Manual on Low-flow Estimation and Prediction

Operational Hydrology Report No. 50

Manual on Low-flow Estimation and Prediction

Operational Hydrology Report No. 50

WMO-No. 1029

World
Meteorological
Organization
Weather • Climate • Water

Contents

Foreword

The Commission for Hydrology (CHy) decided at its twelfth session (Geneva, October 2004) to prepare a manual on low-flow estimation and prediction to meet the identified needs of National Hydrological Services. The Manual on Low-flow Estimation and Prediction, which consists of 13 chapters, was drafted by the Open Panel of CHy Experts (OPACHE) on Disaster Mitigation – Floods and Droughts (Hydrological Aspects). The list of authors is provided on page IX.

The drafting team was initially led by Mr Siegfried Demuth (Germany), then by Mr Bruce Stewart (Australia), who also took part in the review process. Mr Charles Pearson (New Zealand) and Mr Syed Moin (Canada) were the reviewers.

The Manual's objective is to publish state-of-the-art analytical procedures for estimating and predicting low river flows at all sites, regardless of the availability of observational data. The Manual will be useful for many applications, including water resources planning, effluent dilution estimates and water resources management during low-flow conditions.

It is a great pleasure to express WMO's gratitude to the authors, the reviewers and to the president of CHy, Mr Bruce Stewart, for their efforts during the preparation of the Manual.

(M Jarraud)
Secretary-General

Preface

More often than not, the thought of rivers conjures up the image of high water levels and even floods. However, many communities depend on the availability of water through non-regulated river systems for their water supply. Therefore, periods of low flow are critical for managing their water resources. Similarly, it is the function and role of dams to level out the fluctuations of high and low flows and to provide a balanced water supply to meet demands. Knowledge of low-flow periods is therefore fundamental for reservoir design and determining allocations.

Many factors have an impact on the low-flow regimes of rivers. Whenever we change our land uses, we change the way in which water interacts with the landscape, and this can affect the water available in rivers, lakes and dams. Most nations are experiencing population growth, resource depletion and the overextraction of water. Low flows are critical elements in terms of meeting demands for often competing uses and requirements.

More recently, there have been growing concerns over the relationship between water and the environment, and many counties are conducting research into the requirements for, and delivery of, environmental flows.

The topic of this Manual, namely low-flow estimation, is thus of paramount importance for the development and implementation of sustainable water resources management practices. I highly recommend this Manual and congratulate its contributors on the guidance provided therein.

I note that the Manual does not have the full geographical coverage that the Commission for Hydrology would like to see in its publications.

However, we consider this a challenge for future publications and will seek your support in addressing the issue when we next address the topic. We would, of course, be interested in any feedback on the use and implementation of this Manual.

(Bruce Stewart)
President of the Commission for Hydrology

Acknowledgement

List of Authors

Chapter 1:
Introduction
Alan Gustard and Siegfried Demuth

Chapter 2:
Estimating, predicting and forecasting low flows
Alan Gustard and Siegfried Demuth

Chapter 3:
Hydrological data
Gwyn Rees

Chapter 4:
Processes and regimes
Kerstin Stahl, Henny A.J. van Lanen and
Stefan Uhlenbrook

Chapter 5:
Low-flow indices
Alan Gustard and Lena Tallaksen

Chapter 6:
The flow-duration curve
Hege Hisdal and Alan Gustard

Chapter 7:
Extreme value analysis
Lena Tallaksen and Guna A. Hewa

Chapter 8:
Streamflow deficit
Hege Hisdal

Chapter 9:
Estimating low flows at ungauged sites
Andy Young, Denis Hughes and Siegfried Demuth

Chapter 10:
Estimating low flows in artificially influenced rivers
Alan Gustard and Andy Young

Chapter 11:
Low-flow forecasting
Trevor Daniell, Rory Nathan, Francis Chiew and
Alexander Osti

Chapter 12:
Case studies
Andy Young, Kerstin Stahl, Gwyn Rees,
Alan Gustard, James Dent, Hege Hisdal and
Denis Hughes

Chapter 13:
Recommendations and conclusions
Alan Gustard, Siegfried Demuth, Roland Price and
Stefan Uhlenbrook

Summary

The Manual's objective is to publish state-of-the-art analytical procedures for estimating and predicting low river flows at all sites, regardless of the availability of observational data. The Manual will be used for estimating and predicting low flows for many applications, including water resources planning, effluent dilution estimates and water resources management during low-flow conditions.

This Manual will be one of the technical guidance documents included in the WMO Quality Management Framework in Hydrology and discussed by the thirteenth session of the Commission for Hydrology.

Chapters 1 and 2 of the Manual introduce the objectives, structure and major issues involved in predicting and forecasting low flows. Chapter 3 discusses the data requirements for low-flow estimation, including river flow and associated basin properties, for example, soil type, hydrogeology and climate. Chapter 4 presents key low-flow processes and the resulting wide range of low-flow response, an understanding of which is essential for analysing and interpreting low-flow information. Chapter 5 describes simple low-flow indices, including the 95 percentile exceedance discharge and base-flow and recession characteristics. Chapters 6, 7 and 8 provide step-by-step guidelines on estimating the flow-duration curve, extreme value distributions and the analysis of streamflow deficits, respectively.

Chapter 9 describes a range of methods for estimating low flows at ungauged sites, including the use of short and nearby flow records to reduce the uncertainty of flow estimation. Chapter 10 presents key practical problems of how to estimate low flows in rivers influenced by artificial controls, such as abstractions, effluent returns and impoundments. Chapter 11 describes the main applications for which forecasts of low flows are required and presents methodologies for forecasting flows on a range of timescales. Chapter 12 presents a number of case studies on, among others, transboundary issues, a water resources decision-support tool, a regional approach to estimating small-scale hydropower and the estimation of residual flows below abstraction points.

Chapter 13 presents some significant conclusions and recommendations relating to data collection and capacity-building. Together with the techniques presented in the rest of the Manual, it is hoped that these conclusions and recommendations will reduce the uncertainty of estimating low flows and improve methods, for the benefit of all users.

Résumé

Le présent manuel a pour objet de faire largement connaître les méthodes analytiques les plus avancées en matière d'estimation et de prévision des débits d'étiage en tous points des cours d'eau, quelles que soient les données d'observation disponibles, et cela dans la perspective de nombreuses applications, dont la planification des ressources en eau, les estimations de la dilution des effluents et la gestion des ressources en eau pendant les périodes d'étiage.

Ce manuel sera l'un des documents techniques d'orientation qui seront pris en compte dans le Cadre de référence de l'OMM pour la gestion de la qualité en hydrologie et qui seront examinés par la Commission d'hydrologie à sa treizième session.

Les chapitres 1 et 2 portent sur les objectifs, la structure et les principales questions relatives à la prédétermination et à la prévision des débits d'étiage. Le chapitre 3 est consacré aux données nécessaires pour l'estimation de ces débits, y compris l'écoulement fluvial et les propriétés des bassins connexes (types de sols, hydrogéologie, climat, etc.).

Au chapitre 4 sont présentés les principaux processus liés aux étiages ainsi que le large éventail des réponses possibles, qu'il est indispensable de bien comprendre pour analyser et interpréter les informations relatives aux étiages. Au chapitre 5 sont indiqués les indices d'étiage simples, y compris le débit de dépassement correspondant au quatre-vingt-quinzième percentile et les caractéristiques propres aux débits de base et aux décrues. Les chapitres 6, 7 et 8 fournissent respectivement des indications, étape par étape, sur l'estimation de la courbe des débits classés, la distribution des valeurs extrêmes et l'analyse des déficits d'écoulement fluvial.

