an optional tertiary stage. Validation is very much a two-way process, where each step feeds back to the previous step any comments or queries relating to the data provided. The diverse hydrological environments found in India mean that staff conducting data validation should be familiar with the expected climate and flow patterns of individual rivers in order to identify potentially anomalous behaviour. The data processing steps comprise:

1. Receipt of data according to prescribed target dates. Rapid and reliable transfer of data is essential, using the optimal method based on factors such as volume, frequency, speed of transfer/transmission and cost. Maintenance of a strict time schedule is important because it gives timely feedback to monitoring sites, it encourages regular exchanges between field staff, Sub-Divisional offices, State and Central agencies, it creates continuity of processing activities at different offices, and it ensures timely availability of final (approved) data for use in policy and decision-making.

2. Entry of data to computer, using the eSWDES module of e-SWIS, is primarily done at a Sub-Divisional office level where staff are in close contact to field staff who have made the observations and/or collected the chart or digital data. Historical data, previously only available in hardcopy form, may also be entered this way. Each Central/State agency should have a programme of historical data entry.

3. Primary data validation which should be carried out in State DPCs for State data and CWC local offices for CWC data, as soon as possible after the observations are made, data

extracted from charts, or data downloaded from loggers, using the eSWDES module of e-SWIS. This ensures that any obvious problems (e.g. indicating an instrument malfunction, observer error, etc) are spotted at the earliest opportunity and resolved. Other problems may not become apparent until more data have been collected, and data can be viewed in a longer temporal context during secondary validation.

4. Secondary data validation which should be carried out in State DPCs for State data and CWC local offices for CWC data, to take advantage of the information available from a large area by focusing on comparisons with the same variable at other good quality, nearby monitoring sites (analogue stations) which are expected to exhibit similar hydrological behaviours (e.g. comparison of cumulative runoff from two flow gauging stations), uses the eHYMOS module of e-SWIS. States should have access to CWC data during secondary validation, and may receive support from CWC in this activity.

5. Tertiary data validation (also known as hydrological or supplemental) which focuses on comparisons with inter-related variables at the same or analogue stations to identify inconsistencies between time series or their derived statistics, using tools like regression analysis and rainfall-runoff modelling. This stage of validation is time-consuming and is applied selectively.

6. Data correction and completion are elements of data validation which are used to infill missing value, sequences of missing values or correct clearly erroneous values, in order to make the time series as complete as possible. Some suspect (doubtful) data values may still justifiably remain after this stage if correction is not possible so that the original data value remains the best estimate of the true value for that day and time.

7. Data storage. The e-SWIS HIS database, of both approved data and unapproved data undergoing primary and secondary validation, is backed up automatically. Therefore, there is no need to make regular back-ups, unless any data are stored outside the HIS database, for instance in Excel files or other formats awaiting data entry, or in stand-alone real-time databases – such files should be securely backed up, ideally onto an external back-up device and/or backed up network server, so that there is no risk of data loss. All PCs should have up-to-date anti-virus software.

   Raw field data, in the form of handwritten forms and notebooks, and charts should also be stored in a secure manner after database entry to ensure that original field data remain available should any problems be identified during validation and analysis. Such hardcopy data should ultimately be securely archived, in the State DPC for State data or CWC local office for CWC data, possibly by scanning documents and storing them digitally.

8. Interagency data validation by CWC – CWC should aim to validate at least 20% of current and historic data from State surface water monitoring stations every year, on a rolling programme, so that CWC has independently validated the data from every State gauge at least once every 5 years. Interagency validation is a 2-way process and CWC should discuss any identified issues and agree final datasets with State DPCs through a 2-way consultative process, to build capacity for data validation within the States.

For water level, stage-discharge and flow data, Sections 4 to 6 of this Handbook, respectively, cover the process from data entry through primary and secondary validation to correction and completion of data, and also compilation (i.e. the transformation of data observed at one time interval to another time interval e.g. daily mean flow to monthly mean flow, or the transformation of data from one unit to another e.g. flow to runoff) and analysis of data.

4. Water Level Data Processing and Analysis

4.1 Data entry

4.1.1 Overview

Entry of data to computer is primarily done at a Sub-Divisional office level where staff are in close contact to field staff who have made the observations and/or collected the chart or digital data. Data entry is carried out using e-SWIS, the data entry module of which replicates the SWDES software from HPI, and is referred to as eSWDES. Prior to entry to computer, two manual activities are essential: registration of receipt of the data, and manual inspection of the water level charts, forms and notebooks from the field, for complete information and obvious errors. Data entry (see Table 3.1) and primary validation of field data from observational stations is required to be completed at Sub-Divisional/Divisional office level by the 10th working day of the following month (e.g. for June data by 10th working day in July), ready for secondary validation by State offices.

4.1.2 Manual inspection of field records

Prior to data entry to computer an initial inspection of field records is required. This is done in conjunction with notes received from the observation station on equipment problems and faults, missing records or exceptional flows. Water level sheets and charts are inspected for the following:

- Is the station name and code and month and year recorded?
- Does the number of record days correspond with the number of days in the month?
- Are there some missing values or periods of no flow?
- Have the autographic hourly water levels been extracted?
- Is the record written clearly and with no ambiguity in digits or decimal points?
- Do digital records downloaded from the data loggers have valid station/instrument identification, dates and timings, etc.

Where an AWLR is present, a rapid visual comparison should also be made between tabulated staff gauge readings and levels registered on the autographic chart, in particular peaks and troughs in the two records should be compared for coincidence.

Any queries arising from such inspection should be communicated to the observer to confirm ambiguous data before data entry. Any unresolved problems should be noted and the information sent forward with the digital data to Divisional/State offices to assist in initial secondary validation. Any equipment failure or observer problem (e.g. improper entry to the 31st day of a month with 30 days) should be communicated to the supervising field officer for rectification.

4.1.3 Entry of sub-daily water level data

Using the eSWDES module in e-SWIS, the user selects the correct station and water level series. The screen for entry (or editing) of sub-daily water level is displayed, along with the upper and lower warning levels used to flag suspect values (which can be altered for different seasons), the maximum and minimum levels for that station, and the maximum rates of rise and fall of the water level for that station. The user selects the correct year and month, and enters the sub-daily water levels, with each row corresponding to a different day and each column to a different time, adding comments where appropriate. Non-numerical entries are automatically rejected. For each month, the user also enters the maximum, minimum and average water levels for each observation time.

The software also calculates the maximum, minimum and average water levels for each observation time as the user enters the data.

Two types of data entry checks are performed for this case of water level data at multiple time a day:

- The entered data are compared against the upper and lower warning levels, maximum and minimum levels, and maximum rates of rise and fall. This identifies potentially suspect values to the user who can refer back to the field documents to see if there was some error in entering the data. If values which exceed any of the level or rate limits are actually reported in the field documents, the user should add an appropriate comment.
- The maximum, minimum and average water levels for each observation time entered by the user are compared with the values calculated by the software. In the case of a mismatch the user is prompted by colour highlighting and can refer back to the field documents to see if there was some error in entering the data.

Any mismatch remaining after thorough checking of the field documents must be due to incorrect field computations by the observer and should be communicated to the supervising field officer.

The user should also view entered data graphically to identify potentially suspect data not apparent in tabular form, which may reflect an error in data entry. There are two ways in which the entered data can be plotted: sub-daily data for the month, and sub- daily data for the year.

Missing data When data are missing, the corresponding cell is left as -999 (not zero) and a comment entered against that day.

4.1.4 Entry of hourly water level data

Hourly rainfall data are obtained either from the chart records of AWLRs or from the digital data of DWLRs. Digital data can also be imported directly, but can undergo entry checks and be viewed graphically using this option.

Using the eSWDES module in e-SWIS, the user selects the correct station and water level series. The screen for entry (or editing) of hourly water level is displayed, along with the upper and lower warning levels used to flag suspect values (which can be altered for different seasons), the maximum and minimum levels for that station, and the maximum rates of rise and fall of the water level for that station. The user selects the correct year and month, and enters the hourly water levels, with each row corresponding to a different day and each column to a different time, adding comments where appropriate. Non-numerical entries are automatically rejected. For each day, the user also enters the maximum, minimum and average water levels. The software also calculates the maximum, minimum and average water levels for each day as the user enters the data.

Two types of data entry checks are performed for this case of hourly water level data:

- The entered hourly data are compared against the upper and lower warning levels, maximum and minimum levels, and maximum rates of rise and fall. This identifies potentially suspect values to the user who can refer back to the field documents to see if there was some error in entering the data. If values which exceed any of the level or rate limits are actually reported in the field documents, the user should add an appropriate comment.
- The maximum, minimum and average water levels for each day entered by the user are compared with the values calculated by the software. In the case of a mismatch the user is prompted by colour highlighting and can refer back to the field documents to see if there was some error in entering the data.

Any mismatch remaining after thorough checking of the field documents must be due to incorrect field computations by the observer and should be communicated to the supervising field officer.

The user should also view entered data graphically to identify potentially suspect data not apparent in tabular form, which may reflect an error in data entry. There are two ways in which the entered data can be plotted: hourly data for the day, and hourly data for the month.

Missing data are handled in the same way as for entry of sub-daily water level data (Section 4.1.3).

4.1.5 Import/entry of digital data

Digital data from DWLRs take the form of water levels at pre-set time intervals (e.g. 1 hour, 15 minutes, etc). DWLR data can be imported directly should an appropriate import interface be available (bespoke to each type of data logger), and hourly data can undergo entry checks and be viewed graphically as described in Section 4.1.4.

4.2 Primary validation

4.2.1 Overview

Primary validation is primarily done at a Sub-Divisional office level where staff are in close contact to field staff who have made the observations and/or collected the chart or digital data. Primary validation is carried out using e-SWIS, the data entry module of which replicates the SWDES software from HPI, and is referred to as eSWDES. Primary validation (see Table 3.1) of field data from observational stations is required to be completed at Sub-Divisional/Divisional office level by the 10th working day of the following month (e.g. for June data by 10th working day in July), ready for secondary validation by State offices. This time schedule ensures that any obvious problems (e.g. indicating an instrument malfunction, observer error, etc) are spotted at the earliest opportunity and resolved. Other problems may not become apparent until more data have been collected, and data can be viewed in a longer-term context during secondary validation.

Primary validation of water level data focuses on validation within a single data series by making comparisons between individual observations and pre-set physical limits, and between two measurements of water level at a single station (e.g. manually-read water level from a staff gauge and autographic or digital data from an AWLR or DWLR, respectively). Examples of many of the techniques described in this section are given in Surface Water Training Module 22 “How to carry out primary validation of water level data” and Training Module 24 “How to correct and complete water level data”.

4.2.2 Typical errors

Staff should be aware of typical errors in water level measurement, listed in Table 4.1, and these should be considered when interpreting data and possible discrepancies (SW8-OM(I) Chapter 9.2).

Staff gauge errors are more readily detected if there is a concurrent record from an AWLR or DWLR. As these too are subject to errors (of a different type), comparisons with the staff gauge are very important (Section 4.2.4). The final check by comparison with water levels at analogue (neighbouring) stations should show up further anomalies, especially for those stations which do not have an AWLR or DWLR at the site. This is carried out during secondary validation where more stations are available for comparison (Section 4.3).

Table 4.1 Measurement errors for water level data

Staff gauge measurement errors

- Observer reads staff gauge incorrectly
- Observer enters water level incorrectly in the field sheet (e.g. misplacement of decimal point in the range 0.01 to 0.10, writing 4.9 m instead of 4.09 m)
- Observer enters water level to the wrong day or time
- Observer fabricates readings, indicated by sudden changes in flow regime, extended periods of uniform water level, or extended periods of uniform mathematical sequences of observations
- Observer cannot access staff gauge (e.g. due to high flows)
- Instrument fault - damaged or broken staff gauge

AWLR measurement errors

- Chart trace goes up when the river goes down
  - ➢ Float and counterweight reversed on float pulley
- Chart trace goes up when the river goes down
  - ➢ Tangling of float and counterweight wire
  - ➢ Backlash or friction in the gearing; blockage of the intake pipe by silt or float resting on silt
- Flood hydrograph truncated
  - ➢ Well top of insufficient height for flood flows and float sticks on floorboards of gauging hut or recorder box
  - ➢ Insufficient damping of waves causing float tape to jump or slip on pulley
- Hydrograph appears OK but the staff gauge and chart level disagree
  - ➢ There are many possible sources including operator setting problems, float system, recorder mechanism or the operation of the stilling well, in addition to those noted above. The following may be considered:
    - Operator Problems
      - ➢ Chart originally set at the wrong level
    - Float system problems
      - ➢ Submergence of the float and counterweight line (in floods)
      - ➢ Inadequate float diameter and badly matched float and counterweight
      - ➢ Kinks in float suspension cables
      - ➢ Build up of silt on the float pulley affecting the fit of the float tape perforations in the sprockets
    - Recorder problems
      - ➢ Improper setting of the chart on the recorder drum
      - ➢ Distortion and/or movement of the chart paper (humidity)
      - ➢ Distortion or misalignment of the chart drum
      - ➢ Faulty operation of the pen or pen carriage
    - Stilling well problems
      - ➢ Lag of water level in the stilling well behind that in the river due to insufficient diameter of the intake pipe in relation to well diameter
      - ➢ Partial blockage of stilling well and/or intake pipe
- Chart time and clock time disagree
  - ➢ Chart clock in error and should be adjusted

DWLR measurement errors

- DWLRs using float systems in stilling wells will be subject to the same potential measurement faults as AWLRs
- Failure of electronics due to lightning strike etc. (though lightning protection usually provided)
- Incorrect set up of measurement parameters by the observer or field supervisor

4.2.3 Comparison with upper and lower warning levels, maximum and minimum limits and maximum rates of rise and fall

Both hourly and sub-daily water level data should be validated against physical limits, which are required to be quite wide to avoid the possibility of rejecting true extreme values, and should also be reviewed graphically to identify any sequences of data which represent unacceptable hydrological behaviour.

The values of the absolute maximum and minimum water levels at a particular station are pre-set such that values outside these limits are clearly incorrect. These limits are normally set for the full year and do not vary with month or season. The maximum is set after considering the topography of the floodplains around the control section and also the previously observed maximum at the station. It is normal to set the minimum to the zero gauge level i.e. no flow. However, for some natural channels and controls, negative stage values may be acceptable if the channel is subject to scour such that flow continues below the gauge zero. Such conditions must be confirmed by inspection of the accompanying station files. Checks against maximum and minimum limits are carried out automatically and values violating the limits are flagged and listed.

However, validation of water level data against maximum and minimum limits does not discriminate those unusually high or low values which are within the prescribed limits but which may be incorrect. In view of this, it is advantageous to consider less extreme upper and lower warning levels, which can be employed to filter high or low data values outside the warning range. The underlying objective in setting the upper and lower warning levels is that such limits are violated 1–2 times every year by a flood event. This ensures that, on an average, the one or two highest floods or deepest troughs are examined more closely.

Finally, the maximum rates of rise and fall (i.e. the maximum acceptable positive or negative change between successive observations) are used to compare each data value with the one immediately preceding and following it. Such a test is of particular relevance to parameters exhibiting significant serial correlation, such as water level data. However, what is an acceptable change in water level during a rising flood hydrograph during the monsoon may be unacceptable during the dry season. Violations of rise and fall limits are therefore more readily identified from graphical plots of the hydrograph.

Visual checking of water level data is often a more efficient technique for detecting data anomalies than numerical checking. However, the majority of rivers in India are artificially influenced to a greater or lesser extent e.g. abstractions, return flows, bund dams, reservoirs, etc. Influences are most clearly seen at low to medium flows, where in some rivers the hydrograph appears entirely artificial; high flows may still observe a natural pattern. In such rivers validation becomes more difficult and the application of objective rules may result in the listing of many queries where the observations are, in fact, correct. The user performing validation should be aware of the principal artificial influences within the basin, the location of those influences, their magnitude, their frequency and seasonal timing, to provide a better basis for identifying values or sequences of values which are suspect. Potential problems identified using numerical tests should be inspected and interpreted in terms of the performance of observer, instruments or station. Problems should be accepted as correct, or flagged as suspect and, where possible, corrected.

4.2.4 Comparison of manual and autographic/digital data

For stations with an AWLR or a DWLR, a staff gauge is always also available. Thus, water level data are available from at least two independent sources. Discrepancies may arise either from the staff gauge readings, the recorder readings or from both.

Comparison of staff gauge and recorder water level data can be best carried out in graphical form, with a second graph axis showing the residual series. The two water level series should correspond. The following discrepancies should be noted:

- If there is a systematic but constant difference between the staff gauge and the recorder, it is probable that the recorder has been set up at the wrong level. The user should check the chart annotations and field documents, in particular steps in the hydrograph at the time of chart changing → **Accept staff gauge and adjust AWLR or DWLR** by the constant difference from the staff gauge.

- If there is a change from good correspondence to poor correspondence in flood conditions, a failure associated with the stilling well or the recorder should be suspected and the staff gauge record is more likely to be correct → **Accept staff gauge and adjust AWLR or DWLR** either by replacing the suspect part of the recording gauge record with the staff gauge record or interpolation if the time interval is sufficiently small in relation to changes in water level, or by the use of relation curves (Sections 4.3.4 and 4.4). This approach also applies to unacceptable recording gauge water level traces which may result for a wide variety of instrument problems (e.g. silting of stilling well, blocking of intakes, some obstruction causing the float to remain hung, kinks in the flat tape, etc), and are often displayed as stepped or flat traces.

- A gradual increase in the error may result from the recorder clock running fast or slow, or from the pen drifting from its true position. Both errors may readily be detected from the graphical plot → **Accept staff gauge and adjust AWLR or DWLR**. For ***timing errors***, either by expanding or contracting the chart time signature (x-axis), or by inserting or removing data values at appropriate time intervals, to match the correct time at the staff gauge. For ***pen level errors***, either by expanding or contracting the water level trace (y-axis), to match the correct water level at the staff gauge.

- If the comparison is generally good but there are occasional discrepancies, it is probably the result of error in the staff gauge observations by the observer or incorrect extraction from the chart. The users should firstly check the chart extraction. If the chart extraction is incorrect, the data should be corrected and the graph plotted again. If it is correct, a staff gauge error is the more likely → **Accept AWLR or DWLR and adjust staff gauge** by making the staff gauge data values equal to the concurrent values at the AWLR/DWLR. Persistent and erratic differences from the recording gauge indicate a problem with the observer's performance or record fabrication, and should be notified to the supervising field officer for rectification.