Au chapitre 9 sont décrites un certain nombre de méthodes d'estimation du débit d'étiage sur des sites non jaugés, y compris l'utilisation de relevés de débit de courte durée et exécutés à proximité afin de réduire l'incertitude des valeurs estimées. Au chapitre 10 sont présentés les principaux problèmes pratiques que pose l'estimation des débits d'étiage dans les cours d'eau soumis à l'influence de contrôles artificiels (dérivations, renvois d'effluents, retenues, etc.). Au chapitre 11 sont abordées les principales applications nécessitant des prévisions du débit d'étiage et les méthodes de prévision du débit à diverses échelles de temps. Au chapitre 12 sont présentées un certain nombre d'études de cas portant notamment sur des questions de caractère transfrontalier, un outil d'aide à la décision pour les ressources en eau, une approche régionale de l'estimation de l'énergie hydroélectrique à petite échelle et l'estimation des débits résiduels en aval des points de dérivation.

Au chapitre 13 figurent quelques conclusions et recommandations importantes concernant la collecte des données et le renforcement des capacités. Il est à espérer qu'à l'instar des techniques présentées dans le reste du manuel, ces conclusions et recommandations contribueront à atténuer l'incertitude propre aux valeurs estimées des débits d'étiage et à améliorer les méthodes employées, pour le plus grand profit de tous les utilisateurs.

Резюме

Цель настоящего Наставления заключается в том, чтобы опубликовать современные аналитические процедуры для расчета и прогнозирования низкого речного стока на всех объектах, независимо от наличия данных наблюдений. Наставление будет использоваться для расчета и прогнозирования низкого стока для многих применений, включая планирование водных ресурсов, оценку разбавления стоков и управление водными ресурсами в условиях низкого стока.

Это Наставление будет являться одним из технических руководящих документов, включенных в Структуру управления качеством ВМО в области гидрологии, которые были обсуждены на тринадцатой сессии Комиссии по гидрологии.

В главах 1 и 2 Наставления представлены цели, структура и основные вопросы, связанные с предсказанием и прогнозированием низкого стока. В главе 3 рассматриваются требования к данным для оценки низкого стока, включая речной сток и связанные с ним свойства бассейнов, например, тип почвы, гидрогеология и климат. В главе 4 представлены ключевые процессы низкого стока и получаемый широкий диапазон реагирования низкого стока, понимание которого необходимо для анализа и толкования информации о низком стоке. В главе 5 описываются простые индексы низкого стока, включая 95-процентильное превышение расхода и характеристики базисного стока и истощения стока. В главах 6, 7 и 8 представлены поэтапные руководящие принципы для расчета кривой продолжительности стока, распределения экстремальных значений и анализа дефицита речного стока соответственно.

В главе 9 описывается ряд методов для оценки низкого стока на участках, где не проводятся постоянные измерения, включая использование краткосрочных данных о стоке с близлежащих станций в целях снижения неопределенности при расчете стока. В главе 10 описываются ключевые практические проблемы, касающиеся расчета низкого стока в реках под влиянием искусственных контрольных сечений, таких как отводы, возврат истоков и запруживание. В главе 11 описаны основные применения, для которых требуются прогнозы низкого стока, и представлены методики для прогнозирования стока по диапазону временных масштабов. В главе 12 представлен ряд тематических исследований, посвященных, среди прочего, трансграничным вопросам, инструменту, поддерживающему принятие решений, касающихся водных ресурсов, региональному подходу к оценке гидроэнергии в небольших масштабах и расчетов остаточного стока ниже точек отвода.

В главе 13 представлены некоторые важные выводы и рекомендации, касающиеся сбора данных и наращивания потенциала. Наряду с методами, представленными в остальной части Наставления, выражается надежда, что эти выводы и рекомендации позволят понизить неопределенность при расчете низкого стока и улучшить методику на благо всех пользователей.

Resumen

El objetivo del Manual es publicar los procedimientos analíticos más avanzados para estimar y predecir el caudal de estiaje en cualquier lugar, con independencia de la disponibilidad de datos de observación. El Manual se usará para estimar y predecir el caudal de estiaje, lo que facilitará la realización de numerosas aplicaciones -tales como la planificación de los recursos hídricos, la estimación de la dilución de efluentes y la gestión de los recursos hídricos- cuando se dé un caso de estiaje.

Este Manual será uno de los documentos de orientación técnica que se incluyan en el Marco de gestión de la calidad de la OMM – Hidrología y que examine la Comisión de Hidrología en su decimotercera reunión.

En los capítulos 1 y 2 del Manual se enuncian los objetivos, la estructura y las principales cuestiones pertinentes de la predicción y previsión del caudal de estiaje. En el capítulo 3 se estudian los datos que se necesitan para realizar estimaciones del caudal de estiaje, entre ellos el caudal fluvial y las propiedades relacionadas de las cuencas hidrográficas, como por ejemplo el tipo de suelo, la hidrogeología y el clima. El capítulo 4 presenta procesos fundamentales del caudal de estiaje y la amplia gama resultante de respuestas existente en ese ámbito, cuya comprensión es esencial para analizar e interpretar la información sobre el caudal de estiaje. En el capítulo 5 se describen índices sencillos de caudal de estiaje, en particular el percentil 95 de excedencia de caudales y las características del caudal de base y de la recesión. En los capítulos 6, 7 y 8 figuran directrices de fases progresivas sobre la estimación de la curva de duración de caudales, la distribución de los valores extremos y el análisis de los déficits de flujo fluvial respectivamente.

En el capítulo 9 se describe un conjunto de métodos para estimar el caudal de estiaje en lugares que no han sido aforados, entre los que cabe citar la utilización de registros de caudales de períodos cortos y de lugares cercanos para reducir la incertidumbre de su estimación. En el capítulo 10 se presentan problemas prácticos fundamentales de la estimación del estiaje en ríos que están bajo la influencia de controles artificiales, tales como las extracciones, los retornos de efluentes o las retenciones. En el capítulo 11 se describen las principales aplicaciones para las que se necesitan las predicciones del caudal de estiaje y se presentan métodos para predecir el caudal en diversas escalas temporales. En el capítulo 12 se presentan varios estudios de casos sobre, entre otras cosas, cuestiones transfronterizas, así como un instrumento de apoyo para la adopción de decisiones sobre los recursos hídricos, un enfoque regional para estimar la energía hidroeléctrica en pequeña escala y la estimación de los caudales residuales por debajo de los puntos de extracción.

En el capítulo 13 se presentan algunas conclusiones y recomendaciones importantes relacionadas con la recogida de datos y la creación de capacidad. Se espera que estas conclusiones y recomendaciones, junto con las técnicas presentadas en el resto del Manual, sirvan para reducir la incertidumbre de las estimaciones del caudal de estiaje y para mejorar los métodos utilizados a tal fin, en beneficio de todos los usuarios.

1. Introduction

1.1   Objectives

One of the aims of the World Meteorological Organization (WMO) is to promote the standards of meteorological and hydrological observations and ensure the consistent and appropriate analysis of environmental data. A number of WMO guidance manuals have been published which describe in detail the practices, procedures and specifications that WMO Members are invited to implement. This Manual is a contribution to this task, and its key objective is to publish state-of-the-art analytical procedures for estimating, predicting and forecasting low river flows at all sites, regardless of the availability of observational data.

The Manual will be used by operational agencies to predict and forecast low flows for a wide range of applications, including national and regional water resources planning, abstraction management, public water-supply design, instream flow determination, effluent dilution estimates, navigation, the run design of river hydropower schemes, the design of irrigation schemes and water resources management during low-flow conditions. The Manual will also make it possible to mitigate the hydrological impacts of low flows and facilitate the design of flow-monitoring networks. The Manual includes a description of current methodologies used for low-flow prediction and forecasting and practical examples of operational applications. It addresses the estimation of low flows from continuous flow records, at ungauged sites and from short flow records including natural and artificially influenced catchments. The Manual will be of value primarily to hydrologists from operational agencies where low-flow estimation procedures are being developed or updated and to professionals teaching short technical courses and first degree and Master of Science courses in applied hydrology.

1.2   Background

The Manual is part of a new series of WMO publications consisting of several manuals and guidelines within the WMO Quality Management Framework in Hydrology. The manuals all have a practical approach to hydrological and water resources design and are targeted at meeting the needs of National Hydrological and Meteorological Services. These manuals include theoretical information only when it is needed for a better understanding of the subject. In this series, manuals are planned on the following subjects: flood forecasting; probable maximum precipitation/probable maximum floods; design floods; low-flow estimation; and water resources assessment. These manuals will complement the information available in the Guide to Hydrological Practices (WMO-No. 168) and the WMO Technical Regulations (WMO-No. 49).

This Manual complements the Hydrological Operational Multipurpose System (HOMS) established by WMO for the transfer of technology in hydrology and water resources. This technology is usually in the form of descriptions of hydrological instruments, technical manuals or computer programs. The material included in HOMS is used operationally by the Hydrological Services of WMO Members. This ensures that the technology transferred is not only ready for use, but also works reliably. Participating countries designate a HOMS National Reference Centre (HNRC), usually in the National Hydrological Service. This centre provides national components for use in HOMS, handles national requests for the HOMS components to be supplied by other HNRCs, advises users on HOMS, and generally coordinates and publicizes HOMS activities.

The terminology used in this report is consistent with the UNESCO and WMO International Glossary of Hydrology (UNESCO/WMO, 1992) and Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater (Tallaksen and van Lanen, 2004). The latter also provides a broader perspective on a wide range of drought issues, including the hydrological processes controlling drought response, and methods for analysing river flows and groundwater droughts, stream ecology and flow management.

1.3   Manual structure

The Manual presents a range of different techniques for analysing hydrological data to provide operational information for low-flow prediction and forecasting. These are summarized in Table 1.1, which lists different ways of describing the low-flow regime of a river, the specific property of the analysis technique, data requirements and some common applications. The Manual provides step-by-step guidance for calculating these low-flow properties from recorded flow data and presents methods for estimating them at ungauged sites and for forecasting low flows on a range of time scales. Analysis techniques are illustrated by practical examples of their use in operational hydrology.

This chapter and Chapter 2 of the Manual introduce the objectives, structure and key issues involved in predicting and forecasting low flows. These are followed by Chapter 3, which provides a comprehensive review of the data requirements for low-flow estimation, including river-flow and associated catchment properties, for example, soil type, hydrogeology and climate. Chapter 4 presents key low-flow processes and the resulting wide range of low-flow response, an understanding of which is essential for analysing and interpreting low-flow information. Chapter 5 describes simple low-flow indices, including the 95 percentile exceedance discharge and base-flow and recession characteristics. Chapters 6, 7 and 8 provide step-by-step guidelines for estimating the flow-duration curve, extreme value distributions and the analysis of streamflow deficits, respectively.

Chapter 9 describes a range of methods for estimating low flows at ungauged sites, including the use of short and nearby flow records to reduce the uncertainty of flow estimation. The key practical problems of how to estimate low flows in rivers influenced by artificial controls, such as abstractions, effluent returns and impoundments, are presented in Chapter 10. Chapter 11 describes the main applications for which low-flow forecasts are required and presents methodologies for forecasting flows on a range of timescales. Chapter 12 presents a number of case studies, which include the topics of transboundary rivers, a water resources decision-support tool, a regional approach to estimating small-scale hydropower and the estimation of residual flows below abstraction points. It is hoped that some of the procedures described in the analytical chapters will thereby be placed in a broader context.

Table 1.1 Summary of low-flow regime measures (based on Gustard and others, 1992)

Regime measured	Property described	Data employed	Applications
Mean flow	Arithmetic mean of the flow series	Daily or monthly flows	Resource estimation
Coefficient of variation in annual mean flow	Standard deviation of annual mean flow divided by mean flow	Annual mean flow	Understanding of regime interannual variability; definition of carry-over storage requirements
Flow-duration curve	Proportion of time a given flow is exceeded	Daily flows or flows averaged over several days, weeks or months	General regime definition; licensing abstractions (water rights) or effluents (discharge consents); hydropower design
Annual minimum series	Annual lowest flows (of a given duration)	Annual minimum flows – daily or averaged over several days	Drought return period; preliminary design of major schemes; first step in some storage/yield analyses
Streamflow deficit durations	Frequency with which the flow remains below a threshold for a given duration	Periods of low flows extracted from the hydrograph followed by a statistical analysis of durations	More complex water quality problems, such as fisheries and amenity, navigation; general indication of drought frequency
Streamflow deficit volumes	Frequency of requirement for a given volume of "make-up" water to maintain a threshold flow	Same as above, except the analysis focuses on the volume below the threshold	Preliminary design of regulating reservoirs; general indication of drought frequency
Recession indices	Rate of decay of hydrograph	Daily flows during dry periods	Short-term forecasting; hydrogeological studies; modelling
Base-flow index	Proportion of total flow which comes from stored catchment sources	Daily flows	Hydrogeological studies; preliminary recharge estimation

Chapter 13 presents some key conclusions and recommendations relating to data collection, operational hydrology and capacity-building. Together with the techniques presented in this Manual, it is hoped that these will lead to a reduction in the uncertainty of estimating low flows and to improved methods for transferring this information to a range of stakeholders.

1.4   Methodologies not included in the Manual

Although the most common procedure for mitigating the impact of low flows is to provide reservoir storage, storage yield relationships for reservoir design are outside the scope of this Manual. An excellent review of this topic is provided in McMahon and Mein (1978). Trends in hydrological data are discussed in the context of identifying inhomogeneities in streamflow data in Chapter 3 (section 3.3.3). However, this Manual does not describe the wide range of techniques available for trend detection which are fully described in WMO (2000). Although catchment modelling is presented in Chapter 9, primarily from the perspective of flow estimation at ungauged sites, the Manual does not present a detailed review, description or step-by-step procedures for model design, calibration, evaluation and validation. Beven (2001) reviews the principles and practice of hydrological modelling, and contains comprehensive references to their application. A similar approach is adopted in relation to low-flow forecasting. The key issues associated with different forecasting periods and forecasting methodologies are reviewed; however, a detailed step-by-step description of how forecasting models can be calibrated and operated in real time is also beyond the scope of this Manual. Although the Manual highlights the importance of ecological issues in low-flow design, it does not review the ecological processes and models used for setting instream flows. These are reviewed in detail in Tallaksen and van Lanen (2004).