Where a doubtful or incorrect water level is identified, and there is any uncertainty as to the correct action, this should be marked with an appropriate flag to indicate that it is suspect. The data flagged as suspect are reviewed at the time of secondary validation.

4.3 Secondary validation

4.3.1 Overview

Secondary validation of water level data is primarily carried out at State DPCs, to take advantage of the information available from a larger area, and is largely applicable only to river water level data (not dam water level data). Secondary validation is carried out using e-SWIS, the validation module of which replicates the HYMOS software from HPI, and is referred to as eHYMOS. Data may also be exported to Excel for secondary validation. For the Hydrology Project, secondary validation (see Table 3.1) should be completed by the end of the following month (e.g. for June data by 31st July). Some secondary validation (including comparison with CWC data) will not be possible until the end of the hydrological year when the entire year's data can be reviewed in a long-term context, so data should be regarded as provisional approved data until then (e.g. for June data by the end of the hydrological year plus 3 months), after which data should be formally approved and made available for dissemination to external users.

Data entering secondary validation have already received primary validation on the basis of knowledge of the station and instrumentation and field documents. Data may have been flagged as missing or suspect for some other reason e.g. a timing error between staff gauge and other recorder. Secondary validation focuses on comparisons with neighbouring stations to identify suspect values. The main comparisons are between water level series at successive points on the same river. Comparisons are also made between water level data and incident rainfall. Data processing staff should continue to be aware of field practice and instrumentation and the associated errors which can arise in data. Since the actual value of water level is controlled by specific physical conditions at the station, the amount of secondary validation of level is limited. Most of the check comparisons with neighbouring stations must await transformation from water level to flow through the use of stage-discharge relationships. Only as flow, or runoff (flow expressed as a depth over the basin area), can volumetric comparisons be made. Examples of many of the techniques described in this section are given in Surface Water Training Module 23 “How to carry out secondary validation of water level data” and Training Module 24 “How to correct and complete water level data”.

4.3.2 Comparison of water level from multiple stations

Graphical displays of water level data from multiple stations in a region provides an efficient way of identifying anomalies such as timing errors and shifts in reference level. Where only two stations are involved in the comparison, the identification of an anomaly does not necessarily indicate which station is at fault. For multiple time series plots, select a set of stations, ideally on the same river. Plot the water level series as hydrographs, preferably in different colours for each station. The time interval of observation rather than averaged values should be displayed. For routine monthly validation, the plot should include the time series of at least the previous month to ensure that there are no discontinuities between one batch of data received from the station and the next. In general, peaks and troughs are expected to be replicated at several stations with earlier occurrence at upstream stations and the lag between peaks, based on the travel time of the flood wave, approximately the same for different events. It should be noted that level values at downstream stations are not necessarily higher than upstream stations - the actual value depends on physical conditions at the stations.

Where peaks occur at one station but not at its neighbour, or where the lag time between stations is widely different from the norm, an error at one station may be suspected. However, it must be recognised that the quality of the relationship between neighbouring hydrographs depends not only on the accuracy of the records, but also on a variety of other factors including:

- Rainfall and inflow into the intervening reach between stations. If the intervening basin is large or the rainfall high in comparison to that over the upstream basin, a very poor relationship may result
- River regulation and abstractions between the stations may obscure natural variations, though high flows are usually less affected than low or medium flows
- An average lag between successive stations can be used in making comparisons but the actual lag is variable, generally diminishing up to bankfull stage and increasing again with overbank flow
- One station may suffer backwater effects on the stage hydrograph and not another, obscuring the effects of differences in flow. Where such effects are known to occur, comparison should await transformation to flow

Unexplained anomalies should initially be followed up by checking the field documents to check for unnoticed mistakes during data entry or primary validation, in which case the data can be corrected accordingly. If necessary, the anomaly should be communicated to the supervising field officer and observer to confirm data and/or rectify problems. Data still regarded as suspect after follow-up checking are flagged and commented appropriately for further stage validation or to await validation as flow.

4.3.3 Combined water level and rainfall plots

The addition of rainfall to the comparison plots in Section 4.3.2 provides a means of assessing timing errors and of investigating the effects of inflow into the intervening reach between stations. Comparison may be made using an areal rainfall determined using Thiessen polygons or other methods over the entire basin, or for the intervening sub-basin corresponding to various gauging stations (Precipitation and Climate Handbook, Section 4.5.3). Where the basin is small or the number of raingauges limited, individual rainfall records may be plotted.

In general, a rise in river water level must be preceded by a rainfall event in the basin and, conversely, it is expected that rainfall over the basin will be followed by rise in water level. There must be a time lag between the occurrence of rainfall and the rise in water level. Where these conditions are violated, an error in rainfall or in the water level hydrograph may be suspected. However, the above conditions do not apply universally and the assumption of an error is not always justified, especially for isolated storms in arid areas:

- An isolated storm recorded at a single raingauge may be unrepresentative and much higher than the basin rainfall. The resulting runoff may be negligible or even absent
- Where storm rainfall is spatially variable, it may be heavy and widespread but miss all the raingauges, thus resulting in a rise in river level without preceding measured rainfall
- The amount of runoff resulting from a given rainfall varies with the antecedent catchment conditions. Rainfall at the onset of the monsoon on a very dry catchment may be largely absorbed in soil storage and, thus, little reaches the river channel

The use of comparative plots of rainfall and water level is, therefore, qualitative but it provides valuable ancillary information when used with the multiple hydrograph plots.

4.3.4 Water level relation curves

If two water level stations are located on the same river and no major branch joins the main stream between the two locations, a relationship can be expected between the water levels recorded at the two stations. Using this relationship, the water level at one station may be derived from the available water level series at the other station (Figure 4.1). Two conditions need to be satisfied to obtain a high degree of relationship between the water level data of adjacent stations:

- No major tributary joins the main stream in between the two adjacent stations
- Time of travel of the flood wave between the two stations is taken into consideration

The occurrence of lateral inflow between stations, as a main tributary inflow or distributed over the reach as surface and groundwater inflows, limits the quality of the relationship. The travel time between the two stations may be assessed using physical reasoning (the travel time of a flood wave can be approximately determined by the division of the inter station distance by the estimated flood wave velocity) or from an analysis of time series (e.g. using cross-correlation analysis).

It is recommended to fit a polynomial relationship not greater than order 2 or 3 and, in many cases, a simple linear relationship will be acceptable:

$$Y_t = c_0 + c_1 X_{t+t1} + c_2 X_{t+t1}^2 + c_3 X_{t+t1}^3 + \ldots\ldots$$

The least squares principle is applied to estimate the coefficients. Where inspection of the scatter plot indicates the presence of breakpoints, separate relationships may be established for different ranges of water level (analogous to different ranges of the stage discharge relationship).

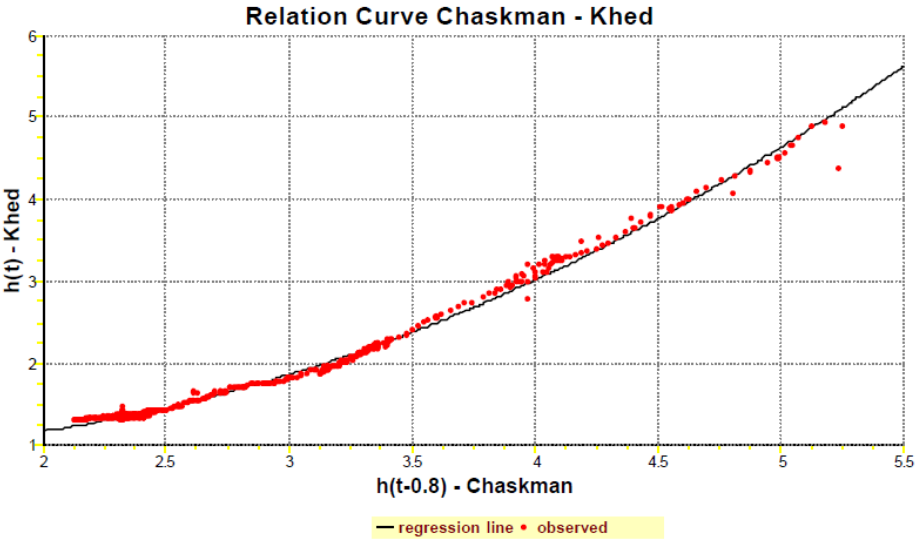


Figure 4.1 Example water level relation curve

In secondary validation, relation curves can be plotted and relation equations valid for different time periods can be compared. If there is a defined relationship between two water level series, random errors will be shown on a relation curve plot as outliers. After determining in which series the problem has arisen and the actual value at fault, taking into account the lag time between stations, a corrected value is estimated using the relation equation and substituted in the time series. Shifts in the relationship between the two water level series indicate a physical change at one of the stations, such as shifts in gauge zero, changes in cross-section, relocation of station, etc. Where such shifts in the relationship are accompanied by changes in the stage-discharge relationship at one station, the changed relation curve is acceptable. However, where no such accompanying change in the stage-discharge has been notified, further clarification should be requested from the supervising field officer (Section 4.4.3). For more information see SW8-OM(II) Chapters 7.4 and 8.5.

4.4 Correction and completion

4.4.1 Overview

Completion – the processing of filling in missing values and correcting erroneous values – is done as a continuous process with primary and secondary validation. Although the HIS Manual SW separates correction and completion in SW8-OM(II) Chapter 8 from secondary validation in SW8-OM(II) Chapter 7, and from primary validation in SW8-OM(I) Chapter 9, there is substantial overlap between the techniques used. In this Handbook, some correction and completion techniques have been included in the appropriate parts of Sections 4.2 and 4.3, and others are described below. Examples of many of the techniques described, which should be carried out by experienced staff with appropriate training, are given in Surface Water Training Module 24 “How to correct and complete water level data”.

The majority of secondary validation, and therefore the majority of correction and completion, is carried out by State DPCs to take advantage of the information available from a larger area. For the Hydrology Project, correction and completion (see Table 3.1) should be completed by the end of the following month (e.g. for June data by 31st July). Some secondary validation, correction and completion will not be possible until the end of the hydrological year when the entire year’s data can be reviewed in a long-term context, so data should be regarded as provisional approved data until then (e.g. for June data by the end of the hydrological year plus 3 months), after which data should be formally approved and made available for dissemination to external users.

Correction and completion may be carried out with respect to the water level series or it may await transformation to flow using a stage-discharge relationship. The choice of water level or flow for correction depends on the type of error, the duration of missing or erroneous records and the availability of suitable records with which to estimate. Correction as water level has the advantage that it is the primary measurement, whereas errors in flow may be a consequence either of error in the water level record or in the stage-discharge relationship. However, it also has the disadvantage that it provides no volumetric water balance checks so that records completed as stage will receive further validation as discharge, and may require further correction.

Circumstances where correction and completion will usually be carried out as water level include:

- Where the level record is complete but the recorder has gone out of adjustment and periodic check observations are available
- Where the level record is correct but shifted in time
- Where the primary record (e.g. from a DWLR) is missing but an alternative level record of acceptable quality is available at the same station
- Where the record is missing but the duration is short during a period of low flow or recession
- Where a record is available from a neighbouring station with little lateral inflow or abstraction between the stations

Circumstances where correction and completion will usually be carried out as flow include:

- Where a record is available only from a neighbouring station with much lateral inflow or abstraction
- Where one or both stations are affected by variable backwater effects
- Where the only available means of infilling is from basin rainfall and the use of a rainfall-runoff model

It should be recognised that values estimated from other gauges are inherently less reliable than values properly measured. There will be circumstances where no suitable neighbouring observations or stations are available, such that missing values should be left as -999 and incorrect values should be set to -999, and suspect original values should be given the benefit of the doubt and retained in the record with an appropriate flag. In all cases, the water level data should be revalidated after correction and/or completion.

4.4.2 Correcting missing and erroneous data

Missing values (-999 or incorrect zeros) may be the result of the observer failing to make an observation, failing to enter the observation in the record sheet, or entering the observation incorrectly. It may the case that only a staff gauge is available at a station, or that a suspect part of the AWLR/DWLR record needs replacing and the staff gauge time interval is not sufficiently small in relation to water level changes.

Gaps or erroneous values may be infilled by linear interpolation where they occur during periods of low flow or during recession and the difference between the level at the beginning and end of the gap is small. During periods of low flow, gaps of one to several days may be infilled in this way, but it is recommended that infilling by linear interpolation during the monsoon or on a heavily regulated rivers should not exceed 6 hours. For longer gaps during a recession, when the change in water level is a result only of baseflow contribution from groundwater, the hydrograph shows an exponential decay, which, when plotted on a semi-logarithmic scale, plots as a straight line. Gaps of a month or more may be infilled in this way.

Otherwise, a relation curve based on the data of two water level series can also be used to infill missing or erroneous data (Section 4.3.4). The relation equation is used to calculate the missing value(s) at the station under consideration that correspond to the observed values at the upstream or downstream analogue station. The infilled data should always be revalidated. Where there is some doubt as to the interpretation, the value should be left unchanged but flagged as suspect.

4.4.3 Correcting shifted data

Shifts in water level observations due to change in gauge zero or changes in cross-section conditions can be detected by comparing two relation curves or the plot of one period with that of another. For routine validation and completion, the comparison will be between data for the current period and an established curve for the station. If the new relation differs and there is a new stable relationship between the records and the deviation from the previous relation is constant, then a shift in the reference gauge is suspected. The time of its occurrence can be identified from the comparison plots. If there is a change in slope of the relation curve compared with the established curve, then a change in cross-section at one of the stations may be suspected.

Where such shifts in the relationship are accompanied by changes in the stage-discharge relationship at one of the stations station, the changed relation curve is acceptable. However, where no such accompanying change in the stage-discharge has been notified, further clarification should be requested from the supervising field officer to identify the station causing the error:

- Where additional stations are available for comparison, further relation curves may be developed and the station in error identified
- Field staff should re-survey gauge datums and the cross-sections at both stations
- If, after survey, the gauge zero at one station is found to have inadvertently altered, then it should be reset to its former level. The stage level during the period between gauge shift and resetting should be corrected by the deviation shown by survey (and confirmed by the constant difference in relation curves)
- If no change in gauge zero is found but the cross-section at one station has altered, then field staff should intensify flow gauging to establish a new stage-discharge relationship. Usually the stage record will not be changed but the revised rating curve applied over the period from the occurrence of the change in cross-section (usually during a flood)

5. Stage-Discharge Data Processing and Analysis

5.1 Data entry

5.1.1 Overview

Flow measurements and the associated measurement of river level at a gauging station provide the means of establishing a relationship between stage and discharge, known as the rating curve, for any river gauging station. Discharge is determined using either a current meter to measure velocity at a number of points across a cross-section and the associated cross-sectional area of flowing water, or an ADCP to measure flow directly across a river channel. Where neither of these options is available, velocity may be determined more approximately using the float method and, in flood flows, the slope-area method may be used to compute discharge using a measurement of the slope of the water surface.

Entry of data to computer is primarily done at a Sub-Divisional office level where staff are in close contact to field teams who have made the flow gauging and collected the stage-discharge data. Data entry is carried out using e-SWIS, the data entry module of which replicates the SWDES software from HPI, and is referred to as eSWDES. Prior to entry to computer, two manual activities are essential: registration of receipt of the data, and manual inspection of the notebooks and/or computer files from the field, for complete information and obvious errors. Data entry (see Table 3.1) and primary validation of flow gauging data from observational stations is required to be completed at Sub-Divisional/Divisional office level by the 10th working day of the following month (e.g. for June data by 10th working day in July), after which all data should be available in State DPCs for State data, and CWC local offices for CWC data.

5.1.2 Manual inspection of field records

Prior to data entry to computer an initial inspection of field records – notebooks and/or computer files - is required to ensure that location and date/time details are complete and correct. Indeed, this should be done immediately upon receipt of the records at the Sub-Divisional offices as resolution of such faults is much more difficult at a later stage when forms from several gauging stations are present. Inspection of numerical values is also essential to eliminate obviously erroneous values arising from faulty observation or recording of data.

Any queries arising from such inspection should be communicated to the gauging team to confirm ambiguous data before data entry. Any unresolved problems should be noted for further review during primary validation. Any equipment failure or observer problem should be communicated to the supervising field officer for rectification.

5.1.3 Entry of gauging reference information

There are two types of gauging reference information which are entered through the eSWDES module in e-SWIS. One type relates to the cross-sectional data at the river gauging station, necessary for velocity-area methods. The gauging section is normally surveyed twice per year, before and after the monsoon but may be surveyed more frequently if changes are suspected. Hence, these data are only entered when they are updated and not for every flow gauging. Cross-sectional data comprise pairs of distance and elevation points on the cross-sectional profile of the river gauging section. The distances are taken with respect to an origin on the gauging section and the elevations are reported with respect to the mean sea level as the datum. The date of survey is always associated with the cross-sectional data. Any number of pairs of cross-section data points can be entered. At the time of data entry, distances are checked if they are in increasing or decreasing order of the magnitude, and cross-sectional profiles may be plotted to check for a realistic channel shape.

The second type of gauging reference information is entered for every flow gauging, and specifies:

- Location
- Date/time information for the beginning and end of the gauging
- Method of gauging (i.e. the mode of crossing, the method of velocity observation, the location of the gauging site, and the depth-sounding method)
- Conditions of water and weather during the gauging which might influence either the stage-discharge relationship or the accuracy of the measurement (i.e. water temperature, air temperature, wind speed and direction, condition of water, condition of weather)
- Water level at the beginning and end of the gauging - where the gauging site is known to be affected by backwater effects and a second set of gauges is available downstream for estimating fall then the coincident water level readings at main and twin station are entered

The user is prompted should any of the entered data not be in the correct alphanumeric format or expected range. Each flow gauging is assigned a unique reference number.

5.1.4 Entry of current meter gaugings

For current meter flow gauging, the discharge is estimated as the sum of segment (or sectional) discharges across the cross-section. These are computed as the product of the mean velocity and segment area, which is in turn based on the measurement of segment widths and depths. The field team making the flow gauging are required to compute the discharge in the field from the raw data, but during data entry the user enters only the raw data and computation of discharge is repeated automatically by the software, for comparison during primary validation.