1.5   Guidelines for national practices

It is difficult to present standard guidelines for national practices for all aspects of low-flow estimation because of the diversity of hydrological environments and water resources problems, the extent of existing data, model availability and the time and skills needed to address a specific problem. Where possible, guidance for specific aspects of low-flow estimation has been provided. This is appropriate where a methodology is largely fully prescribed, for example, in calculating low-flow indices or fitting distributions to annual minima. However, many of the components for establishing national hydro-

metric networks that underpin low-flow estimation, the development of statistical regional models, deterministic catchment models and comprehensive forecasting procedures cannot be summarized as a series of simple steps. Each specific approach will often involve choosing from a range of available options, which, in turn, requires the skills of the hydrological analyst and the experience gained from hydrological research and operational practice. This strategy can be applied usefully to developing national low-flow estimation procedures. There are clear advantages to having standard procedures formally approved by the national agencies responsible for water resources policy. However, this should not be extended to prescribing each and every aspect of low-flow estimation. Some useful guidance on the advantages and disadvantages of standardizing national flood design is given by Reed (1999). Much of this guidance is also relevant to low-flow estimation.

References

Beven, K.J., 2001: *Rainfall-Runoff Modelling: The Primer*. John Wiley & Sons, Chichester, United Kingdom.

Gustard, A., A. Bullock and J.M. Dixon, 1992: *Low Flow Estimation in the United Kingdom*. Institute of Hydrology Report No. 108, Wallingford, United Kingdom.

McMahon, T.A. and R.G. Mein, 1978: *Reservoir Capacity and Yield*. Developments in Water Science 9, Elsevier, Amsterdam, the Netherlands.

Reed, D.W., 1999: *Flood Estimation Handbook – Volume 1: Overview*. Institute of Hydrology, Wallingford, United Kingdom.

Tallaksen, L.M. and H.A.J. van Lanen (eds), 2004: *Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater*. Developments in Water Science, 48, Elsevier Science B.V., Amsterdam.

United Nations Educational, Scientific and Cultural Organization/World Meteorological Organization, 1992: *International Glossary of Hydrology*. Second edition, UNESCO, Paris.

World Meteorological Organization, 1988, 2004, 2006: *Technical Regulations* (WMO-No. 49), Geneva.

2000: *Detecting Trend and other Changes in Hydrological Data* (Z.W. Kundzewicz and A. Robson, eds) (WMO/TD-No. 1013/WCDMP-45), Geneva.

2008: *Guide to Hydrological Practices*. Volume I, sixth edition (WMO-No. 168), Geneva (Volume II in preparation).

2. Estimating, Predicting and Forecasting Low Flows

2.1 Introduction

There are three primary scenarios when low-flow information is required. The first is when a water resources scheme is being developed. This normally requires a pre-feasibility study to determine whether the objectives of the proposal can be achieved. For schemes with a large capital investment, this is followed by much more detailed design work, including estimates of the frequency of low flows. The second is during the operational phase of a water resources scheme once it is constructed, and includes decisions on how to manage the scheme on a day-to-day basis. For example, it may be necessary to determine how much water can be diverted from a river for hydropower purposes without infringing legal abstraction conditions. These may depend on the time of the year or on the river discharge at a downstream point. In many countries, such operational constraints are not formalized and the operator must be aware of, and sympathetic to, the needs of many downstream water users. For example, water could be needed by households, or for agriculture, electricity production, navigation, industrial abstractions, tourism, the dilution of industrial or domestic effluent, maintaining an ecosystem for food production, or maintaining the natural biodiversity of a river. The third scenario is when it is necessary to make operational decisions today based on estimates of future river flows which look days, weeks or sometimes months ahead. These forecasts can increase the efficiency of water use and are of economic importance in terms of reducing the operational costs of water resources schemes. More general warnings of below average precipitation several months in advance are of value for long-term planning and for making contingency plans for severe droughts (Chapter 11).

Historically, most applications of low-flow information have been in the design and operation of schemes for a specific water sector, such as public water supply, irrigation, energy, navigation and industry. It is now recognized that there is a need to provide long-term baseline monitoring and analysis of low flows to support integrated river basin management. This provides a framework for environmental agencies to make decisions regarding the catchment-wide development of water resources and prevents ad hoc decisions from being made on a case-by-case basis. For example, by comparing current abstractions with estimates of low flows for all tributaries in a catchment, rivers that can no longer support further abstraction can be identified. Similarly, rivers that have potential for further abstraction without damaging downstream interests, including ecological demands, can be highlighted. Techniques for assessing water resources will be described in detail in the WMO Manual on Water Resources Assessment (in preparation). Long-term baseline information can also be used to give early warning of any natural or artificial change in the low-flow regime.

2.2 Low-flow information

2.2.1 Basin management
Low-flow information is required for a wide range of applications that are often controlled by national and international water law and policy. For example, in Europe the Water Framework Directive was adopted by the European Parliament and the Council of the European Union in October 2000. This Directive established a strategic framework for the sustainable management of both surface water and groundwater resources. The Directive requires management by river basin authorities and not by administrative or political boundaries (see 12.3.2). A key component is to produce long-term river basin plans for integrated water resources management. This, in turn, will require estimates of low flows to mitigate the environmental impact of current abstractions and plan future water resources development.

2.2.2 River abstraction
Traditionally, one of the most common uses of low-flow information has been the design and operation of public water-supply schemes. Information on the frequency of low river flows is required to assess the probability of the abstraction not meeting the anticipated demand. The abstraction could be direct to a water treatment plant or reservoir storage facility. In terms of hydrological

analysis, the issues are similar for abstraction and irrigation, although there is normally a much higher seasonal and interannual (in temperate climates) variability in agricultural demand, which is dependent on crop type and the local climate. A frequent objective is to estimate the area that can be irrigated for a given crop type with a given risk of failure. Although the design of hydropower schemes is dependent on the complete range of flows, low flows can be critical in determining how much water must bypass a run-of-river hydroplant to maintain downstream river ecology and how much is available for power generation in the dry season. Thermal power stations are dependent on cooling water, and information on low flows when the availability of water for abstraction and the dilution of cooling water is at a minimum is essential for design purposes. For all these applications there may be a need to forecast flows in order to implement restrictions on water use to minimize the risk of very severe restrictions in the future. In some instances, licences to extract water in excess of the available supplies have been issued, and, thus, low-flow forecasts are an essential management tool.

2.2.3 Effluent dilution

A common application of low-flow information is that of estimating the dilution of domestic or industrial discharge released into a river. A legal consent is frequently required to discharge a pollutant. Waterquality models based on the rate and quality of the discharge and the flow and quality of the receiving stream are used to determine the frequency distribution of downstream water quality. The flow-duration curve (cumulative distribution function) of receiving river flows is the most commonly used form of analysis (Chapter 6). This design application contrasts with the real-time application of assessing the impact of specific pollution incidents, for example, a discharge of oil after an industrial accident. Flow rates are required to estimate the rate of dispersion and time of travel so as to warn downstream public water-supply abstractors that abstraction must be ceased.

2.2.4 Navigation

River systems provide an important transport facility for both industrial and leisure navigation. Navigation is interrupted during low-flow periods because the reduced water levels cannot accommodate vessels and the water available is insufficient for locks to be operational. The critical hydrological variable is water depth, and, in the absence of field observations, the depth profile must be estimated using the time series of river flows and hydraulic models. These enable the frequency

of interrupted navigation for different vessel sizes to be estimated and proposals can be made for improved channel design, while protecting the natural ecosystem. Navigation is driven by long-term investment and the related infrastructure cannot be easily relocated, redesigned or reconstructed. It is therefore important to forecast low flows so that shipping agencies are warned of navigation restrictions and have an opportunity to provide alternative means of transport in extreme conditions.