Using the eSWDES module in e-SWIS, the user selects the correct station. The screen for entry of current meter gauging data is displayed. For each flow gauging, details of the current meter used are selected from a previously entered list of meters for which calibration details are held in the database. Having chosen the meter, the appropriate calibration between meter revolutions and water velocity is automatically applied to compute point velocity from the number of measured revolutions in given time. The user is required to enter the results of a spin test to demonstrate the condition of the meter. Next the user enters the method of suspending the meter, the weight used with the meter, and the number of compartments (usually 1 unless the gauging site is a bridge with multiple piers or a braided river). The remainder of the raw data is entered through a tabular form, with one row for each reading and column fields as follows:

- Column 1: Compartment serial number
- Column 2: Total number of segments and segment number
- Column 3: Reduced distance of segment i.e. the distance at which the velocity measurements are taken
- Column 4: Observed water depth of segment
- Column 5: Vertical angle of sounding reel
- Column 6: Airline depth
- Column 7 & 8: Airline and wetline corrections
- Column 9: Corrected water depth of segment
- Column 10: Area of segment
- Column 11: Number of velocity observations in segment (up to 3)
- Column 12: Details of velocity observations
- Column 13: Depth of each velocity observation in segment
- Column 14: Coefficient to be used for computation of mean velocity in segment
- Column 15: Number of meter revolutions for each velocity observation in segment
- Column 16: Time taken for each velocity observation in segment

- Column 17: Point velocity for each velocity observation in segment – automatically calculated by software
- Column 18: Mean velocity in segment
- Column 19: Angle of current with gauge line
- Column 20: Corrected mean velocity in segment
- Column 21: Drift distance during velocity observation
- Column 22: Time for drift
- Column 23: Drift correction
- Column 24: Final corrected velocity in segment
- Column 25: Discharge for segment – automatically calculated by software
- Column 26: Discharge for segment from field documents
- Column 27: Comments

After entering the tabular data for all sections of each compartment, totals for the entire cross-section are automatically computed for top width, wetted perimeter, total area and total discharge. Further details about the content of each column are provided in SW8-OM(I) Chapter 10.4.2. Where no data are available for one or more of these columns, a facility is provided for hiding columns.

After data entry, the discharge values in Columns 25 and 26 are compared and if the difference is more than 1% of the discharge, the user is prompted to check the entries for errors. Where there is a consistent difference, the current meter calibration used by observer and computer should be compared. This checking provides a means of avoiding data entry errors.

Two different graphs may be plotted after data entry. The first shows the velocity distribution across the gauging section giving the point velocities at each vertical segment and the profile of mean velocity along the gauging section. The second shows the distribution of discharge giving the histogram of discharge flowing through each segment in percentage and absolute form.

5.1.5 Entry of float observations

eSWDES allows entry of data from the float method, used to estimate the flow during high water levels when it is very difficult to make velocity or flow measurements with a current meter or ADCP, respectively. For the float method, the velocity of flow is estimated from floats and multiplied by the cross-sectional area to get the discharge. During data entry, the user enters the type of float, length of float run and float coefficient, followed by the cross-sectional details for computing compartmental area, and the float observations for computing velocity and discharge in each compartment.

5.1.6 Entry of ADCP gaugings

ADCP flow gauging are entered as stage-discharge summary data (Section 5.1.8). The guidance note "How to process and validate ADCP river discharge measurements", included in Annex IV of this Handbook, presents general advice on the processing and validation of the river discharge measurements obtained.

5.1.7 Entry of slope-area observations

eSWDES allows entry of data from the slope-area method, used to estimate the flow during high water levels when it is very difficult to make velocity or flow measurements with a current meter or ADCP, respectively. For the slope-area method, the mean slope of the water surface is estimated from observed water level readings at the gauging site and upstream and downstream staff gauges, and the velocity of flow is estimated using the Manning's formulae and multiplied by the cross-sectional area to get the discharge. During data entry, the user enters the distances between the three sets of staff gauges and the observed water levels at those gauges, and the software calculates the mean slope. The required value of Manning's n for the velocity calculation may be based on the type of bed and condition of flow, or estimated from previous gaugings when the flow was estimated from direct velocity observations.

5.1.8 Entry of stage-discharge summary data

Only summary flow gauging information is needed for developing stage-discharge relationships. This summary information may be automatically generated from the detailed data already entered.

However, if the detailed data are not available, as in the case of historical flow data or ADCP data, the summary information may be entered directly. Using the eSWDES module in e-SWIS, the user selects the correct station. The screen for entry of summary flow gauging data is displayed. For each flow gauging, the date and time of observation together with the unique gauging reference number observation number are entered, followed by, where available, the mean water level, the measured discharge, the cross-sectional area, the surface slope, top width and wetted perimeter. From these the hydraulic radius, mean velocity and Manning's n are automatically calculated. Optional information, where available, include the gradient and fall. Other information concern the mode of crossing, method of velocity observation, number of verticals, maximum velocity, weather condition, wind velocity, wind direction and any comments. Where no data are available for one or more of these columns, a facility is provided for hiding columns.

Scatter plots of the stage and discharge data for a year assist in detecting data entry errors since erroneous data points will normally plot as outliers, though these should not be rejected without further investigation.

5.2 Primary validation

5.2.1 Overview

Primary validation is primarily done at a Sub-Divisional office level where staff are in close contact to field staff who have made the flow gaugings. Primary validation is carried out using e-SWIS, the data entry module of which replicates the SWDES software from HPI, and is referred to as eSWDES. Primary validation (see Table 3.1) of flow gauging data from observational stations is required to be completed at Sub-Divisional/Divisional office level by the 10th working day of the following month (e.g. for June data by 10th working day in July), after which all data should be available in State DPCs for State data, and CWC local offices for CWC data. This time schedule ensures that any obvious problems (e.g. indicating an instrument malfunction, observer error, etc) or potential shifts in the rating are spotted at the earliest opportunity and resolved. Other problems may not become apparent until more data have been collected, and data can be viewed in a longer-term context.

Primary validation of flow gauging data focuses on inspection of field documents from the gauging, comparison of field-computed and office-computed discharge, and comparison of the flow gauging with the existing rating curve. Inspection of the field documents is necessary to check that the ancillary information in the notebooks and/or computer files is complete and that any change at the station which may have influenced the relationship between stage and discharge is available for interpretation of the computed discharge. Information which may be relevant includes:

- Rates of rise and fall in level during measurement (possible unsteady flow effect)
- Backwater due to very high stages (i.e. flooding) in receiving river or contributing tributary downstream of gauging station
- Flood in deposition or scour of the channel at the gauge or at the downstream control, based on observer observations

- Gravel extraction at the station or downstream
- Bunding or blockage in the downstream channel
- Weed growth in the channel
- Change in datum at the station, adjustment or replacement of staff gauges

The stage recorded at the beginning and end and during the flow gauging must be compared with the hourly or other water level observation by recorder or manually. Any discrepancy must be investigated by reference to the supervising field officer. The error may be in the water level record or in the stage observation during flow gauging; if the latter then the mean stage in the summary form for the flow gauging should be amended. Examples of many of the techniques described in this section are given in Surface Water Training Module 28 "How to carry out primary validation of stage-discharge data".

5.2.2 Comparison of field-computed and office-computed discharges

The calculation of discharge from current meter flow gaugings is initially carried out in the field by the gauging team. On receipt in the office, the flow gauging data are entered to computer and the discharge is recomputed. If the discharge determined from the two calculations differs, the source of the difference must be identified and the necessary correction made. In particular, line by line comparisons of the two calculations should be made to identify data entry errors to computer. If none are found, arithmetic errors should be sought in the field calculation. Other potential sources of discrepancy in current meter gauging are in the use of the wrong current meter rating in one of the calculations or incorrect entry of current meter rating parameters. Any errors in the field computation should be notified to the supervising field officer.

5.2.3 Comparison of computed discharge with existing rating curve

Flow gaugings are validated by a combination of graphical and tabular approaches. Gaugings are compared graphically with the existing rating curve, and through a table of the actual and percentage deviation of the gauging from the previously established rating, with respect to flow. The percentage deviation of a flow gauging from the existing rating curve that initiates further investigation depends on the physical characteristics of the station and the assumed accuracy with which individual measurements can be made. For instance, at a station with sensitive control and a regular gauging section an error of ± 5% may be achieved, but at irregular sections with erratic velocity distribution an error of ± 10% may be acceptable. In general, flow gaugings should be investigated further if the deviation from the existing rating curve exceeds 10% or, if a sequence of gaugings shows persistent positive or negative deviations from the established rating. Significant deviations may be due to:

- ***The reliability of the individual gauging*** – an individual current meter gauging may be unreliable due to:
    - An inadequate number of verticals taken to define total area and mean velocity
    - Very low velocities in the section not measured accurately by available equipment
    - No air/wet line corrections made to depth measurement in high flow
    - No angle correction for gaugings taken oblique to the flow
    - A faulty current meter

  The first four points can be identified from the tabulated gauging, and the last point from field inspection or by persistent differences between the results from the specified meter and other meters at the same station revealed by a plot of cross-sectional velocity against stage for individual gaugings.

- ***The general accuracy with which gaugings can be made at a station*** - this depends to a large extent of the regularity of the bed and banks at the gauging cross-section, and on the bed roughness and the existence of a bend in the approach channel, and whether or not these are subject to change. These factors control the velocity distribution across the section irregularities may result in rapid velocity variations across the section and deviation from a typical logarithmic velocity profile in the vertical, particularly affecting current meter gaugings, and identified from plots of velocity contours or velocity vectors across the cross-section.

- ***Actual changes in the stage-discharge relationship*** - deviation from a single power law rating curve may arise from:
  - Unsteady flow causing hysteresis with rising and falling floods - an unsteady flow rating should be adopted
  - Changes in cross-section at the control section due to natural scour or deposition or gravel extraction – a new rating or rating with shift adjustment should be considered
  - Discharge for given level may be affected by downstream bed changes even if no change is found at the station itself – a new rating or rating with shift adjustment should be considered
  - Discharge for given level may be affected by downstream backwater conditions caused, for example, by a confluence or by tidal effects - rating curves with backwater corrections should be applied
  - Weed growth at or downstream from the station may be identified by changes in the mean velocity profile across the section – a rating with shift adjustment should be considered
  - Bed profile and mean velocity profiles remain sensibly constant from one gauging to another but the plotted point deviates from the existing rating – possibly caused by a change in the datum or a shift in the staff gauge – a new rating should be adopted

Early identification of the cause of any significant deviation is necessary so that gauging practice can be adjusted or, in the case of rating changes, so that gauging programme can be intensified to establish a new relationship.

5.3 Fitting rating curves

5.3.1 Overview

Flow is the variable usually required for hydrological analysis, but continuous measurement of flow past a river section is usually impractical or prohibitively expensive. However, stage (or water level) can be observed continuously or at regular short time intervals with comparative ease and economy, and a relationship derived between stage and the corresponding discharge (or flow) at a specific river gauging station. This stage-discharge relationship is known as a rating curve.

A rating curve is established by making and fitting a relationship to a number of concurrent observations of stage and discharge over a period of time covering the expected range of stages at the river gauging section. However, because it is difficult to measure flow at very high and low stages due to their infrequent occurrence and also to the inherent difficulty of such measurements, extrapolation is often required to cover the full range of flows (Section 5.3.4). The rating curve may be shown graphically as the curve fitting the plot of stage-discharge measurements at a river cross-section (Figure 5.1). The established rating curve is used to transform observed stages into corresponding discharges.

The shape, reliability and stability of the rating curve are controlled by a section or reach of channel at or downstream of the gauging station, known as the station control. The establishment and interpretation of rating curves requires an understanding of the nature of controls and the types of control at a particular station. The channel characteristics forming the control include the cross-sectional area and shape of the channel, expansions and restrictions in the channel, channel sinuosity, the stability and roughness of the streambed, and the vegetation cover, all of which collectively constitute the factors determining the channel conveyance. Station controls are classified as:

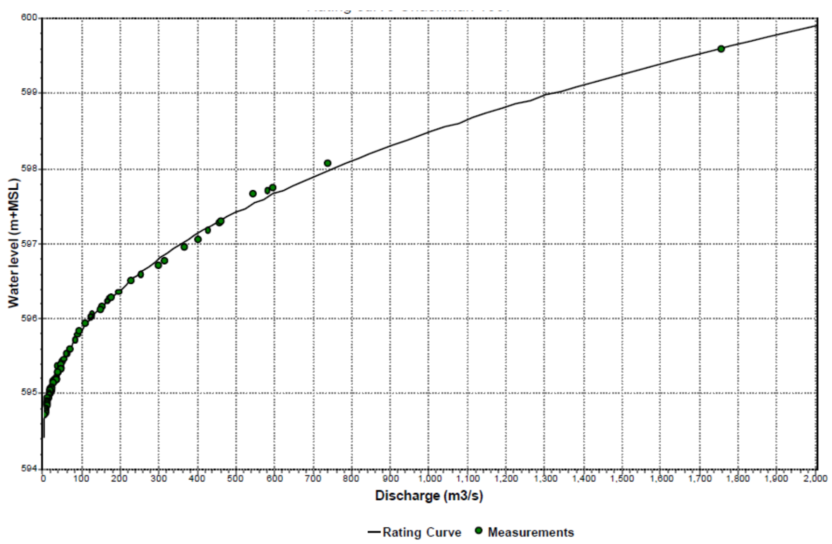


Figure 5.1 Example of stage-discharge relationship or rating curve

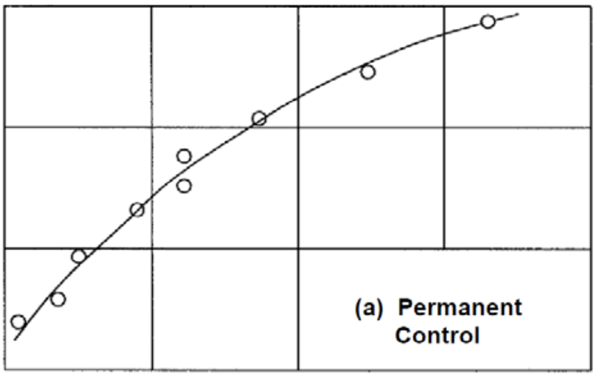
- Section and channel controls – a natural structure (section) or reach of channel (channel) prevent the stage-discharge relationship being affected by any disturbance in the channel downstream
- Natural and artificial controls – a natural or artificial structure controls the stage-discharge relationship
- Complete, compound and partial controls – different controls (partial), or a combination of controls (compound), may operate at different water level ranges
- Permanent and shifting controls – controls may change with time (shifting) as a result of scour and fill, growth and decay of aquatic vegetation, etc

The gauging effort and maintenance cost to obtain a stage-discharge record of adequate quality is much greater for shifting controls than for permanent controls. Since rating curves for the unstable controls must be updated and/or validated at frequent intervals, regular and frequent flow measurements are required. In contrast, for stable controls, the rating curve can be established and validated periodically. Therefore, it is preferable to select a gauging site with a section or structure control. However, this is not practicable in many cases, and many gauging sites have a channel control or a compound control.

For the Hydrology Project, fitting, extrapolating and validating of rating curves is primarily done at State level, with support from CWC local offices as necessary. Staff should be familiar with hydrometry and the expected hydrological behaviour of the flow gauging station, and should have received appropriate training in fitting, extrapolating and validating stage-discharge relationships. Staff should know how stable the stage-discharge relationship at each flow gauging station is and, therefore, how frequently the rating curve at each station needs to be checked and updated. Rating curves are fitted using e-SWIS, the validation module of which replicates the HYMOS software from HPI, and is referred to as eHYMOS.

5.3.2 Fitting rating curves

The form of the fitted rating curve (used to transform stage to discharge) depends on physical conditions at the station and in the river reach downstream. The discharge may not be a unique function of stage, and variables may also be needed e.g. surface slope, rate of change of stage with respect to time, etc. When there is negligible scatter in the plotted points, the stage-discharge data are fitted by a single power law rating curve, valid for a given time period and water level range, of the form:



$$Q = c(h+a)^b$$

Where:

Q = discharge (m^3s^{-1})
h = measured water level (m)
a = water level (m) corresponding to Q = 0
b, c = exponent and coefficient derived for the relationship corresponding to the station characteristics

Figure 5.2 Form of single power law rating curve

The rating curve equation may also be parabolic (usually derived from modelling rather than from stage-discharge data) or compound to include floodplain flow which may have a different hydrological behaviour to the main channel, and may be corrected for unsteady flow and backwater effects, of for a shifting control. The general principle of fitting rating curves, and examples of more complex stage-discharge relationships are given in SW8-OM(II) Chapter 9.3 and Surface Water Training Module 29 “How to validate rating curve”.

5.3.3 Primary validation of rating curves

Validation of a rating curve is required, initially, after the stage-discharge relationship has first been fitted and, subsequently, when new flow gaugings have been carried out, to assess whether these indicate a change in rating. Flow gauging is carried out with variable frequency depending on previous experience of the stability of the control and of the rating curve. As a minimum it is recommended that six check gaugings per year are carried out even with a station with a stable section and previously gauged over the full range of level. At unstable sections many more gaugings are required. Validation is also used to assess the reliability of historical ratings.

The deviation of check gaugings from the previously established stage-discharge relationship is examined using a combination of graphical and numerical tests designed to show whether the check gaugings fit the current relationship equally and without bias over the full range of flow and over the full time period to which it has been applied. If they do not, then a new rating should be developed, taking into account the deficiencies noted in validation. More details and examples of many of the techniques described in this section are given in Surface Water Training Module 30 “How to validate rating curve”.

Graphical tests are often the most effective means of validation, though may be indicative of a potential change rather than prescriptive to the details of the change:

- ***Stage-discharge plot with new gaugings*** – as in primary validation, plotting the existing rating curve with the new check gaugings is the simplest means of validating the rating curve with respect to subsequent gaugings. If there is no change it is expected that 19 out of 20 check gaugings will lie inside the existing rating curve’s 95% confidence limits (derived as t-times the standard error) if the standard error is considered at a 5% significance level. However, unless the majority of the check gauging plot either above or below the existing rating curve, the graph does not show any significant change in behaviour. If a certain pattern of deviation (with respect to time) is perceivable and significant then a revision of the rating is recommended.
- ***Period-flow deviation scattergram*** – the percentage deviation of each gauging from the existing rating curve, with respect to flow, is plotted against gauging time order as a scattergram to show whether there has been a gradual or sudden shift in the direction of

deviations within the period to which the rating has been applied. It shows whether recent check gaugings show deviation from the existing rating curve. If there are far more gaugings with deviations in one direction than the other, the rating is biased and a revision of the rating is recommended.