2.2.5 Ecosystem protection and amenities

Ecosystems are most vulnerable during low-flow periods because of a reduction in the availability of habitats, water temperature extremes, a reduction in dissolved oxygen, a deterioration in water quality (owing to reduced effluent dilution) and habitat fragmentation (caused by natural or artificial barriers to fish movement). Related techniques include simple methods based on low-flow indices often known as "standard setting" and include the mean annual minima of a given duration (Chapter 5) or a percentile from the flow-duration curve (Chapter 6). The estimated discharge is then used to set a minimum flow in a river so that when the discharge falls below this level, abstractions should cease (or be reduced). More advanced methods include habitat modelling where the impact of specific flow regimes on different species and life stages are assessed (Tallaksen and van Lanen, 2004). In addition to supporting complex ecosystems, rivers are natural assets for sport and recreational activities (for example, canoeing, fishing, ornithology and walking). Ensuring adequate water depth or velocity even when flow rates are very low can artificially enhance the natural appeal of rivers.

2.3 Design issues

2.3.1 Estimation, risk and forecasting

This Manual employs the general term "low-flow estimation". This may be applied to a specific measured discharge on a given day, a low-flow statistic calculated from data, a statistic estimated from a model or a forecast of future low flows. The term "estimation" implies that there is a calculation error and that the predicted value will differ from the observed one.

The WMO *Guide to Hydrological Practices* (WMO-No. 168) considers estimation errors in detail. Low flows can be analysed in a number of different ways. Some are single values such as a recession constant, the proportion of base flow or the mean of a series.

These are called low-flow indices. More complex methods estimate low-flow probability. For example, the cumulative frequency distribution (flow-duration curve) of daily flows describes the relationship between discharge and the percentage of time that a specific discharge is exceeded (Chapter 6). Extreme value techniques are used in Chapter 7 to estimate the non-exceedance probability of annual minima. The essential difference in the two techniques is that the flow-duration curve considers all days in a time series and hence the percentage of time over the entire observational period that a flow is exceeded. In contrast, the extreme value techniques applied to annual minima data estimate the non-exceedance probability in years, or the average interval in years (return period) when the annual minima are below a given value. It is therefore often helpful to specify the design life of a particular water resources scheme. The risk r of experiencing one or more annual minima lower than the T-year minimum discharge during a design life of M years is:

$$r = 1-(1-1/T)^M \qquad (2.1)$$

The risk probability r of experiencing the 100 year annual minima during a design life of 100 years can be estimated by setting T = 100 and M = 100 in the above equation. This gives a probability of 0.63 and provides a useful approach for demonstrating that the probability of "failure" during the life of any scheme is significant and that contingency plans for extreme events should be incorporated into design aspects. Although the design of water resources schemes is outside the scope of this Manual, it should be noted that a key concept of any such scheme is the "level of service". This is an estimate of how frequently and for how long the planned demands of a water resources scheme user will not be met. For example, an irrigation scheme may provide only 50 per cent of the full design abstraction for three months, once every 20 years. Low-flow estimation is a key component in estimating the level of service.

These methods do not attempt to estimate when a specific discharge or low-flow statistic will occur. In contrast, the forecasting techniques described in Chapter 11 estimate both the magnitude of low flow and the time of the event days or months ahead. As forecast lead time increases, forecast accuracy decreases, and, for very long lead times, forecasts may be no more accurate than those made using the long-term statistical mean. Forecasting methods are categorized according to the time interval for which the forecast is made. Short-term forecasts have a typical forecast lead time of less than seven days; medium-term forecasts cover up to six months, and long-term forecasts over six months.

2.3.2 Annual, seasonal and different durations

Low-flow information has traditionally been based on estimating statistics from all the available data. However, for many applications, it may be more appropriate to consider data according to months, groups of months or specific seasons. For example, in designing an irrigation scheme, the analysis should focus on the period of the year when the abstraction for irrigation will take place, and data for the rest of the year may be redundant. Similarly, ecological modelling may establish that the flow for a particular species and life stage are important, and, once again, the analysis should focus on a critical seasonal period. Annual minimum and flow-duration analysis can both be carried out for specific months or groups of months. It may be appropriate to consider annual minima of different durations, for example 7-day, 10-day, 30-day and 90-day durations, to meet the requirements of a specific design problem.

2.3.3 Scales of estimation

A key issue in operational hydrology is the management unit, which could be the river network or infrastructure (for example, reservoirs, aqueducts, pumps, water treatment plants, distribution networks, sewerage treatment plants). The primary management unit for environmental protection is the river basin, and the importance of upstream hydrology and upstream developments on downstream issues has highlighted the need for integrated river basin management. For hydropower generation, the management unit is often the reservoir and turbine facilities, with some consideration given to release regimes to protect downstream interests. Water-supply management units are often very complex and may involve the combined use of surface water and groundwater systems or the reuse of sewage effluent. Such systems require complex hydrological, water resources and water use modelling.

Water resources problems occur over a wide range of space scales. These range from detailed estimates at individual reaches of the order of 100 m within 10 km^2 catchments to the estimation of low-flow frequency at the river basin scale covering areas in excess of 1 million km^2. In developing countries, for large river basins in excess of 1 000 km^2, rivers are normally gauged with long (greater than 50 years) time series of daily flow data. This enables design problems to be most commonly based on an analysis of gauged data.

However, these larger catchments often present the interesting challenge of separating the myriad of ar-tificial influences from the natural flow regime. In developing countries, however, because of a lack of good-quality and continuous observational data, many key river basins are ungauged and low-flow analysis must therefore be based on model estimates. Even in countries with dense river-gauging networks, there are a large number of ungauged river reaches. This has led to the development of a wide range of regional models for estimating low flows at ungauged sites. Lastly, to compare the resources of countries on the continental scale, reliable estimates of resources availability determined using a consistent methodology are needed. Simple hydrological models are appropriate in these situations because the key requirement is to identify the spatial variability of the resources, and a simple low-flow index is often sufficient. Low-flow investigations may take place on the scale of the river reach, the catchment, national and international basins, the region (group of countries) or globally. The scale of the study will be a primary influence on the approach adopted and the information required.

2.3.4   The low-flow cube

Hydrologists can adopt a variety of procedures for hydrological design and water management, the selection of which is determined by the nature of the output required – the design requirement. The choice is determined by the risk associated with the design decision. For example, the investment risk linked to the construction of a large impounding reservoir would necessitate the establishment of gauging stations and the analysis of observed river flows. These data provide the basis for hydrological design, typically the storage/yield characteristics and spillway capacity. In contrast, an application for a small-scale abstraction licence would frequently be at an ungauged location, not warranting gauging station construction, and the design would often be based on a flow-regime statistic, such as the dry season flow of a given reliability, without necessarily requiring time-series analysis.

The complexity of different design scenarios (UNESCO, 1997) can be simplified by the conceptuali-zation of a "Design Scenario Cube" (Figure 2.1), defining three dimensions to the design requirement, as follows:

1. The location of the design problem, for example, at a site where recorded hydrological data is not available. Alternatively, there may be a nearby upstream or downstream gauging station. This distinguishes between the gauged and ungauged situation.

2. The operational requirements of the hydrological design. For example, the water sector and magnitude of the capital investment will determine whether simple statistics are required or a long and continuous hydrological time series. This is the data characteristics dimension that distinguishes between the requirement for time-series or low-flow statistics.

3. The catchment may be relatively natural or heavily modified by water resources development, in which case it may be necessary to naturalize the flow record (Chapter 3). The catchment water-use dimension distinguishes between the requirements for natural or artificially influenced flows.