- ***Stage-flow deviation scattergram*** – the percentage deviation of each gauging from the existing rating curve, with respect to flow, is plotted against gauging water level as a scattergram to show whether the existing rating curve is biased over certain stage ranges. It shows whether recent check gaugings show deviation from the existing rating curve. If there are greater deviations at different stages, part of the rating is biased and a revision of the rating is recommended.
- ***Cumulative deviation plot of gaugings*** - the cumulative deviation of gaugings from the existing rating curve is plotted against gauging time order as a line graph, to give another indication of bias and whether that bias changes with time. It shows whether recent check gaugings show deviation from the existing rating curve. If the line shows a significant upward or downward trend, the rating is biased and a revision of the rating is recommended.
- ***Stage-discharge plots with gaugings distinguished by season*** - it is sometimes helpful to separate gaugings between seasons to demonstrate the effect of varying weed growth or other seasonal factors on the stage-discharge relationship. The effects of weed growth may be expected to be at a maximum in low flows before the onset of the monsoon; monsoon high flows wash out the weed which increases progressively from the end of the rains. The discharge for given stage may thus differ from one month to another. This shows up more clearly in rivers where winter low flows are less affected by weed growth than summer low flows.

Numerical tests include:

- ***Student's t-test to check flow gauging*** - used to decide whether check gaugings may be accepted as part of the homogeneous sample of observations making up the existing stage-discharge relationship. Such a test will indicate whether or not the rating curve requires updating or the section requires recalibration.
- ***Test for absence of bias in signs*** – used to see if the rating curve has been established in a balanced manner so that the two sets of discharge values, observed and estimated (from the curve), may be reasonably supposed to represent the same population. A well-balanced rating curve has an even distribution of positive and negative deviations of the gaugings from the rating curve i.e. the difference in numbers between the two should not be more than can be explained by chance fluctuations.
- ***Test for absence of bias in values*** – used to see if a particular rating curve, on average, yields significant under-estimates or over-estimates as compared to the actual flow gauging on which it is based (numerical equivalent of the graphical period-flow deviation and stage-flow deviation scattergrams).
- ***Goodness of fit test*** – used to ensure a balanced fit in reference to the deviations over different stages. Due to changes in the flow regime, or a badly fitted rating curve, it is possible that long runs of positive and/or negative deviations of flow gauging from the rating curve are obtained at various stages (numerical equivalent of the graphical stage-flow deviation scattergram and cumulative deviation plot of gaugings).

5.3.4 Extrapolating rating curves

Extrapolation of rating curves is required because the range of water levels over which flow gauging has been carried out does not cover the full range of observed water levels. The rating curve may fall short at both the lower and the upper ends. Extreme flows are often the most important for design and planning and it is important that the best possible flow estimates are made. ·Very high flows are particularly difficult to gauge because they occur infrequently, are of short duration and may occur at night, so the gauging team may not be on site at the peak of the flood. Furthermore, the flow conditions may be too dangerous to gauge safely as the gauging site may be inaccessible, the gauging facilities no longer serviceable and/or the river may have spread from a confined channel to an inaccessible floodplain. Low flows are also difficult to gauge because the depth of water in may be insufficient for accurate flow gauging and the channel may bifurcate into several small channels.

Extrapolation is usually more complex than simply extending the rating from existing gaugings to extreme levels (although in some cases this may be acceptable), because a different control may apply, the channel geometry may change, flow may occur over the floodplain and form and vegetation roughness coefficients may change. Applicable methods of extrapolation depend on the physical condition of the channel, whether inbank or overbank and whether it has fixed or shifting controls. Consideration must also be given to the kinematic effect of open channel flow when there may be reduction in the mean velocity in the main channel during inundation of the floodplain. More details and examples of many of the techniques described below are given in Surface Water Training Module 31 “How to extrapolate rating curve” and Training Module 32 “How to carry out secondary validation of stage-discharge data”.

High flow extrapolation methods include:

- ***Double log plot method*** - where the hydraulic characteristics of the control section do not change much beyond the measured range, extrapolation of the logarithmic stage-discharge relationship may be used. The relationship is extended graphically beyond the measured range by projecting the last segment of the straight line relationship in log-log space.
- ***Stage-area-velocity method*** - where extrapolation is needed either well beyond the measured range, or there are known changes in the hydraulic characteristics of the control section, a combination of stage-area and stage-mean velocity curves may be used. For stable channels the stage-area relationship is fixed and is determined by survey up to the highest required stage. The stage-mean velocity curve is based on flow gauging within the measured range and, since the rate of increase in velocity at higher stages diminishes rapidly, this curve can be extended without much error for inbank flows. Discharge for a given (extended) stage is then obtained by the product of area and mean velocity from the extrapolated stage-area and stage-mean velocity curves. This method may be used for extrapolation at both the upper and lower end of the rating curve.
- ***Manning’s equation method*** – a variation of the stage-area-velocity method uses the Manning equation which may be written as:

  $$v = K_m R^{2/3} S^{1/2}$$

  Where: v = mean velocity (i.e. discharge Q/area A)
  K_m = 1/n where n is Manning’s roughness coefficient
  R = hydraulic radius
  S = slope

  At higher stages the value of $K_m S^{1/2}$ approaches a constant value, and the equation may be rewritten as:

  $$v = K^* R^{2/3} \quad \text{or} \quad K^* = v / R^{2/3}$$

  A graph of stage against K* is plotted from flow gaugings to identify the value at which K* becomes nearly constant. This value of K* is used in conjunction with extrapolated relationships between stage and A, and between stage and R, based on survey. Discharge for extrapolated stage is obtained by applying the Manning equation with K* and extrapolated values of A and R.
- ***Conveyance slope method*** – also based on the Manning equation, separating out the conveyance term, and is particularly useful for sections with overbank flow:

  $$Q = K S^{1/2}$$

  Where: K = conveyance given by:

  $$K = K_m A R^{2/3}$$

> To assess K for a given stage, A and R are based on survey and values of n are estimated in the field, and a graph of K against stage is plotted up to the maximum required stage. For flow gaugings, $S^{1/2}$ may be computed by dividing the measured discharge by its corresponding K value, and a graph of S against stage is plotted and extrapolated to the maximum required stage (as S tends to become constant at higher stages). Discharge for extrapolated stage is obtained by multiplying the corresponding values of K from the K curve and $S^{1/2}$ from the S curve.

Low flow extrapolation is best performed manually on natural graph paper rather (because the coordinates of zero flow cannot be plotted on log graph paper), with an eye-guided curve drawn between the lowest point of the known rating to the known point of zero flow, obtained by observation or by survey. Improvement can only come from further low flow gaugings.

One means of providing a further check on the reliability of an extrapolated rating curve is to make comparisons of flows computed using rating curves between neighbouring stations (Section 6.2.3). If there is an inconsistency or an abrupt change in the relationship between flow series at sequential stations on a river or around a confluence, the most likely source is the stage-discharge relationship at one or more of the compared stations. Where such inconsistencies are observed, rating curves and their extrapolations must be reviewed.

.

6. Flow Data Processing and Analysis

6.1 Data computation

6.1.1 Overview

With limited exceptions, flow cannot be measured both directly and continuously. Instead measurements of stage (or water level) are made continuously or at specified intervals at a gauging station and converted to discharge (flow) by the use of stage-discharge relationships or rating curves. Computation of discharge is normally carried out monthly on the stage data from the previous month once they are validated. For the Hydrology Project, secondary validation, correction and completion of water level data at State level should be completed by the end of the following month (e.g. for June data by 31st July). The computed flow data then undergo secondary validation themselves, by the end of the following month plus one (e.g. for June data by 31st August). Some secondary validation will not be possible until the end of the hydrological year when the entire year's data can be reviewed in a long-term context, so data should be regarded as provisional approved data until then (e.g. for June data by the end of the hydrological year plus 3 months), after which data should be formally approved and made available for dissemination to external users.

Computation of discharge is primarily done at a State level (see Table 3.1). Data computation is carried out using e-SWIS, the validation module of which replicates the HYMOS software from HPI, and is referred to as eHYMOS. Prior to computation, it is essential to have available a summary of all the relevant information for the station, including:

- The stage record - to ensure that it is complete and without abrupt discontinuities
- A listing of stage-discharge relationships to check that periods of application do not overlap or have gaps between ratings
- Ancillary information based on field documents and/or on information from validation of stage or stage-discharge relationships, in particular, information on datum changes, scour and deposition, blockage and backwater effects, adjustments or corrections applied during validation

6.2 Secondary validation

6.2.1 Overview

Secondary data validation is largely carried out at State DPCs, to take advantage of the information available from a larger area. Secondary validation is carried out using e-SWIS, the validation module of which replicates the HYMOS software from HPI, and is referred to as eHYMOS. Data may also be exported to Excel for secondary validation. For the Hydrology Project, initial secondary validation (see Table 3.1) should be completed by the end of the following month plus one (e.g. for June data by 31st August). Some secondary validation (including comparison with CWC data) will not be possible until the end of the hydrological year when the entire year's data can be reviewed in a long-term context, so data should be regarded as provisional approved data until then (e.g. for June data by the end of the hydrological year plus 3 months), after which data should be formally approved and made available for dissemination to external users.

The quality and reliability of a flow series depends primarily on the quality of the water level measurements and the stage-discharge relationship from which it has been derived. Validation flags inserted during the validation of water level data are transferred through to the flow time series. Hence, the flow data entering secondary validation will contain flagged values whose accuracy is suspect, corrected, or missing. These will need to be reviewed, corrected, or inserted. New errors may also show up during secondary validation e.g. errors may also arise from the use of the wrong water level series, or the wrong or out-of-date stage-discharge relationship, causing discontinuities in the discharge series. Secondary validation of flow data includes both validation within a single data series by making comparisons between individual values and pre-set physical limits, and comparisons with neighbouring stations to identify suspect values. The main comparisons are between flow series at successive points on the same river. Comparisons are also made between flow data and incident rainfall. Examples of many of the techniques described in this section are given in Surface Water Training Module 32 “How to carry out secondary validation of stage-discharge data”, Training Module 36 “How to carry out secondary validation of discharge data”, Training Module 37 “How to do hydrological data validation using regression”, Training Module 38 “How to do hydrological data validation using hydrological models” and Training Module 39 “How to correct and complete discharge data”.

6.2.2 Single station validation methods

Single station validation against data limits and expected hydrological behaviour is carried out by the inspection of the data using a combination of graphical and tabular displays. Flow data at a particular station are checked numerically against maximum and minimum flows, relative departures from the mean, and maximum rates of rise and fall.

Values which exceed a maximum limit or fall below a minimum limit may be flagged. The specified values are normally the previously observed maximum and minimum limits at the station. The object is to screen out spurious extremes, but care must be taken not to remove or correct true extreme values as these may be the most important values in the series. A larger number of values may be flagged which exceed specified departures (α and β) from the mean of the flow series (Qmean) by some multiple of the standard deviation (Sx):

$$Q_{upper} = Q_{mean} + \alpha\, s_x$$

$$Q_{lower} = Q_{mean} - \beta\, s_x$$

The object is to set screen out a manageable number of outliers for inspection whilst giving reasonable confidence that all suspect values are flagged. Finally, values are flagged which exceed a specified difference from their adjacent values. Acceptable rates of rise and fall may be specified separately and, generally, allowable rates of rise will be greater than allowable rates of fall.

Visual checking of flow data is often a more efficient technique for detecting data anomalies than numerical checking. The flow data may be displayed alone or with the associated water level data, and the plot should covers at least two months to reveal any discontinuities which may appear between successive monthly updates of the flow series. The plots may show the maximum, minimum and relative limits, and may be displayed in the natural units or the values may be log-transformed where the data cover several orders of magnitude and enables flows near the maximum and minimum to be displayed with the same level of precision. Log-transformation is also a useful means of identifying anomalies in dry season recessions as, while recessions are curved in natural units, they show as straight lines in log-transformed plots.

The main purpose of graphical inspection is to identify any abrupt discontinuities in the data or the existence of positive or negative spikes which do not conform to expected hydrological behaviour. These may be caused by: use of the wrong stage-discharge relationship, use of incorrect units, abrupt discontinuity in a recession, and isolated highs and lows of unknown source. However, anomalous hydrological behaviour should not be confused with genuine artificial influences on the natural flow regime e.g. the natural pattern may be disrupted by reservoir releases which may have abrupt onset and termination, combined with multiple abstractions and return flows. Artificial influences are most clearly seen in low to medium flows where, in some rivers, the hydrograph appears entirely artificial; high flows may still observe a natural pattern. Data processing staff performing validation should be aware of the principal artificial influences within the basin, the location of those influences, their magnitude, their frequency and seasonal timing, to provide a better basis for identifying values or sequences of values which are suspect.

6.2.3 Multiple station validation methods

- ***Comparison plots*** - Comparative time series plots are an effective visual method for identifying potential anomalies between stations and should be the first validation test that is carried out. Where only two stations are involved in the comparison, the identification of an anomaly does not necessarily indicate which station is at fault. For multiple time series plots, select a set of stations, ideally on the same river. Plot the flow series as hydrographs, preferably in different colours for each station. The time interval of the flow values rather than averaged values should be displayed. For routine monthly validation, the plot should include the time series of at least the previous month to ensure that there are no discontinuities between one batch of data received from the station and the next. In general, peaks and troughs are expected to be replicated at several stations with earlier occurrence at upstream stations and the lag between peaks, based on the travel time of the flood wave, approximately the same for different events, though the flow series may be shifted relative to each other with respect to time to take into account the different lag times. It should be noted that flow values at downstream stations are not necessarily higher than upstream stations - the actual value depends on physical conditions at the stations. There will be differences in the plots depending on the contributing catchment area, differing rainfall over the basins and differing response to rainfall. However, gross differences between plots may be identified.

  Comparison of flow series may permit the acceptance of values flagged as suspect because they fell outside the warning ranges, when viewed as water level or when validated as a single station. When two or more stations display the same behaviour there is strong evidence to suggest that the values are correct. Comparison plots provide a simple means of identifying anomalies but not of correcting them, which should be done through interpolation, regression analysis or hydrological modelling.

- ***Balance series (also known as residual series)*** - An alternative method of displaying comparative time series is to plot the difference between two or more time series, in the case of flow data to detect anomalies in the water balance and to flag suspect values or sequences. Water balances are made of discharge series of successive stations along a river or of stations around a confluence, where there should be a surplus, balance or deficit depending on whether water is gained or lost. Anomalous values are displayed as departures from the mean difference line. Sharp negative spikes may be eliminated from the plot by applying the appropriate time shift between the stations or by carrying out the analysis at a higher aggregation level. Considering Zi as the balance series of the flow series $X_{1,i}$ and $X_{2,i}$ and $X_{3,i}$ etc, the computations can be done as:

  $$Z_i = aX_{1,i} \pm bX_{2,i} \pm cX_{3,i} \pm dX_{4,i.....}$$

  Where: a, b, c, d = user-defined multipliers (e.g. 1)
  ± = user-defined sign

- ***Double mass analysis*** - Double mass analysis is a technique to detect a systematic shift, like abrupt or gradual changes, in a flow time series, or more normally an aggregated runoff time series (Section 6.4.3), persisting for a considerable period of time. A note may be available in the station files of the known changes of site and instruments and can be used to corroborate the detection of inconsistencies. The application of double mass analysis to runoff data is not be possible until a significant amount of historical data is available. The accumulated runoff at

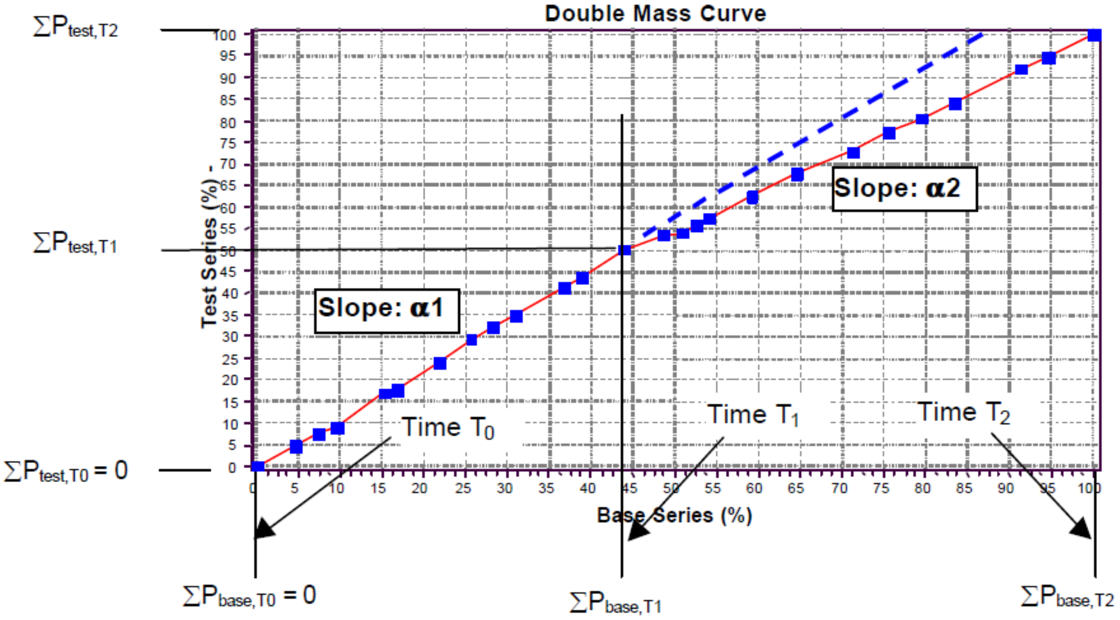


Figure 6.1 Definition sketch for double mass analysis

the test station (the station under scrutiny) is compared with another accumulated runoff series that is expected to be homogeneous. Accumulation of runoff can be made from daily data to monthly or yearly duration. It is only possible to include a brief description of the technique below, but more detailed information is provided in SW8-OM(II) Chapter 2.12 and Chapter 3.5.