The three-dimensional cube presents eight distinct combinations of different design scenarios. Each one is summarized below:

1. Natural gauged time series: A time series of (daily) flows at a gauged site which represent the river-flow regime from a natural catchment. An application of this design requirement may be in setting environmental river-flow regimes at a location in the vicinity of a gauging station.

2. Artificial gauged time series: A time series of daily flows at the gauged site which represent the river-flow regime from an unnatural, artificially influenced catchment. Different definitions of "artificial" can be adopted including historic, current or future scenario-based water use. An application of this design requirement is to evaluate the extent to which different upstream abstractors have reduced downstream flows over a historical period.

3. Natural gauged statistics: A flow regime statistic, such as the 95 percentile flow, which represents the river-flow regime from a natural catchment at a gauged site. This may be needed to determine whether to approve a proposed abstraction.

4. Artificial gauged statistics: A flow regime statistic that represents the river-flow regime from an artificially influenced catchment at a gauged site.

   This design may be required to determine the extent to which upstream abstractors have diminished the 95 percentile low-flow discharge at a gauging station.
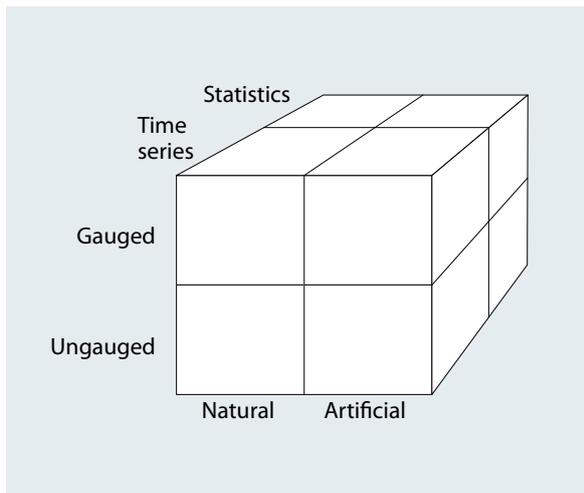
Figure 2.1. Design Scenario Cube: A conceptualization of the variety of approaches to estimate low flows

5. Natural ungauged time series: A time series of river flows that represents the natural regime at an ungauged site. This would be needed to design a complex abstraction scheme at an ungauged site and would require the development of a catchment simulation model (Chapter 9).

6. Artificial ungauged time series: A time series of river flows which represents an artificially influenced regime at an ungauged site. A typical application of this design requirement may be in the design of a joint use (surface water and groundwater) scheme in a catchment that has groundwater pumping but no discharge measurements.

7. Natural ungauged statistics: A flow regime statistic that represents the natural regime at an ungauged site. This may be required for preliminary regional water resources assessment.

8. Artificial ungauged statistics: A flow regime statistic that represents the artificially influenced regime at an ungauged site. A typical application of this requirement may be in the preliminary design of a small-scale hydropower scheme in an artificially influenced catchment.

The added complexity of this scheme includes evaluating the impact on downstream river flows of artificial influences based on historic sequences, current water use or future abstraction scenarios. In most cases, this will require the naturalization of a continuous flow record or low-flow statistics (Chapter 10).

2.4   Previous studies

Before embarking on a low-flow investigation, it is essential to review previous work carried out in the region. Procedures for collating this information are described in detail in WMO (2008). Such procedures should include a review of all hydrological data. Also, if methods for estimation at an ungauged site are being considered, then thematic data (Demuth, 1993) describing the climate, soil, geology and geomorphology should also be collated. For example, although a regional low-flow study may not have been carried out in a region, a flood study might have compiled a useful set of catchment descriptors (Chapter 3). The main sources of data that should be reviewed include: hydrometeorological data, physiographic data, anthropogenic data, hardcopy and digital maps and previous hydrological studies published in reports or journals. This information may be available from metadata catalogues, project archives, libraries, personal communications and the Internet.

2.5   Dissemination of results

A key component in any low-flow investigation is to determine at the outset how the results will be disseminated to the user community (WMO, 2008). Users may range from hydrological specialists familiar with low-flow analysis methods, to professionals in the disciplines of engineering, ecology or law, to the general public with an appreciation of the natural environment. Traditionally, results have been provided in report and map format; but, this is now being supplemented or replaced by software for calculating regional low-flow estimates and the digital display of results or online bureau services. This is possible because of the increasing operational use of digital hydrological information including elevation models and stream networks (Chapter 3). There is still a need to ensure that low-flow methods and results are fully understood, and it is essential for online dissemination to be supported by comprehensive training in the methods and application of low-flow information.

2.6   Key principles in low-flow design

Several general principles in hydrological design (Reed, 1999) are contained in this Manual and should be considered by hydrologists when carrying out low-flow design for a specific scheme or when developing national estimation procedures. The common objective of all design procedures is to reduce the uncertainty of low-flow estimation. Some general principles are as follows:

(a) Low-flow estimation should, wherever possible, be based on recorded data;

(b) In the absence of recorded data at the site, data transfer upstream or downstream or from a nearby catchment will lead to reduced estimation error;

(c) The estimation of low-flow statistics at un-gauged sites from catchment descriptors may be enhanced by some kind of formal or informal data transfer;

(d) The ability to select the most appropriate low-flow analysis and estimation method is a matter of experience. The decision will always be influenced by the nature of the design problem, the catchment, the availability of data and the experience of the practitioner;

(e) The enquiring analyst can usually find more information, which, if used, will lead to reduction in estimation error;

(f) Given the growing automation of modern analysis and estimation software, professionals are being increasingly obliged to take more care in hydrological design work and to always seek advice from a professionally qualified expert;

(g) Positive and negative feedback from a user community, together with advances in methodologies and data availability, enables minor revisions to national design procedures and software. It is important for any errors or shortcomings of low-flow estimation techniques to be rectified immediately. However, continual minor adjustments to design methods are not welcomed by the user community, which generally prefers major updates to be less frequent.

References

Demuth, S., 1993: *Untersuchungen zum Niedrigwasser in West-Europa. Freiburger Schriften zur Hydrologie*, Bd. 1.

Reed, D.W., 1999: *Flood Estimation Handbook*. Volume 1, Institute of Hydrology, Wallingford, United Kingdom.

Tallaksen, L.M. and H.A.J. van Lanen (eds), 2004: *Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater*. Developments in Water Science, 48, Elsevier Science B.V., Amsterdam.

United Nations Educational, Scientific and Cultural Organization (UNESCO), 1997: *Southern Africa – FRIEND*. Technical Documents in Hydrology No. 15, UNESCO, Paris.

World Meteorological Organization, 2008: *Guide to Hydrological Practices*. Volume I, sixth edition (WMO-No. 168), Geneva (Volume II in preparation).

3. Hydrological Data

3.1 Introduction

Hydrological and related data encompasses all data commonly used by hydrologists (WMO, 1958, 2006). Meaningful hydrological analysis will always rely on good-quality data that are representative of conditions in the drainage basin, study area or region concerned over the period of interest. The aim of this chapter is to introduce the reader to the data types most commonly used in low-flow hydrology and provide guidance on preparing such data for analysis. This chapter emphasizes the preparation of river-flow (or streamflow) data, because of their specific importance in low-flow studies. However, the chapter deliberately excludes details on hydrometry, hydrometric data processing and management, network design, and the determination and management of hydrological data: several WMO technical publications and reports (for example, WMO, 1980, 2008a) and other publications (for example, Herschy, 1999) already cover these topics adequately. Where necessary, reference is made to relevant publications. The WMO Manual on Water Resources Assessment (in preparation) will provide specific details on the collection and processing of biophysical data (topography, soil, geology and vegetation), socio-economic data (land use and demography) and climate data (precipitation and evaporation). The chapter provides a summary of some of these variables.