Firstly, the double mass plot between the accumulated runoff values in absolute or percent form at test and base stations is drawn and observed for any visible change in its slope. The tabular output giving the ratio between the accumulated runoff values at test and base stations in absolute and percent form is also obtained. The analysis can be carried for only a part of the years or months, if there are some missing flow values within the time series (which may themselves indicate some change at the station).

Secondly, any visible change in the slope of the double mass plot should be noted. If the data of the test station is homogeneous and consistent with the data of the base station(s), the double mass curve will show a straight line. An abrupt change in the test runoff series will create a break in the double mass curve, whereas a trend will create a curve. A change in slope is not usually considered significant unless it persists for at least 5 years, and it does not imply that either period is incorrect, simply that it is inconsistent. Furthermore, double mass analysis is based on the assumption that only a part of the flow time series under consideration is subject to systematic shift. Where the whole flow time series has such a shift, the double mass analysis will fail to detect any inconsistency. Any significant inconsistency that is detected should be investigated further to explore possible causes. Inconsistencies may identify changed conditions at or upstream of the station (e.g. a shift in the rating, or a new abstraction) or shift in the station location or systematic instrumental error, in which case the flow series should be considered suspect until clarification has been obtained from the supervising field officer.

In the double mass plot shown in Figure 6.1, there is a distinct break at time T_1. If the start and end times of the period under consideration are T_0 and T_2, respectively, then the slopes of the curve before α_1 and after α_2 the break point can be expressed as:

$$\alpha_1 = \frac{\sum_{i=0}^{T_1} P_{test,i}}{\sum_{i=0}^{T_1} P_{base,i}}$$

$$\alpha_2 = \frac{\sum_{i=T_0}^{T_2} P_{test,i} - \sum_{i=T_0}^{T_1} P_{test,i}}{\sum_{i=T_0}^{T_2} P_{base,i} - \sum_{i=T_0}^{T_1} P_{base,i}}$$

In the case that the earlier part between T_0 and T_1 needs to be corrected for, the correction factor and the corrected observations at the test station can be expressed as:

$$P_{corr,i} = P_{test,i} \times \frac{\alpha_2}{\alpha_1}$$

After making such a correction, the double mass curve should be plotted again to check that there is no significant change in the slope of the curve.

6.2.4 Combined flow and rainfall plots and tables

The principal comparison of flow and rainfall is done through hydrological modelling (Section 6.2.5). However, a quick insight into the consistency of the data may be made by graphical and tabular comparison of areal rainfall and runoff. Comparison may be made using an areal rainfall determined using Thiessen polygons or other methods over the entire basin, or for the intervening sub-basin corresponding to various gauging stations (Precipitation and Climate Handbook, Section 4.5.3). Areal rainfall is also subject to error which depends upon the density of stations within the basin and the spatial variability of the rainfall. Where the basin is small or the number of raingauges limited, individual rainfall records may be plotted. The basin rainfall over an extended period such as a month or year should exceed the runoff (in mm) over the same period by the amount of evaporation and changes in storage in soil and groundwater. Tabular comparisons should be consistent with such physical changes e.g. an excess of runoff over rainfall either on an annual basis or for monthly periods during the monsoon should be considered suspect. In general, a rise in river water level must be preceded by a rainfall event in the basin and, conversely, it is expected that rainfall over the basin will be followed by rise in water level. There must be a time lag between the occurrence of rainfall and the rise in water level. However, precise correspondence should not be expected owing to the imperfect assessment of areal rainfall and to the variable proportion of rainfall that enters storage.

Optional tertiary data validation cum analysis can also be used to compare and rainfall data. The two main techniques – regression analysis and hydrological modelling – have some utility in the correction and completion of flow data but, generally, are likely to be of interest only to experienced hydrologists at State level and at CWC as they are time-consuming and, therefore, applied selectively.

6.2.5 Regression analysis

Regression analysis is a widely-used statistical technique in hydrology for: making estimates of dependent variable Y (i.e. the flow at the test station) based on independent variables X (e.g. the areal rainfall for the test basin corresponding to the event in question, or the flow at an upstream or downstream analogue station); for investigating the functional relationship between two or more variables; for infilling missing values in the Y time series; and for validating the Y time series.

Regression relations may be obtained for annual, monthly or daily flow series. The most common model is based on the assumption of a linear relationship between two variables and has the general form:

$$Y_i = a X_i + c$$

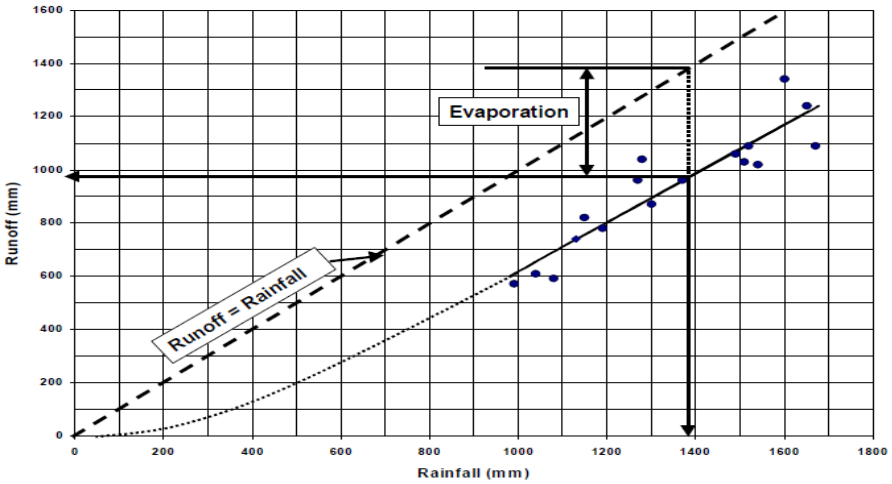


Figure 6.2 General form of relationship between annual rainfall and runoff

In simple linear regression, the Y variable is regressed on one X variable. In multiple and stepwise linear regression, the Y variable is regressed on more than one X variable. In non-linear regression, the coefficients appear as a power:

$$Y_i = c\ X^a_i$$

The type of regression equation that is most suitable to describe the relation depends on the variables considered and, with respect to hydrology, on the physics of the processes driving the variables. Furthermore, it also depends on the range of the data of interest. A non-linear relationship may well be described by a simple linear regression equation within a particular range of the variables e.g. annual runoff regressed on annual rainfall (Figure 6.2). For low rainfall amounts the relationship is highly non-linear due to evaporation, but for very high rainfalls the relationship is linear as evaporation has reached its potential level.

For tertiary validation of flow data, a regression model is developed where runoff is regressed on areal rainfall and/or on flow at an analogue station (where flow series may be shifted relative to each other with respect to time to take into account the lag time if this is useful). In a graphical plot, any suspect values will generally show up as outliers or deviations (i.e. residuals) from the regression line. Provided that the areal rainfall data are free of errors, any non-stationary behaviour of the residuals may then be explained by change in the drainage characteristics of the basin or incorrect flow data, which in turn can be caused by errors in the water level data or errors in the stage-discharge relationship. Previously identified suspect flow values should be removed before deriving the relationship which, providing it is a good fit, may then be applied to compute corrected flow values to replace the suspect ones. A good fit corresponds to a correlation coefficient of at least 0.90, though reference should also be made to the standard error of estimate. Where no acceptable relationship is found, the missing values should be left missing or an alternative method of in-filling used. The flow data should be revalidated after correction. For more information see SW8-OM(III) Chapter 2.

6.3 Correction and completion

6.3.1 Overview

Completion – the processing of filling in missing values and correcting erroneous values – is done as a continuous process with secondary validation. Although the HIS Manual SW separates correction and completion in SW8-OM(II) Chapter 15 from secondary validation in SW8-OM(II) Chapter 14, and optional tertiary validation in SW8-OM(III) Chapters 2 and 3, there is substantial overlap between the techniques used. In this Handbook, some correction and completion techniques have been included in the appropriate parts of Section 6.2, and others are described below. Examples of many of the techniques described, which should be carried out by experienced staff with appropriate training, are given in Surface Water Training Module 39 “How to correct and complete discharge data”.

The majority of secondary validation, and therefore the majority of correction and completion (see Table 3.1), is carried out by State DPCs offices to take advantage of the information available from a larger area. Some secondary validation, and correction and completion (including comparison with CWC data) will not be possible until the end of the hydrological year when the entire year’s data can be reviewed in a long-term context, so data should be regarded as provisional approved data until then (e.g. for June data by the end of the hydrological year plus 3 months), after which data should be formally approved and made available for dissemination to external users.

Procedures for correction and completion of flow data depend on the type of error, the duration of missing or erroneous records and the availability of suitable records with which to estimate. It should be recognised that values estimated from other gauges are inherently less reliable than values properly measured (i.e. water level and rating curve at the site in question). All flow gauging stations equipped with an AWLR or DWLR have a manually-read staff gauge back-up and, if there is an equipment failure, the observer’s record may be used to complete the instrument record (Section 4.2.4). This is normally done as water level rather than as flow (Section 4.4), and is the preferred option in order to establish an internally consistent database. However, there will be circumstances where there is a staff gauge only, or the gap is too long to infill from the observer’s record, and other methods must be used. Where no suitable neighbouring observations or stations are available, missing values should be left as -999 and incorrect values should be set to -999, and suspect original values should be given the benefit of the doubt and retained in the record with an appropriate flag. In all cases, the flow data should be revalidated after correction and/or completion.

Data completion and correction can also apply to the reprocessing of previously approved flow data. For example, flow data created by applying a stage-discharge relationship to water level data may be reprocessed if it is subsequently discovered that the stage-discharge relationship has changed through changes in the channel, civil works at the station, etc. Similarly, data relating to an extreme hydrological event outside the limits of the rating curve may be reviewed at a later date, in a longer-term context or after comparison with other information not previously available. Appropriate comments regarding changes to previously approved data should always be added to the database and made available to data users.

6.3.2 Correcting missing and erroneous data by interpolation

During periods of low flow, gaps of short duration (e.g. 2 days or less) may be infilled by linear interpolation between the last value before the gap and the first value after it. To confirm that this is acceptable, a graphical display of the hydrograph at the station and one or more analogue stations should be inspected to ensure that that there are no discontinuities in the flow sequence over the gap. This approach is possible because, unlike rainfall, flow shows strong serial correlation i.e. the value on one day is closely related to the value on the previous and following days, especially during periods of low flow or recession.

During recessions, when the flow is dependent on baseflow contribution from groundwater rather than rainfall, the flow exhibits a pattern of exponential decay giving a curved trace on a simple plot of flow against time, but a straight line on a logarithmic plot. During long recession periods, interpolation between the log-transformed points before and after the gap results in a more realistic recession than linear interpolation. It is possible to make this interpolation as water level rather than as flow but, as the principle is based on depletion of a storage volume, it is conceptually more realistic to apply the interpolation to flow rather than to water level. At time t within the gap, Qt is:

$$Q_t = Q_{t_0} \exp\left(-\frac{t - t_0}{k}\right)$$

Where: t_0 is the time of the last value before the gap
K is a coefficient based on the flow recession α:

$$k = \frac{1}{\alpha}$$

$$\alpha = \frac{\ln Q_{t_0} - \ln Q_{t_1}}{t_1 - t_0}$$

Where: t_1 is the time of the first value after the gap
Qt_0 is the flow before the gap at time t_0
Qt_1 is the flow after the gap at time t_1

The gap is filled incrementally with no discontinuity at the beginning and end of the gap. In suitable conditions, periods of a month or more may be interpolated in this way.

During periods of variable flow or for longer gaps, interpolation should not be used and regression analysis (Section 6.2.5) and/or hydrological modelling (Section 6.3.3) may be applied to fill in missing data, provided there are suitable stations on the same river or in a neighbouring basin.

6.3.3 Hydrological modelling

A hydrological rainfall-runoff model is a representation of the transformation of an areal basin rainfall into a flow at the basin outlet. To simplify the complex processes operating over the basin and beneath the land surface, the hydrology of the basin is conceived as a series of interlinked processes and storages. Storages are reservoirs for which water budgets are kept, and processes use mathematical equations to transfer water between storages. Model parameters control the size of the storages and the processes. Rainfall runoff models have a wide variety of uses:

- Infilling and extension of flow series
- Validation of flow or runoff series
- Generation of flow from synthetic rainfall
- Real time forecasting of flood waves
- Determination of the influence of changing land use on the basin (e.g. urbanisation, afforestation, etc) or the influence of water use (abstractions, dam construction, etc)

During model calibration, the model parameters are optimised (i.e. progressively adjusted, automatically or manually) to improve the correspondence between the measured flow and the modelled flow. Automatic optimisation aims to minimise an objective function (i.e. a quantitative measure of goodness of fit) by a defined and efficient search through a multi-dimensional parameter space. Model validation uses part of the measured data, held back from the calibration, to verify the performance of the model by using the calibrated parameters with the new data (without optimisation) to determine the objective function. Validation is a way of ensuring that the optimised parameters are a true representation of the physical behaviour of the basin and not simply a consequence of the model structure. The calibrated and validated model is then ready for application where the rainfall input is known but the flow is unknown.

In the HIS, rainfall-runoff models may be used for infilling missing values and correcting erroneous values. However, the time and effort involved in model calibration does not normally justify application to short gaps, unless the model has previously been calibrated for the same basin, but rather to gaps of several months in length.

A large number of models have been developed, and the selection of a model – and model complexity - depends on the uses to which it will be put and the availability of measured information on inputs, outflows and storages. SW8-OM(III) Chapter 3 presents the Sacramento Model as an example of a hydrological rainfall-runoff model. DDS Planning uses the NAM rainfall-runoff model within MIKE-11 suite.

Flow routing methods (e.g. Muskingham) are a different type of hydrological modelling approach whereby the flow hydrograph at an upstream station is routed downstream to a station at which flow data for the same event are missing. Inflows and abstractions from the intervening reach can be incorporated to achieve a water balance. Flow routing is usually applied to floods but can be extended for use in low flows. Again, for more information see SW8-OM(III) Chapter 3.

6.4 Compilation

6.4.1 Overview

Flow compilation is the process by which computed flow data are transformed:

- From one time interval to another
- From one unit of measurement to another, especially from flow to runoff (depth over a basin)

Compilation is required for validation, reporting and analysis. Hence, some compilation is done prior to and during validation as required, but final compilation is carried out after correction and completion. The majority of correction and completion, and therefore the majority of final compilation (see Table 3.1), is carried out at State level. Examples of many of the techniques described in this section are given in Surface Water Training Module 40 “How to compile discharge data”.

6.4.2 Aggregation of flow to longer durations

Computations for aggregation of data from one time interval to another depend on the data type. If the data are of an instantaneous nature, the aggregation is effected by computing the arithmetic average of the individual constituent data values. If the data are of accumulative nature, the constituent values are arithmetically summed up to obtain the aggregated value. Averaging over longer time intervals is required for validation and analysis. For secondary validation, small persistent errors may not be detected at the small time interval of measurement but may more readily be detected at longer time intervals.

- ***Sub-hourly, hourly and sub-daily to daily mean*** - the daily mean flow (Qd) is computed from hourly values (Qi) by:

  $$Q_d = \frac{1}{24} \sum_{i=1}^{24} Q_i$$

  The daily mean flow is normally calculated for hours commencing 00:01 and finishing 24:00. For some purposes, the daily mean flow is calculated from 08:00 to 07:59 to enable direct comparison to be made with daily rainfall.
- ***Daily mean to weekly mean, 10-day mean, monthly mean, annual mean*** – the daily mean flow is averaged over the required time period by:

  $$Q_{Nd} = \frac{1}{Nd} \sum_{i=1}^{Nd} Q_i$$

  Where: QNd is the discharge for Nd days duration
  Qi is the discharge of ith day in duration of Nd days

A weekly mean flow is either four parts of the month where first three parts are of seven days each and the fourth part is of 7, 8, 9 or 10 days depending on the total days in the month, or 52 parts of a year where first 51 weeks are of 7 days each and the last week is of 8 or 9 days depending upon whether the year is a leap or a non-leap year. A 10-day mean flow corresponds to three parts of every month in which the first two parts are the 1-10 and 11-20 days of the month and the third part is the remaining part of the month. Thus every third value in the series corresponds to 8,9,10 or 11 days depending on the total days in the month. Such flow statistics are often desirable for operational purposes.

6.4.3 Computation of runoff

To facilitate comparisons between rainfall and flow, it is usual to express values of rainfall and flow as a total volume over a specified period (e.g. a month or a year), in m^3, or in Mm^3 or MCM. Alternatively, flow over a specified period (e.g. a day, a month or a year) may be expressed as a depth, in mm, over the basin. This is known as runoff, which is flow divided over area with appropriate unit and time period adjustments. For daily runoff Rd:

$$R_d\ (mm) = \frac{86.4\ Q_d}{Area\ (km^2)}$$

Runoff depths provide not only a ready comparison with rainfalls, but also provide a comparison with other basins standardised by area. Such comparisons may be made for monthly, seasonal and annual totals, but are not generally useful for daily or shorter duration totals, where basins respond at different time scales to incident rainfall. However, daily or sub-daily runoff may be required for irregular periods to compare with rainfall depths for specific storm events (where it may also be necessary to separate the storm flow, resulting from the incident rainfall, and the baseflow from groundwater sources). For the purposes of annual reporting, it is usual to compare the monthly and annual runoff from a station with the long term average, maximum and minimum monthly runoff derived from the previous record. This requires the annual updating of runoff statistics with the concatenation of the previous year with earlier statistics.

Another unit which is sometimes used to standardise with respect to area is specific discharge which may be computed with respect to instantaneous flows or the mean flow over any specified duration as flow over area, in $m^3s^{-1}km^{-2}$.

6.4.4 Compilation of maximum and minimum series

The annual, seasonal or monthly maximum series of flow is frequently required for flood analysis, whilst minimum series may be required for drought analysis. The eHYMOS module of e-SWIS provides options for the extraction of daily, monthly and seasonal maximum and minimum values for any defined period within the year or for the complete year, between a specified start and end date.

6.5 Analysis

6.5.1 Overview

Some analysis of flow data is required for validation and further analysis may be needed for data presentation and reporting. The majority of analysis (see Table 3.1) is carried out at State level. Examples of many of the techniques described in this section are given in Surface Water Training Module 41 “How to analyse flow data”. It is only possible to include an overview of the techniques below, but more detailed information is provided in SW8-OM(III) Chapter 7. Some of the analysis techniques are described in the appropriate sections of this Handbook:

- Balance series for conservation of the water balance in Section 6.2.3

- Relation curves for validation in Section 4.3.4
- Regression analysis for validation in Section 6.2.5
- Double mass analysis for consistency testing in Section 6.2.3
- Hydrological modelling for flow simulation in Section 6.3.3

6.5.2 Computing basic statistics

Basic statistics are widely required for validation and reporting including:

- Arithmetic mean:

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i$$

- Median - the median value of a ranked series Xi
- Mode - the value of X which occurs with greatest frequency or the middle value of the class with greatest frequency
- Standard deviation - the root mean squared deviation Sx:

$$S_x = \sqrt{\frac{\sum (X_i - \overline{X})^2}{N-1}}$$

- Skewness – the extent to which the data deviate from a symmetrical distribution
- Kurtosis – the peakedness of a distribution

6.5.3 Flow duration curves (also known as cumulative flow frequency curve)

Flow duration curves are standard reporting output from the processing and analysis of flow data. A flow duration curve is a plot of flow against the percentage of time the flow was equalled or exceeded, and is usually applied to daily mean flow. Some of their uses are:

- In evaluating dependable flows in the planning of water resources engineering projects
- In evaluating the characteristics of the hydropower potential of a river
- In assessing the effects of river regulation and abstractions on river ecology
- In the design of drainage systems
- In flood control studies
- In computing the sediment load and dissolved solids load of a river
- In comparing with adjacent catchments

The analysis procedure takes N years of daily mean flow data from a flow gauging station, giving 365N data values. Firstly, the number of data values or frequency in selected flow class intervals is counted. The flow class intervals do not need to be the same size, with smaller classes at lower flows and larger classes at higher flows common. Then, the class frequencies are converted to cumulative frequencies starting with the highest flow class. Next, the cumulative frequencies are then converted to percentage cumulative frequencies. The percentage cumulative frequency represents the percentage time that the flow equals or exceeds the lower value of the flow class interval. Finally, flow is plotted against percentage time. The representation of the flow duration curve is improved by plotting the cumulative discharge frequencies on a log-probability scale (Figure 6.3). If the daily mean flows are log-normally distributed they will plot as a straight line on such a graph, and it is common for them to do so in the centre of their range.

The slope of the flow duration curve indicates the response characteristics of the river. A steeply sloped curve indicates very variable flow, usually for small basins and/or basins with little storage. Those with a flat curve indicate little variation in flow regime, usually for large basins and/or basins

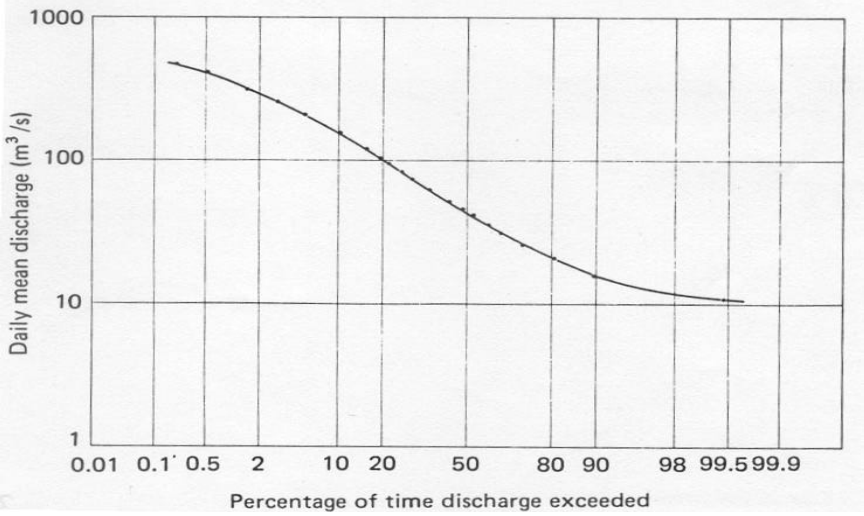


Figure 6.3 Flow duration curve on a log-probability scale (after: Shaw, 1988)

with a high proportion of baseflow. Percentage exceedance statistics may be derived to give the median flow that occurred 50% of the time or the flow that occurred 5%, or 95%, of the time.

Flow duration curves provide no representation of the chronological sequence. Flow duration curves may also be generated by month or by season. Comparisons between basins are made by plotting the log of flows as percentages of the daily mean flow for that basin (i.e. the flow is standardised by daily mean flow). A common reporting procedure is to show the flow duration curve for the current year compared with the curve over the historic period.

6.5.4 Fitting frequency distributions

The following are widely used for reporting or for subsequent use in frequency analysis of extreme i.e. high/flood and low/drought) flows:

- Maximum series. The maximum instantaneous flow of an annual series, or of a month or season. Maximum daily mean flows may also be used for analysis.
- Exceedance series (also known as peaks-over-threshold series and partial duration series). All instantaneous flow values over a specified threshold may also be selected
- Minimum series. With respect to minimum the daily mean or period mean is usually selected rather than an instantaneous value which may be unduly influenced by zeros, data error or a short-lived regulation effect.

The objective of flood or low flow frequency analysis is to assess the magnitude of a flow of given probability or return period of occurrence. Return period is the reciprocal of probability and may also be defined as the average interval between flows of a specified magnitude. Such information can be used in the design of flood alleviation schemes, bridges and culverts, reservoir spillways, etc.

Frequency analysis usually involves the fitting of a theoretical frequency distribution using a selected fitting method, although empirical graphical methods can also be applied. The fitting of a particular distribution implies that the flow sample of annual maxima, annual exceedance or annual minima were drawn from a population of that distribution. For the purposes of application in design, it is assumed that future probabilities will be the same as past probabilities. However there is nothing inherent in the series to indicate whether one distribution is more likely to be appropriate than another, and a wide variety of distributions and fitting procedures has been recommended for application in different countries and by different agencies. See the e-SWIS/eHYMOS manual for details about which frequency distributions and fitting procedures are available.

Different distributions can give widely different estimates, especially when extrapolated or when an outlier (an exceptional value, well in excess of the second largest value) occurs in the dataset. No single distribution represents equally the population of annual floods at all stations. Therefore, although the methods are themselves objective, a degree of subjectivity is introduced in the selection of which distribution to apply, based on experience of flood frequency distributions in the surrounding region and the physical characteristics of the basin. Output typically includes:

- Estimation of parameters of the distribution
- A table of flows of specified probabilities or return periods with confidence limits
- Results of goodness of fit tests
- A graphical plot of the data fitted to the distribution

When fitting frequency distributions, graphical, as well as numerical output, should always be inspected.

A standard statistic which characterises the flood potential of a basin and has been used as an "index flood" in regional analysis is the mean annual flood, which is simply the mean of the maximum instantaneous flows in each year. This may be derived from the data or from distribution fitting. An alternative index flood is the median annual maximum, similarly derived. These may be used in reporting of general basin data.

6.5.5 Time series analysis

Time series analysis may be used to test the variability, homogeneity or trend of a flow series, or to give an insight into the characteristics of the series as graphically displayed. For more information see SW8-OM(III) Chapter 7.5.

- ***Moving averages*** - moving average curves enable investigation of the long-term variability or trends in a flow series. A moving average series Yi of series Xi is derived as:

$$Y_i = \frac{1}{(2M+1)} \sum_{j=i-M}^{j=i+M} X_j$$

  Where averaging takes place over 2M+1 elements. The original series can be plotted together with the moving average series (e.g. Figure 6.4).

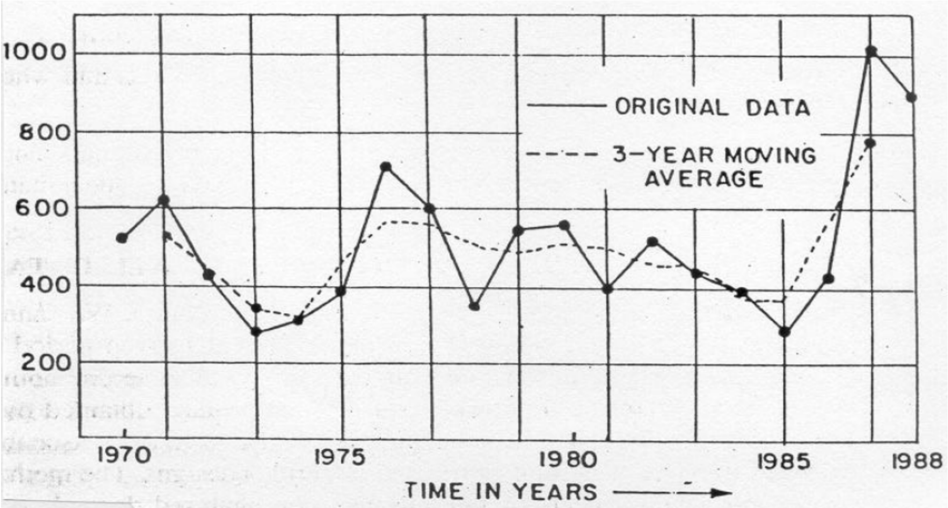


Figure 6.4 Example of moving average of annual runoff

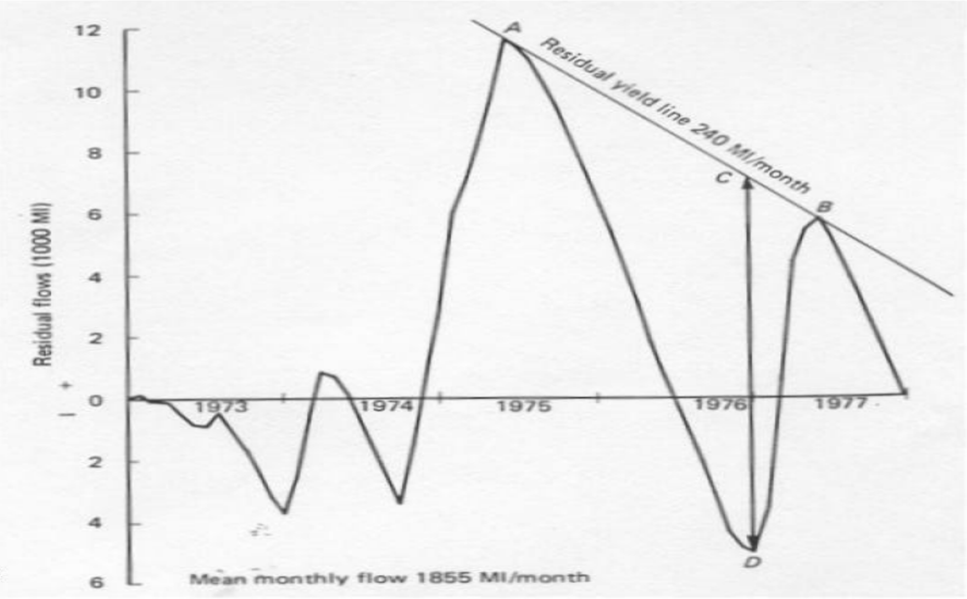


Figure 6.5 Example of residual mass curve for reservoir design

- ***Residual mass curves*** – Usually applied to the analysis of droughts, residual mass curve represents accumulative departures from the mean (Figure 6.5). It is an effective visual method of detecting flow variabilities or other inhomogeneities. An upward curve indicates an above average sequence, a horizontal curve an about average sequence, and a downward curve indicates a below average sequence. The residual mass curve is derived as:

$$Y_i = Y_{I-1} + (X_i - m_x) = \sum_{j=1}^{i} (x_j - 1/N \sum_{k=1}^{N} X_k)$$

Where: N = number of elements in the series
mx = mean value of Xi , i=1,N

For reservoir design, a line drawn tangential to the peaks of the residual mass curve represents a residual cumulative constant yield that requires a reservoir of capacity CD to fulfil, assuming the reservoir is full at A and at B.

- ***Run-length and run-sum characteristics*** – Also commonly used in drought analysis are run-length and run-sum. For a flow series $X_1,...X_n$, and a threshold flow value q_0 (e.g. flow below which a drought is defined to exist), a negative run occurs when the flow at time t X_t is less than q_0 for one or more time intervals, and a positive run occurs when X_t is consecutively greater than q_0 (Figure 6.6, where: di = duration of drought i, si = deficit volume of drought i, ti = inter-event time following drought i (i.e. time between two consecutive droughts) and vi = inter-event volume following drought i (i.e. volume of flow above the threshold occurring between two consecutive droughts). A negative run can be defined by its length (the continuous length of time for which the flow is below the chosen threshold), magnitude (the average flow deficit over the run's duration), and severity (the cumulative volume of flow deficit, for the whole run duration).

- ***Storage analysis (sequent peak algorithm)*** – For reservoir design, for a daily inflow series q_i and a required yield q_0, equivalent to the threshold flow, then the storage S_i required at the beginning of day i is:

$S_i = S_{i-1} + q_0 - q_i$ for $q_i<q_0$
$S_i = 0$ for $q_i>q_0$

An uninterrupted sequence of positive S_i defines a period with storage depletion and a subsequent filling up. The required storage in that period (the maximum value of S_i) defines

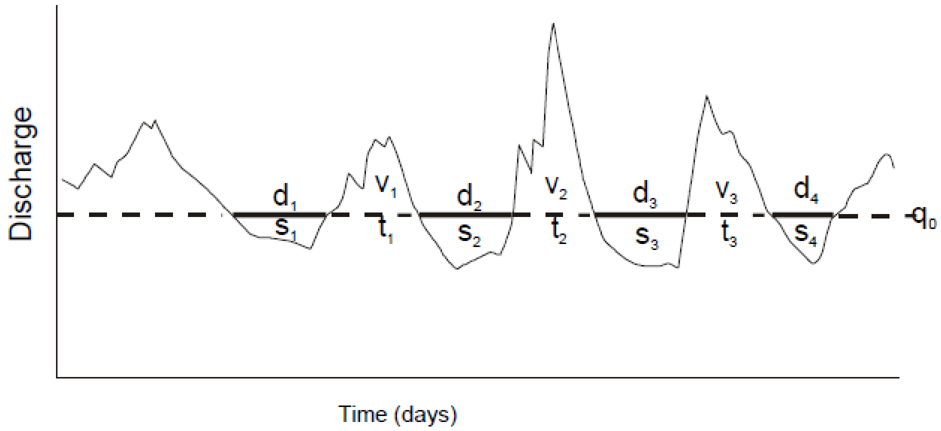


Figure 6.6 Definition sketch of the threshold level approach for run-sum analysis

the drought deficit volume, and the time interval from the beginning of the depletion period to the time of the maximum depletion defines the drought duration. Two droughts are pooled if the reservoir has not totally recovered from the first drought by the time the second drought begins.

6.5.6 Single site homogeneity testing

For statistical analysis, flow data from a single series should ideally be homogenous i.e. the characteristics of different portions of the data series do not vary significantly (Section 4.6.6), and for regional analysis, flow data for multiple series at neighbouring stations should ideally possess spatial homogeneity. Single site testing for homogeneity involves statistical analysis and is likely to be of interest only to experienced hydrologists at State level and at CWC. Furthermore, it will normally only be used with long datasets and, therefore, has to await the data entry of historical data. Time series may be inspected graphically for evidence of inhomogeneity (e.g. trend) which may result from a wide variety of factors including climatic variability, changes in land use in the basin, changes in abstractions and river regulation, and global climate change. However, statistical hypothesis testing can be more discriminative in distinguishing between expected variation in a random series and real trend or more abrupt changes in the characteristics of the time series.

Hypothesis testing forms a framework for many statistical tests. An assumption about the distribution of a statistical parameter (e.g. the mean of a flow time series) is stated in the null-hypothesis H0 and is tested against an alternative formulated in the H1 hypothesis. The statistical parameter under investigation is called the test statistic. Under the null-hypothesis, the test statistic has some standardised sampling distribution e.g. standard normal distribution. For the null hypothesis to be true, the value of the test statistic should be within the acceptance limits of the sampling distribution of the parameters under the null-hypothesis. If the test statistic does not lie within the acceptance limits, expressed as a significance level, the null-hypothesis is rejected and the alternative is assumed to be true. Some risk is involved however in being wrong in accepting or rejecting the hypothesis. Common tests include Student's t-test, Wilcoxon W-test, and Wilcoxon-Mann-Whitney U-test. See the e-SWIS/eHYMOS manual for details about which tests are available. For more information see SW8-OM(II) Chapters 5.5.4 to 5.5.6

7. Data Dissemination and Publication

7.1 Hydrological products

The traditional primary visible output of hydrological data archives is published reports, usually in the form of annual hydrological yearbooks. However, this is not generally the most convenient format of surface water quantity data for data users who often require long-term records for a single station or a group of stations i.e. data by station rather than by year. For data users in the past, this necessitated the collation of data from a set of annual reports and the keying in of the data for the required analysis. In many countries, recent advances in IT, combined with well-established links between data suppliers and data users, mean that annual reports are no longer published in print, with the same information being provided online, and data requests met with a rapid and bespoke response.

A further consequence is that data suppliers have more time to focus on data analysis, periodic reports and short-term operational reports of interest to key data users e.g. reports on unusual flood events, water level bulletins for fisheries, navigation and recreation sectors, real-time water level or flow data for flood forecasting and for hydropower and reservoir operation, etc. A combination of digital and hardcopy hydrological products and online dissemination provide an effective means of demonstrating the capability of the HIS, in particular:

- Providing information on availability of data for use in planning and design, and making reporting and use of data more efficient by reducing the amount of published data and cost of annual reports
- Advertising the work of the HIS and its capability, and to create interest and awareness amongst potential data users
- Providing tangible evidence to policymakers of a return on substantial investment
- Providing feedback to data producers, and acknowledging the contribution of observers and co-operating agencies
- Providing a clear incentive to keep archives up to data and a focus for an annual hydrometric audit

Hence, the long-term goal of the HIS is web-based dissemination of user guidance and station metadata (additional datasets that include items that could assist users of the data to understand the data, their accuracy and any major influencing factor), which is usefully complemented by the publication of catalogues or registers of hydrometric stations (e.g. Marsh & Hannaford, 2008) and occasional reports, and by a dedicated enquiry and data retrieval service.