3.2 Data for low-flow analysis

The relevant data for low-flow analysis may be grouped as follows: hydrometeorological, physiographical or anthropogenic. Hydrometeorological data describe elements of the hydrological (water) cycle which continually vary over time. Physiographical data, on the other hand, represent natural terrestrial features that do not change, or vary insignificantly, over the relatively short timescales considered by most hydrological analyses. Anthropogenic data help explain the influences of human activity on both natural and artificial (man-made) systems.

Most hydrological data may be further subdivided into point measurements and spatial data. A point measurement describes the measurement of a certain entity at a specific location. A sequence of measurements, samples, observations or readings of a time-varying entity at a single location results in a time series of that entity at that point. Time-series data can be manipulated to produce further time series of aggregated data and statistics. For example, calculating the average of 96 15-min streamflow measurements during one day gives a single daily mean flow value. Repeating this for several days' data produces a time series of daily mean flow values. Further aggregation of the daily data could produce weekly, 10-day, monthly, or annual time series. A wide range of statistics (for example, means, maxima, minima, variance) can be determined for different periods covered by the time series to provide a useful summary of the data and form the basis of analysis. To remove short-term fluctuations and study the general behaviour of data, it is sometimes useful to generate a moving average through a time series. In low-flow hydrology, 7-, 30- or 120-day moving averages, derived from daily data, are frequently used, for example, to calculate 7-day annual minimum flow, for a single year, or the mean of the 7-day annual minima (MAM(7)), for several years.

Spatial data can simply be defined as any data that can be represented on a map. Spatial data are often derived from the interpolation of many point measurements. The contours on a topographical map, for instance, are usually derived from interpolating a series of spot elevation readings. When digitized (namely, stored in digital form on a computer), line, arrow, contour, point and polygon features of a map are referred to as vector data. Computerized grid-, cell- or lattice-based information, such as a digital elevation model, is generically called raster data. For convenience and ease of analysis, digital spatial data are normally stored on computer as data coverages in geographic information systems (GIS). Some examples of the different types of data that a low-flow hydrologist may use are given in the following subsections.

3.2.1 Hydrological data

Hydrological data include (WMO. 2006) hydrometric, groundwater and climatological data for hydrological purposes. They provide information on the spatial and temporal distribution of water, as it occurs in its various states, in the hydrological cycle. Here, only brief descriptions are given of the types of hydrological data most commonly used in low-flow studies.

Hydrometric data

Hydrometric data include streamflow and river- and lake-level (stage) data. Of all the different types of hydrological data, streamflow (synonymously river-flow or discharge) data are arguably the most useful in low-flow hydrology because they represent the combined response of all physical processes operating in the upstream catchment (Herschy, 1995). River flow is the rate at which water flows through a given river cross-section and is usually expressed in units of m³/s, l/s or ft³/s. Several different methods can be used to measure river flow, with the choice of method depending on the conditions at a particular site (WMO, 2008a). The methods generally involve the measurement of water level, or stage, at a gauging station and the subsequent application of a stage-discharge relationship to derive a flow estimate.

Most countries have long-established hydrometric networks comprising many gauging stations, from which data are used for a variety of purposes ranging from water resources management and planning to flood control, environmental monitoring and impact assessment. However, in all countries, gauging stations contribute unevenly to the understanding of low flows, with the most valuable stations being those with the best hydrometric performance, the least human disturbance and a long time series (Rees and others, 2004).

The reader is referred to the WMO Manual on Stream Gauging (WMO-No. 519), the WMO Guide to Hydrological Practices (WMO-No. 168), technical guidance manuals of the International Organization for Standardization (ISO), such as Liquid Flow Measurement in Open Channels (ISO, 1981, 1982) and textbooks (for example, Herschy, 1995, 1999) for further information on hydrometric practices and gauging station network design.

The WMO INFOHYDRO Manual (WMO-No. 683) should be consulted for information on the status of networks, and data availability, in different countries.

Climatological data for hydrological purposes

This data include measurements of precipitation, evapotranspiration, air temperature, radiation, wind, humidity and barometric pressure, and synoptic data, which describe weather features, such as high- and low-pressure areas and weather fronts, and atmospheric circulation patterns and indices (for example, El Niño/Southern Oscillation and the North Atlantic Oscillation Index). Information on methods for observing data can be found in the WMO Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8).

Precipitation falls either in liquid form, as rain, drizzle or dew, or in solid form, as snow, sleet, hail, hoar frost or rime. Knowledge of precipitation distribution in time and space is valuable in any low-flows analysis. The total amount of precipitation reaching the ground during a given period is expressed as the depth that would cover a horizontal projection of the Earth's surface (WMO, 2008a). Precipitation is most commonly sampled by individual precipitation gauges (raingauges, if only liquid precipitation is measured), at varying intervals, depending on the equipment and measurement method. Precipitation gauges are sensitive to exposure, particularly wind, and the amount measured may be less than the actual precipitation by up to 30 per cent or more (WMO, 2008b). The systematic error of precipitation varies according to the type of precipitation (measurement errors for solid precipitation are often an order of magnitude greater than those normally associated with liquid precipitation), the location of the gauge (exposure or shielding at the site) and the instrumentation used (for example, gauge type, orifice height or diameter). For many studies it may be necessary to adjust observed data to allow for systematic errors. Care must always be taken when adjusting data, and changes should always be adequately documented. The WMO Operational Hydrology Report No. 21, Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use (WMO-No. 589), describes methods to adjust point precipitation measurements.

Observed precipitation is representative only of precipitation falling over a limited area in the immediate vicinity of the gauge, and, to understand the spatial distribution of precipitation over a wider area (for example, a catchment or drainage basin), data should be obtained from a network of gauges. A variety of interpolation methods can be applied to raingauge measurements to produce isohyetal maps, showing lines (contours) of equal rainfall (isohyets), or grids of rainfall.

Thiessen polygon area averaging (Thiessen, 1911), inverse distance weighting (Barnes, 1973), thin-plate splines (Champion and others, 1996) and kriging (Dingman and others, 1988) are some of the most widely applied interpolation methods. The isohyetal maps and rainfall grids can then be used to estimate areal precipitation for larger areas (for example, catchment area rainfall). The interpolation methods can similarly be used to produce isoline maps, grids and areal estimates of many other types of meteorological data (for example, air temperature, atmospheric pressure, evaporation). Areal rainfall data can also be estimated from ground-based radar (see WMO, 1985a) and by satellite remote-sensing (for example, the Japanese/United States Tropical Rainfall Measuring Mission). The latter is proving particularly useful for the estimation of rainfall in areas of low raingauge density.

Data on evaporation, or transpiration (if vegetation is present), are important in low-flow analysis because they describe the amount of water lost (that is, returned to the atmosphere) from open water, soil or plants, much of which would otherwise contribute to aquifer recharge or river flow. In many parts of the world where precipitation is limited, evaporation losses can cause rivers and lakes to dry up. It is not possible to take measurements of evaporation or transpiration from large water bodies or land surfaces (WMO, 2008a). While evaporation pans and lysimeters can measure actual evaporation at a specific point, owing to difficulties in taking direct measurements of evaporation over large areas, indirect methods, using solar (short-wave) and long-wave radiation, air temperature, atmospheric humidity or vapour pressure and wind data, are normally used. These data are usually applied to calculate potential evaporation, which assumes unlimited availability of water from a vegetated surface. Actual transpiration may then be estimated from its relationship with potential evaporation which accounts for available soil moisture. WMO (1985b) provides guidance on appropriate evaporation estimation methods.