7.2 Annual reports

7.2.1 Hydrological yearbooks

Hydrological yearbooks should report over the hydrological year from 1 June to 31 May. The hydrological year corresponds to a complete cycle of replenishment and depletion, so it is appropriate to report on that basis rather than over the calendar year. Annual flow, rainfall and climate data may be presented in a single combined report. The surface water quantity elements of such reports incorporate a summary of information on the pattern of flow over the year, and information on the spatial and temporal pattern of flow in the region and how the recent year compares with past statistics. A limited amount of stage-discharge data may be incorporated with reports on flow, primarily to provide an indication of the reliability of the flow data (see Table 3.1). Annual reports are produced at the State DPC and should be published within 12 months of the end of the hydrological year covered. SW8-OM(III) Annex I presents a template for a Surface Water Yearbook published at State level. The following are typical contents:

- ***Introduction*** – The report introduction should describe the administrative organisation of the flow network and the steps involved in the collection, data entry, processing, validation, analysis and storage of data, including any agencies contributing to the included data. Standard climatic observation practice should be summarised. The report should explain how the work is linked with other agencies collecting or using flow data including CWC and operational departments in hydropower and irrigation. It should also set out how data may be requested and under what terms and conditions they are supplied. The report introduction may change little from year to year.

- ***Observational network*** – Maps and tables should be used to summarise the salient features of the observational network. The flow gauging station map should also show major rivers and basin boundaries and distinguish each site by symbol between operating agencies. Mapped stations should be numbered so that they can be related to information contained in tabular listings. Tables of current stations should be listed by named basin and sub-basin, as well as the latitude, longitude, altitude, basin area, responsible agency, the full period of observational record and the period of observation which is available in digital format. Information for each station should also include a summary description of the gauging station, its controls and limitations, a summary description of the basin including principal features of geology and land use, and a summary of artificial factors affecting flow (e.g. reservoirs and regulation, abstractions and return flows).

  A similar listing of closed stations may also be provided. All additions and closures of stations should be highlighted in the yearly report. Similarly, station upgrading and the nature of the upgrading should be reported.

- ***Descriptive account of flow occurrence during the report year*** - An account of flow occurrence in the region in the year should be given in the form of a concise commentary for each month, placed in its meteorological context and in relation to seasonal norms. Especially severe or prolonged periods of high or low flows should be highlighted.

- ***Basic flow statistics*** – This section forms the core of the report. Full reporting of daily or hourly data is no longer required. For selected key flow gauging stations, tabulations of daily data, together with accompanying statistical information relating to the year in question and comparisons with the previous gauged record, should be provided to illustrate the format of information available:

  - Tabulation of daily mean flow for the current year
  - Mean, maximum and minimum daily mean flow in each month of the current year
  - Monthly flows against the frequency curves for different frequencies for the current year
  - Maximum instantaneous (peak) flow in each month of the current year
  - Monthly flow volumes, runoff (mm) and basin rainfall (mm) and annual summary statistics for the current year
  - Average of monthly means, lowest monthly mean (and year) and highest monthly mean (and year), for the previous record
  - Annual summary statistics, for the previous record

  For the remaining stations, abbreviated summary statistics should include:

  - Monthly and annual mean flows, maximum flows, runoff and basin rainfall for the current year

- ➢ Monthly and annual mean flows, lowest monthly mean, highest monthly mean, highest monthly instantaneous flow, mean monthly runoff, mean monthly and annual basin rainfall, for the previous record

Tables of current stations should be listed by named basin and sub-basin. Values of flow, whether, observed, mean daily or mean monthly should be reported to two decimal places or less.

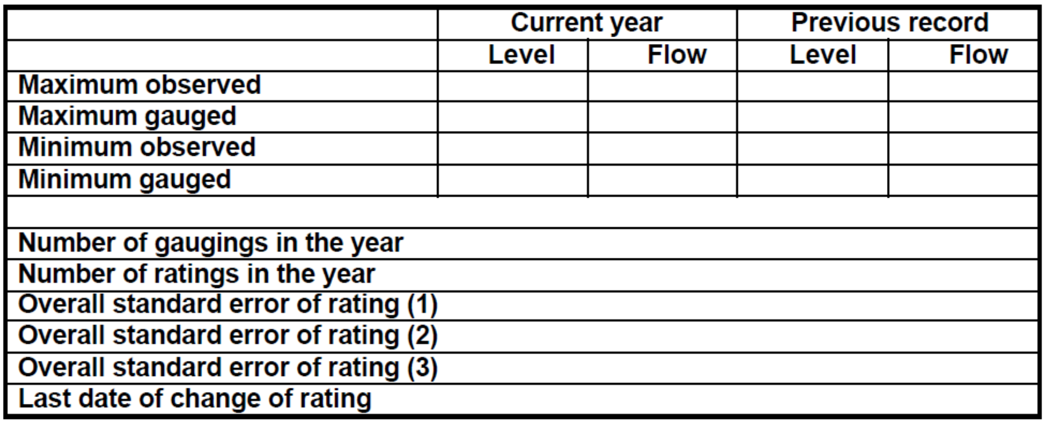
- ***Annual summaries in graphical form*** –Graphical displays illustrate the flow regime during the year and how it relates to the previous record. Figures for selected key gauging stations should include:

  - ➢ Annual hydrograph plot compared with previous maxima and minima
  - ➢ Flow duration curve showing comparison of current year with long-term curve
  - ➢ Generalised map showing annual runoff as a percentage of the long period average (note that the value at a gauging station represents an average value over a basin, whilst the runoff from different sub-catchments within the basin may be quite different in relation to the period norms.

- ***Description and statistical summaries of major floods and droughts*** - Major floods which have caused loss of life or serious or widespread damage to property should be described in more detail, giving details of peak flow and average flow over selected durations for flow gauging stations within the affected area, and showing how these statistics differ from the previous reported maxima. Storms should be described with respect to their meteorological context, the most severely affected areas, and the impact of storm movement across the basin on the resulting flood. The description may be combined with the rainfall report for the storm.

  Similarly, major droughts which have caused serious agricultural impacts or disruption of water supply should be illustrated by comparison of drought flow hydrographs with average and previous reported minima.

- ***Data validation and quality*** - The limitations of the data should be made known to data users. The accuracy of flow data is dependent primarily on the accuracy of the water level data and on the reliability of the stage-discharge relationship. With respect to water level, the number of values corrected or infilled as a total or a percentage may be noted for individual stations, by basin or by agency. With respect to the reliability of the stage-discharge relationship, for each flow gauging station, Figure 7.1 or a variant of it should be included as a guide to the gauging effort and the reliability of ratings.



	Current year		**Previous record**	
	Level	**Flow**	**Level**	**Flow**
Maximum observed				
Maximum gauged				
Minimum observed				
Minimum gauged				
Number of gaugings in the year				
Number of ratings in the year				
Overall standard error of rating (1)				
Overall standard error of rating (2)				
Overall standard error of rating (3)				
Last date of change of rating				

Figure 7.1 Report for stage-discharge data

- ***Bibliography*** - Data users may be interested to know of other sources of flow and related rainfall and climate data, or of other hydrological data, including: concurrent annual reports from the HIS of other hydro-meteorological or hydrological data, and previous annual flow reports (with dates) from the HIS or other agencies; any periodic reports of flow gauging station metadata and time series statistics produced by the HIS or other agencies; and any special reports produced by the HIS or other agencies. A brief note on the administrative context of previous reports, methods of data compilation, and previous report formats may be helpful.

7.2.2 Annual hydrological reviews

Shorter than hydrological yearbooks, annual reviews of the hydrological year provide users with published assessments of the key elements of the hydrological cycle. Hence, the reports combine rainfall, snow (where relevant), climate, flow, reservoir stocks and groundwater, and possibly also water quality. Annual reviews are produced at the State DPC and should be published within 12 months of the end of the hydrological year covered. For an example, see www.ceh.ac.uk/data/nrfa/nhmp/annual_review.html.

7.3 Periodic reports

7.3.1 Metadata catalogues

Periodic reports of water level and flow gauging station metadata and time series statistics may be published by the State DPC at 5-year or 10-year intervals. The reports should incorporate temporal analysis and provide statistical summaries in tabular and graphical to make the information accessible and interesting to data users. The following are typical contents of such a periodic report:

- Introduction
- Data availability - maps and tabulations
- Descriptive account of annual flow and runoff since last periodic report
- Thematic maps of mean monthly and seasonal runoff
- Basic flow statistics - monthly and annual means, maxima and minima: for the standard climate normal period (1961-90) where available; for the updated decade; and for the available period of record
- Analysis of periodicity and trend in flow data

7.3.2 Monthly hydrological summaries

Routine monthly reports and statistics on the current state hydrological situation, including assessments of rainfall, snow (where relevant), evaporation, river flow, groundwater and reservoir stocks, provide users with a snapshot of the current situation and its historical context, and the future outlook. Such information may provide a vital input for planning domestic or industrial water supply, agricultural planning, hydropower and other water use sectors. Monthly summaries are produced at the State DPC and should be published within 10 working days of the month covered. For an example, see www.ceh.ac.uk/data/NRFA/nhmp/monthly_hs.html.

7.4 Special reports

Occasional special reports should also be published by the State DPC providing reactive analysis in the aftermath of notable or significant monsoon floods or droughts. As these may also have unusual hydrological consequences, the reports are normally combined with reports of the resulting causative rainfall over the affected area. For an example, see www.ceh.ac.uk/data/nrfa/nhmp/other_reports.html.

7.5 Dissemination to hydrological data users

Final (approved) surface water quantity datasets are provided by Central/State hydrometric agencies on a request basis. The online HIS data catalogue in e-SWIS, which shows the availability of fully validated (approved) data, supports hydrometric agencies in disseminating their data, and also helps hydrological data users to search available data and formulate their data requests and the formats required and direct them to the appropriate agency. The more comprehensive the information a data catalogue provides, the easier for users to identify the monitoring stations of interest to them, and be aware of any limitations to exploiting the data effectively. Users should be informed of the quality of any data supplied indicated by the data flag (e.g. observed, estimated, suspect, etc). There may be a charge for data which is the product of significant investment in equipment and staff time. Data requests from users should be processed promptly: at least 95% of queries should be dealt with within 5 working days, and the remaining up to 5% of queries, which should be the more complex ones, within 20 working days.

References

Hannaford, J., Holmes, M.G.R., Laize, C.L.R., Marsh, T.J. & Young, A.R. 2013. Evaluating hydrometric networks for prediction in ungauged basins: a new methodology and its application to England and Wales. *Hydrology Research* **44 (3)**, 401-418.

Institute of Hydrology. 1999. *Flood Estimation Handbook*, 5 Volumes. Institute of Hydrology, Wallingford, UK.

Marsh, T.J. 2002. Capitalising on river flow data to meet changing national needs — a UK perspective. *Flow Measurement and Instrumentation* **13**, 291–298.

Marsh, T.J. & Hannaford, J. (eds). 2008. *UK Hydrometric Register*. Centre for Ecology & Hydrology, Wallingford, UK.
www.ceh.ac.uk/products/publications/documents/hydrometricregister_final_withcovers.pdf

Shaw, E.M. 1988. *Hydrology in Practice,* 2nd revised edition, 624pp. Chapman-Hall, UK.

World Meteorological Organisation. 2008. Guide to Hydrological Practices Volume I: Hydrology – From Measurement to Hydrological Information. Report No 168.
www.whycos.org/hwrp/guide/

World Meteorological Organisation. 2009. Guide to Hydrological Practices Volume II: Management of Water Resources and Application of Hydrological Practices. Report No 168.
www.whycos.org/hwrp/guide/

Annex I States and Agencies participating in the Hydrology Project

Phase I (1996-2003)	Phase II (2006-2014)
States	**States**
Andhra Pradesh	Andhra Pradesh
Chhattisgarh	Chhattisgarh
	Goa
Gujurat	Gujurat
	Himachal Pradesh
Kerala	Kerala
Karnataka	Karnataka
Madhya Pradesh	Madhya Pradesh
Maharastra	Maharastra
Orissa	Orissa
	Pondicherry
	Punjab
Tamil Nadu	Tamil Nadu
Agencies	**Agencies**
	Bhakra-Beas Management Board (BBMB)
Central Ground Water Board (CGWB)	Central Ground Water Board (CGWB)
	Central Pollution Control Board (CPCB)
Central Water and Power Research Station (CWPRS)	Central Water and Power Research Station (CWPRS)
Central Water Commission (CWC)	Central Water Commission (CWC)
Indian Meteorological Department (IMD)	Indian Meteorological Department (IMD)
Ministry of Water Resources (MoWR)	Ministry of Water Resources (MoWR)
National Institute of Hydrology (NIH)	National Institute of Hydrology (NIH)

Annex II Summary of Distribution of Hard Copy of HPI HIS Manual Surface Water

Volume	Manual	Part	Training	State DSC	State DPC	Div DPC	Sub-Div DPC	Station/ Lab
1 HIS	Design		+	+	+	+	+	
	Field	I Job description	+	+	+	+	+	
		II ToR for HDUG	+	+	+	+		
		III Data needs assessment	+	+	+	+		
	Reference		+	+	+			
2 Sampling Principles	Design		+	+	+	+	+	
	Reference		+	+	+			
3 Hydro-meteorology	Design		+	+	+	+	+	
	Field	I Network design & site selection	+	+	+	+	+	
		II SRG operation & maintenance	+	+	+	+	+	1 SRG
		III ARG/TBR/SRG operation & maintenance	+	+	+	+	+	1 ARG
		IV FCS operation & maintenance	+	+	+	+	+	1 FCS
		V Field inspections, audits, maintenance & calibration	+	+	+	+	+	
	Reference		+	+	+			
4 Hydrometry	Design		+	+	+	+	+	
	Field	I Network design & site selection	+	+	+	+	+	
		II River stage observation	+	+	+	+	+	+
		III Float measurements	+	+	+	+	+	+
		IV Current meter gauging	+	+	+	+	+	+
		V Field application of ADCP	+	+	+	(+)	+	(+)
		VI Slope-are method	+	+	+	+	+	+
		VII Field inspection & audits	+	+	+	+	+	
		VIII Maintenance & calibration	+	+	+	+	+	
	Reference		+	+	+			
5 Sediment Transport	Design		+	+	+	+	+	
	Field		+	+	+	+	+	+
	Reference		+	+	+			
6 WQ Sampling	Design		+	+	+	+	+	
	Field		+	+	+	+	+	+
7 WQ Analysis	Design		+	+	+			+
	Operation		+	+	+			+
8 Data Processing & Analysis	Operation	I Data entry & primary validation	+	+	+	+	+	
		II Secondary validation	+	+	+	+		
		III Final processing & analysis	+	+	+			
		IV Data management	+	+	+	+	+	
9 Data Transfer, Storage & Dissemination	Design		+	+	+			
	Operation		+	+	+			
10 SW Protocols	Operation		+	+	+	+	+	+
		Forms	+	+	+	+	+	+

Annex III How to specify an ADCP system

III.1 Components of an ADCP system

Acoustic Doppler Current Profilers (ADCPs) are recommended for use by Indian Central/State agencies interested in gauging flow in rivers and streams. ADCPs are deployed by wading, ropes, from bridges and from boats, and on remote-controlled floats. An ADCP can be easily transported in the back of a vehicle, so can be shared between several sites on different rivers. An ADCP system consists of a series of components that together make up an operational flow gauging package:

- An ADCP instrument unit containing all of the required electronics, batteries, compass and tilt sensors, etc;
- A small flotation platform for deployment of the ADCP unit (normally a plastic or fibreglass trimaran, boat or float);
- A data transmission system to transmit data from the ADCP to a receiver on the river bank. This may be a cable (cheap, if the ADCP and receiver are always close to each other), a Bluetooth system (cheap but has a limited range of 100-200 m) or a radio telemetry system (more expensive but with a range of several km);
- A robust laptop PC (e.g. toughbook) to receive and process the data on the riverbank;
- A Differential Global Positioning System (DGPS) instrument to monitor the position of the ADCP on the river (needed in situations where the river bed is unstable and where bed material is moving, which may be the normal situation in Indian rivers during the monsoon);
- Necessary connection cables and spare batteries, etc plus manuals.

III.2 ADCP manufacturers

It is essential that ADCPs are purchased from a reputable company with a long and proven track record in implementation, preferably in rivers similar to those in India, and the necessary infrastructure to provide training and support over a period of time. The two principal ADCP manufacturers, both with Indian agents, are Sontek and Teledyne RDI (TRDI). Both manufacturers use the preferred broad-band technology (a broad-band ADCP puts a complex signal into the water and is able to collect more data per unit time, increasing accuracy), though note that prior to 2011 (when the broad-band patent expired) Sontek ADCPs used narrow-band technology (a narrow-band ADCP uses a simple sine wave signal and has to ping faster to get results).

ADCPs differ in acoustic frequency, number of beams, size/weight, available operating modes, and optional extras. In practical terms, these features need to be translated into ease of use, operational river depth and width and water velocity, and ability to handle sediment load, moving bed and weed growth. The Health and Safety implications of attempting any discharge measurements in flood flows should be taken very seriously. In terms of ease of use, some of the ADCPs are “intelligent”, configuring themselves dynamically to the water conditions and changing configuration as they cross the river, whilst other “manual” ADCPs must be configured by the user and that configuration is used for the whole transect. Although the intelligent ADCPs are undoubtedly easier to operate, the data are typically a slightly poorer quality than from the manual ADCPs. Table III.1 summarises the main features of the different products.

III.3 Training

At least one member of the ADCP field team should have received full training in how to operate the equipment. ADCP technology is continually changing so it is important for ADCP users to keep

Table III.1 Main features of Sontek and Teledyne RDI ADCPs

Instrument	**Features**
Sontek – uses River Surveyor data processing software	
River Surveyor S5	Automatic, adaptive configuration Integrated DGPS High frequency 3 MHz, small transducer Suits shallow water, up to 6m deep Low flows to high flows More susceptible to moving bed, not good for high sediment load Smaller depth range, beam spread and cell sizes
River Surveyor M9	Automatic, adaptive configuration Integrated DGPS Low 1 MHz and High 3 MHz frequency, large transducer Suits shallow and deep water 3-60m deep Low flows to flood flows Greater depth range, beam spread and cell sizes
Teledyne RDI – uses WinRiverII data processing software	
StreamPro	Manual, fixed configuration 2 water modes High frequency 2 MHz, small transducer Suits shallow water 0.3-6.25m deep Low flows to high flows More susceptible to moving bed, not good for high sediment load Smaller depth range, beam spread and cell sizes
Work Horse Rio Grande 1200	Manual, fixed configuration 4 water modes, 2 bottom modes Medium frequency 1200 MHz, large transducer Suits medium rivers 1-30m deep Low flows to flood flows Greater depth range, beam spread and cell sizes
Work Horse Rio Grande 600	Manual, fixed configuration 4 water modes, 2 bottom modes Low frequency 600 MHz, large transducer Suits deep water 3-30m deep Low flows to high flows Greater depth range, beam spread and cell sizes
River Ray	Automatic, adaptive configuration Low frequency 600 KHz, large transducer Suits deep water 0.45-30m deep Low flows to high flows Greater depth range, beam spread and cell sizes

up to date with changes through regular refresher training. This could take the form of joint events with ADCP users in other States and agencies to learn from each other.

III.4 Where to go to for support

The USGS Hydroacoustics Home Page (http://il.water.usgs.gov/adcp/) contains lots of useful reports, technical tips, USGS policy documents, some USGS freeware, live and recorded webinars, and a mailing list (http://hydroacoustics.usgs.gov/list_info.shtml) for queries and support from international community.

Annex IV How to measure river discharge using an ADCP

This note gives advice on the deployment of ADCPs for determining river discharge. Several different ADCPs from different manufacturers are in operation in India, so the note presents a generic approach to determining a single instantaneous measurement of discharge. Not all steps will be applicable for all ADCPs. The note is based on UK Environment Agency guidance, adapted for Indian conditions, and should be used in conjunction with guidance and instruction manuals given to staff during training in flow gauging using ADCPs. The following sections of the HIS Manual SW should be referred to:

- SW4-DM pages 107-124
- SW4-FM(I) pages 2-6, SW4-FM(V), SW4-FM(VIII) pages 6-8
- SW4-RM pages 9.1-9.8

IV.1 Selecting a site and a deployment method

In most instances, the site and method of deployment of the ADCP will have already been selected, as most sites will be at existing flow gauging stations.

IV.1.1 Site selection

Where possible the site will have a straight approach channel, relatively uniform depth, no weed, rocks or other obstacles in the channel, and well-defined edges to channel. The ADCP should be suitable for the water speed and channel depth at the site. The water speed should be greater than the ADCP’s minimum response speed, but should not exceed the ADCP’s maximum response speed and the health and safety considerations of the operators. Sites with moving bed conditions, excessive aeration and turbulence should be avoided where possible. SW4-FM(I) Chapter 2.4.3 refers to site selection.

IV.1.2 Deployment method

The majority of Indian ADCPs are deployed by tethering them from manned boat or mounting them directly from a manned boat. Other methods of deployment which may be appropriate in some circumstances (e.g. low flows) include wading, manually operated tow ropes or pulley system, cableway or bridge, and remote controlled boat. SW4-FM(V) Chapter 3 and SW4-RM Chapter 9.5.1 refer to deployment.

IV.2 Preparation

IV.2.1 Training

At least one member of the ADCP gauging team should have received full training in how to operate the equipment. ADCP technology is continually changing so it is important for users to keep up to date with changes through regular refresher training. This could take the form of joint events with ADCP users in other States and agencies to learn from each other.

IV.2.2 Maintenance

It is important to ensure that the ADCP is maintained in accordance with the manufacturers’ recommendations, and that the ADCP is inspected thoroughly after it has suffered any significant impact or rough treatment e.g. checking the transducers for damage.

IV.2.3 Pre-field checks

If the gauging site is not located at the Field Office, it is important that some pre-field checks are made before travelling to the gauging site. Depending on the ADCP, these checks may include:

- Check the most recent software and firmware are being used for data collection and processing
- Assemble and check all equipment including ancillary items e.g. field notebook, measuring tapes
- Check power supply, cables, mounts, etc and take spare batteries for any equipment using them
- Connect ADCP to the field computer and check all communications
- Check auxiliary sensor, such as the DGPS

SW4-FM(VIII) Chapters 3.2 and 4.2, and SW4-RM Chapters 9.4 and 9.7, refer to ADCP maintenance and pre-field inspections.

IV.3 Pre-gauging procedures

IV.3.1 Set-up ADCP and test communications

At the field site, before the ADCP is placed in the water, all the ADCP equipment should be assembled, the connectors and battery voltages checked and the communications between the ADCP and the field computer tested. SW4-RM Chapter 9.5.2 refers to instrument checks in the field.

IV.3.2 Measure depth of transducers

Depending on the ADCP and method of deployment, after the ADCP is deployed in the water it may be necessary to measure and record the depth of the transducers below the surface (i.e. the vertical distance from the water surface to the centre of the transducer face). SW4-RM Chapter 9.5.1 provides more information.

IV.3.3 Measure water temperature and salinity

An independent measurement of water temperature should be made as close to the ADCP sensors as possible and entered in the ADCP software. If the ADCP is being used in or near saline water, the water salinity should be measured and entered in the ADCP software. SW4-DM Chapters 6.5.5 and 6.5.6 refer to temperature and salinity measurement.

IV.3.4 ADCP diagnostic tests

With the ADCP in the water and ready to use, run the ADCP diagnostic test. Record and keep the results on the field computer along with the discharge measurement data, as they may be needed for future verification of data quality. SW4-FM(VIII) Chapter 3.2 and SW4-RM Chapter 9.5.2 refer to the ADCP diagnostic tests.

IV.3.5 Enter site and gauging metadata

The metadata and other set-up information that need to be entered vary with the ADCP. For instance, a Teledyne RDI Work Horse Rio Grande requires selection of water mode, bottom mode and other parameters, whilst a Sontek River Surveyor is “intelligent” with automatic adaptive sampling. If there is any uncertainty, do a test transect to check that the ADCP settings are appropriate for the site and conditions, that there are few or no lost data, that the bin size is small enough to measure close to the banks, and that the edge start and end points are set appropriately. The edge distances should be the perpendicular distance from the edge of the water to the boat, and the distances and edge profile shapes should be recorded and entered in the ADCP software. If necessary, adjust the settings and repeat the test transect. SW4-DM Chapter 6.5.5, SW4-FM(V) Chapter 4 and SW4-RM Chapter 9.5.4 refer to the operating set-up for some ADCPs.

IV.3.6 Do a moving bed test

When gauging from a moving boat, all water speeds measured by the ADCP are referenced to the river bed, so it is essential that the surface layer of the river bed is not moving. It is important to test for a stationary moving bed at the point of fastest flow in the river before commencing ADCP gauging, and for wide rivers it may be necessary to do a moving bed test at several locations across the gauging transect. To do a stationary moving bed test, hold the ADCP stationary for at least 5 minutes, whilst pinging and recording data. Then check the track plot for any apparent upstream movement of the ADCP relative to the river bed.

If the test indicates signs of significant bed movement, consider moving to an alternative site. If this is not possible, a DGPS capable of better than 0.5m accuracy should be used. When using a DGPS, it is important that the internal compass of the ADCP is calibrated to get an accurate estimate of the local magnetic variation. A DGPS should not be used for small rivers (streams), or near bridges, buildings or overhanging trees. SW4-DM Chapter 6.5.5 refers to moving bed tests and compass calibration.

Update the site and gauging metadata as necessary.

IV.3.7 Do a test transect

At the gauging location do a test transect but do not record the data. Inspect the transect data to ensure a good bottom track, the ADCP measures all the way to the bottom, good data in shallow sections, and minimal lost data (i.e. where applicable, the water mode chosen is good for the conditions).

IV.4 Gauging procedures

Make a minimum of two transects in each direction under steady flow conditions. The measured discharge will be the average of the discharges from all the individual transects. If the discharge for any of the four transects differs by more than 5% from the mean, take a minimum of two additional transects in each direction. Then the measured discharge will be the average of the discharges from all the individual transects. Always try and understand why transects may be varying by more than 5% and document reasons in the field notebook.

Try and start a transect in a position where there are at least 3 good bins of water data, and at least one water depth away from any vertical walls or other obstacles. Collect 10 good ensembles (~15 seconds) of data before the boat is moved across the river, and similarly at the other end of the transect. Transects should always be perpendicular to the flow direction and repeat transects should follow the same path across the river and back. The boat course should be as smooth as possible and the boat speed as steady as possible. It is recommended that, if possible, the boat speed should be <0.5 m/s and the boat speed should be less than the water velocity. USGS research (2007) has shown that the transect measurement time is more important than the number of transects. It is worth experimenting with transect measurement times to identify the optimum measurement time for the gauging site.

SW4-DM Chapter 6.5.5, SW4-FM(V) Chapter 5 and SW4-RM Chapter 9.5.4 refer to measurement runs.

IV.5 Post-gauging procedures

When flow gauging has been completed, remember to stop the ADCP pinging and turn it off. After the ADCP is removed from the water, put on any protective covers and disconnect the battery before transporting.

Before leaving the gauging site, review the collected data for problems and check that the results are broadly in line with expectations. Ensure that the site and gauging metadata are complete, including any comments regarding the site and conditions relevant to later interpretation of the data.

Before leaving the gauging site, back all data on the field computer up to a secure storage medium such as a flash drive.

SW4-DM Chapter 6.5.5, SW4-FM(V) Chapter 6 and SW4-RM Chapter 9.5.5 provide more information.

See Annex V “How to process and validate ADCP river discharge measurements” for guidance on what to do next. SW4-RM Chapter 9.6.1 refers to the need for post-field office procedures and discharge measurement review.

IV.6 Where to go to for support

The USGS Hydroacoustics Home Page (http://il.water.usgs.gov/adcp/) contains lots of useful reports, technical tips, USGS policy documents, some USGS freeware, live and recorded webinars, and a mailing list (http://hydroacoustics.usgs.gov/list_info.shtml) for queries and support from international community.

Annex V How to process and validate ADCP river discharge measurements

This note gives advice on the processing and validation of river discharge measurements obtained using an ADCP. SW4-RM Chapter 9.6.1 refers to the need for post-field office procedures and discharge measurement review, but no other information is provided in the Surface Water HIS Manual. See Annex IV “How to measure river discharge using an ADCP” for guidance on data collection. Several different ADCPs from different manufacturers are in operation in India, so the note presents a generic approach to determining a single instantaneous measurement of discharge as details will vary with the ADCP and the software. Not all of the steps presented will be appropriate to every ADCP, nor will be the actions that can be taken to address any problems that are identified. Hence, this note provides general suggestions about the approach to take, not specific instructions about what to do.

ADCP discharge measurements should be reviewed by different person to the ADCP operator who made the flow gauging, and who has received full training and regular refresher training in how to process and validate ADCP data. Sontek ADCPs use River Surveyor data processing software, whilst Teledyne RDI ADCPs use WinRiverII software. The note is based on UK Environment Agency guidance, adapted for Indian conditions, and should be used in conjunction with guidance and instruction manuals given to staff during training in processing and validating ADCP data.

V.1 Inspecting general data

V.1.1 Inspect diagnostic test

Open the ADCP diagnostic test file to review the data recorded before actual flow gauging commenced. Check that all of the ADCPs systems and sensors were working correctly in the field and establish the impact of any failures on the flow gauging (major failures may invalidate the gauging). If the diagnostic data are satisfactory, proceed to next step.

V.1.2 Inspect metadata

Check essential information was recorded in the ADCP software and/or in the field notebook. This may include station number, station name, river name, gauging location, grid reference, gauging team, ADCP used, deployment type, start and stop stage (if available), weather, water temperature, boat traffic, etc. In particular, look for any specific comments regarding the site and conditions relevant to the specific flow gauging.

V.1.3 Inspect moving bed test

Review the moving bed test(s) to identify any signs of a moving bed (up river movement of the ADCP). If the test(s) indicate(s) signs of significant bed movement, check that the flow gauging used the DGPS and that the ADCP compass was calibrated.

V.1.4 Instrument configuration

Review the ADCP configuration settings to check they were appropriate for the site and conditions. Depending on the ADCP, these may include water mode, bottom mode, transducer depth, blanking distance, bin size, averaging interval, instrument frequency, software version, firmware version, etc. Update the configuration settings if necessary.

V.2 Inspecting transect data

V.2.1 Inspect the first transect

Inspect the first transect in detail and note any issues. Many problems will be common to all transects so it is useful to identify them in the first transect and then watch out for them in the other transects.

From the graphical displays, examine aspects of the transect such as:

- Completeness of data – are there any missing bins or ensembles?
- Water depth and number of depth cells – have a minimum of 2 bins at edge and 4 bins in deeper areas been collected?
- Quality of bottom track – is the graph showing a smooth and believable bed trace, with no spikes or gaps indicating bottom-tracking problems?
- Track plot – is the graph showing a realistic and representative course across the river?
- Velocities – is the graph showing realistic and believable velocities, with no velocities standing out as different from those near them e.g. reverse flow?
- Beam intensities – is there side lobe interference from banks?

From the tabular displays, examine aspects of the transect such as:

- Number of ensembles – are there sufficient ensembles to provide adequate representation of channel x-section?
- Lost ensembles – this should be zero, otherwise it indicates loss of communication between the ADCP and the field computer
- Bad ensembles and bad bins – are missing data distributed throughout transect, which is preferable to missing data concentrated in one or more contiguous zones?
- Total discharge – is the total discharge in line with expectations?
- Discharge breakdown i.e. proportions of measured discharge, top discharge, bottom discharge, left discharge and right discharge making up total discharge – the top discharge should be less than 40% of the total, and the bottom discharge <25%, and the edges both a small %.
- Water temperature – the ADCP water temperature should be in agreement with the manual temperature check, if taken
- Transect duration – were the length of transect and transect duration appropriate for the width of river?

V.2.2 Inspect the remaining transects

Review the other transects for consistency and quality, checking for recurrence of any issues identified in the first transect. Graphical displays are the most useful in this regard. Note any issues in each transect.

V.2.3 Inspect summary table of all transects

Examine aspects such as:

- Total discharge – this should be similar for each transect
- Start bank – an equal numbers of reciprocal transects should be used
- Number of ensembles – this should be similar for each transect
- Discharge breakdown – this should be similar for each transect
- Left bank and right bank distances – these should be similar for each transect (they should not be zero, but are likely to vary depending on the deployment method)
- Total width – this should be similar for each transect, and is usually the largest source of error in discharge. It is recommended that the summary table is copied into Excel to plot width and total discharge for each transect, as well as width against total discharge, in order to check for any correlation. If significant correlation exists, it may be necessary to exclude some transects.

- Total area – the total cross-sectional area of the transect should be similar for each transect
- Mean velocity (Q/A) – this should be similar for each transect
- Boat speed – the boat speed should be steady for the duration of the transect
- Flow speed – the mean velocity of measured area should be similar for each transect
- Start and end water levels, if taken – these should be similar for each transect, and the start stage of a transect should be similar to end stage of previous transect

Note any issues in each transect.

V.3 Discharge calculation

V.3.1 Test top and bottom extrapolations

Inspect how well the top and bottom discharge extrapolation lines fit the measured data line (especially where the highest water speeds are). If necessary change the top and bottom extrapolations to better fit the measured data. If changes are made, reprocess all transects to recalculate the new discharges (noting the discharges before and after any changes).

V.3.2 Filter out ambiguity errors

Depending on the ADCP, it may be possible to adjust the error filtering parameters to filter out errors that have escaped automatic error filtering. It is first necessary to identify if these are water track errors or bottom track errors and then incrementally reduce the value in the water track error velocity threshold or bottom track error velocity threshold, respectively, to filter out the errors whilst losing a minimal amount of good data.

V.3.3 Exclude bad data near to banks

If bad ensembles are near the edges of the channel it is possible to exclude them from the transect. Determine which ensembles need to be excluded, noting their number and distance to edge as removing these ensembles will require the appropriate edge distance(s) to be increased to compensate. Exclude the bad ensembles and then inspect the transect and the summary table to check the new width and cross-sectional area are as expected given changes to ensembles. Poor data in the middle of a transect cannot be removed in this way.

V.3.4 Choose final dataset

Normally, all transects will be used for reporting the total discharge. However, ensure that there are an equal number of transects in each direction, and exclude transects with errors that cannot be remedied e.g. bottom-tracking problems – but do not exclude outlier transects unless their data are poor. Always try and understand why transects may be varying by more than 5% and document reasons. When discharge is varying rapidly, a single transect measurement may be acceptable for comparison to a stage-discharge rating or other instrument.

V.3.5 Lock the measurement

Once processing and editing are complete, lock the flow gauging measurements to prevent further changes (without first unlocking).

V.4 Final checks

V.4.1 Undertake final checks

Check for:

- Failure to collect adequate metadata
- No instrument diagnostic test conducted
- No moving bed test carried out
- Moving bed data wrongly interpreted
- Uneven or too fast boat speed
- Edge distances poorly measured or not at all
- Wrong edge shapes used
- Incorrect ADCP transducer depth set
- Incorrect blanking distance set
- Incorrect extrapolation methods used
- Incorrect number of depth cells for river depth
- Inappropriate water mode used
- Poor configuration of ADCP (i.e. depth cells too big or small)
- Poor data archival procedures
- Use of ferrous metal mounts for ADCP, or close proximity to ferrous metals in banks or bridges, causing errors in navigation data
- Poor synchronisation between ADCP movement and data collection (communication breakdown between computer operator and ADCP operator(s)
- Failure to collect edge ensembles

V.4.2 Archive results

If final checks are satisfactory, enter the result of the ADCP flow gauging manually onto the hydrometric database (Section 5.1.6 of this Handbook). Store the ADCP data files for the flow gauging in an appropriate named folder. Ensure the folders and all associated data files are regularly backed-up.

V.5 Where to go to for support

The USGS Hydroacoustics Home Page (http://il.water.usgs.gov/adcp/) contains lots of useful reports, technical tips, USGS policy documents, some USGS freeware, live and recorded webinars, and a mailing list (http://hydroacoustics.usgs.gov/list_info.shtml) for queries and support from international community.