Data is often available from National Meteorological Services (or weather services) or may be accessed through regional or international data centres. WMO, in collaboration with the International Council for Science, established the World Data Centre (WDC) system that assembles and disseminates many types of climatological and other environmental data. The most relevant centres for low-flow studies are the WDC for Meteorology, the WDC for Global Precipitation and the Global Runoff Data Centre.

Snow-cover data
River-flow regimes in snow-affected areas – normally high latitude and/or mountainous areas – are characterized by low flows during cold winter months and increasing flows in spring, as rising temperatures cause the snow pack to melt. Data on depth, water equivalence and the areal extent of snow cover are of considerable value for low-flow studies in such areas because they help assess the water resources potential of accumulated snow (Singh and Singh, 2001).

Snow stakes are most commonly used to measure snow depth. Snow water equivalence – the equivalent depth of water that would be obtained from melting the snow – is determined by combining the measured depth and a density estimate of the snow. These data may be obtained by snow course surveys and weighing known volumes of snow samples, or by gamma radiation surveys, which detect variations in the gamma radiation that is naturally emitted from the ground. Areal snow cover is usually determined by ground reconnaissance or remote-sensing (namely, aerial photography or satellite observation). Satellite observations from the Landsat Multi-Spectral Scanner, the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer and, more recently, the Moderate Resolution Imaging Spectroradiometer data from the United States National Snow and Ice Data Center have been used extensively to assess snow cover in many river basins globally. Further information on methods for measuring snow-cover data is provided in two WMO publications: Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture (WMO-No. 749); and the WMO Solid Precipitation Measurement Intercomparison: Final Report (Instruments and Observing Methods Report No. 67) (WMO/TD-No. 872).

Groundwater and soil moisture data
Groundwater is often of critical importance in determining low-flow response and river base flow. Groundwater data include groundwater level and discharge data. Soil moisture data is of interest in low-flow analysis because of its strong influence on evapotranspiration and the amount of water that percolates to the underlying aquifer or contributes directly to surface runoff. A variety of direct and indirect methods used to measure soil moisture are described in WMO (1992). Groundwater level data describe the variation of hydraulic head within an aquifer, and can be readily measured using piezometers, observation wells, bore holes or hand-dug wells. Contour maps of seasonal groundwater head are

particularly useful for comparing the variation in conditions between summer and winter or between dry and wet years. Groundwater discharge into a spring or, more diffusely, into a stream or river, is measured in the same way as river flows. Further information on groundwater measurement is provided in the ISO Guidance on the sampling of groundwater (ISO, 1988).

3.2.2 Physiographic data

The drainage basin, or catchment, is the fundamental entity in most low-flow studies, and the physiographical characteristics of the catchment have a considerable effect on the low-flow behaviour of its rivers and streams. The most influential characteristics generally relate to a catchment's topography (for example, catchment area, shape, orientation, elevation, slope, relief, and so forth), stream morphology, land cover, pedology (soils) and geology. Catchment characteristics can usually be obtained from a variety of paper maps or digital spatial data (vector or raster data coverages). The necessary scale, or spatial resolution, of maps depends on the study requirements. Generally, vector maps used in low-flow hydrology vary in scale from 1:10 000 to 1:5 000 000, while raster data can vary in resolution from as little as tens of metres (for example, 10 m x 10 m or 1 km x 1 km) to 0.5° latitude longitude or greater.

Catchment area, a key catchment characteristic, is commonly defined as the area bound by the topographic water divide. The catchment boundary is usually delineated from a topographic map sheet or a suitable digital elevation model. The catchment boundary can be used to identify catchment characteristics, or descriptors, from the various physiographical maps and digital spatial data available. The catchment boundary itself defines the characteristics of catchment (or drainage) area (km²) and shape (for example, shape factor, circularity ratio, elongation ratio). Topographic data (from digital, or paper, maps or digital elevation models) can be further used to establish geomorphological catchment descriptors such as: maximum, mean and minimum elevation; catchment length, defined as the distance along the main river channel from the catchment outlet to the topographic divide; catchment slope, reflecting the rate of change of elevation with respect to distance along the principal flow path; the slope of the main river channel stream defined by the difference in elevation between two points on the main stream (for example, slope between points at 10 and 85 per cent of the main stream length); and drainage density, the ratio of the total length of streams within a catchment and catchment area.

Land cover has an important influence on low flows, particularly its effect on interception, infiltration and evaporation. Descriptors that can readily be derived from land-cover maps include the proportion of catchment area under urban development, the proportion of forest or woodland, the proportion of cultivated land (for example, cropland, irrigated land, pasture), the proportion of uncultivated land (for example, moorland, natural grassland or scrub) and the proportion of catchment occupied by wetlands (namely, bogs, wetlands, lakes). The proportion of different land-cover types in catchments is often derived from ground-based survey maps (paper or digital) published by national cartographic agencies. Much land-cover data generated from satellite observations are available at the national, regional and global levels from numerous sources, such as the European Environment Agency (for example, the Corine Land Cover 2000 project) and the International Geosphere-Biosphere Programme (for example, the Global Land Cover dataset).

Underlying geology and soils have a strong influence on low flows in many catchments. Geological maps, available in paper or digital form, generally describe lithololology, layer depths, faults and folding, and may be used to produce hydrogeological maps, which provide valuable information on the presence of aquifers and their hydraulic properties (for example, conductivity, transmissivity, hydraulic resistance). Soil maps provide details of the spatial distribution of soil, with accompanying soil classifications providing information on texture and structure, from which hydrological properties (namely, soil water retention and storage capacities) can be deduced. As with land cover, geological and soil maps are available from many different national and international sources. Notable examples are the Generalized Geological Map of the World and Databases (Geological Survey of Canada, 1995) and the Soil Map of the World (FAO/UNESCO, 1981).

3.2.3 Anthropogenic data

Few catchments remain unaffected by human activity. The operation of impounding reservoirs, inter-basin transfer schemes, flow augmentation schemes, public water supply and sewerage systems, irrigation and land-drainage schemes, hydropower plants and land-use change all disturb natural flow regimes. The net effect on low flows is often profound, and unadjusted gauged flows can be very unrepresentative of the natural conditions. In many highly developed catchments, the artificial component of flow regularly exceeds the natural component at low flows. Information (for example,

location, volume and timing) on the artificial influences is vital in low-flow analysis to quantify how significantly observed flows are affected and to decide whether the flow record can be used. Where detailed information on artificial influences is available, sometimes it is possible to adjust the observed flow record to produce a more useful naturalized flow record. The process of flow naturalization is described later in this chapter (3.3.4). Chapter 10 provides further guidance on dealing with artificial influences in low-flow analysis.

3.3   Preparation of good-quality data for low-flow analysis

The remainder of the chapter describes the steps for preparing good-quality river-flow (or streamflow) data for low-flow analysis. Although less attention is subsequently given to other types of data, several of the procedures and methods described are also universally applicable.

3.3.1   Establishing data requirements

Hydrological data may be used for many purposes, such as estimating a country's water resources, planning, designing and operating water projects, assessing the environmental, social and economic impacts of water management, quantifying the impacts of urbanization (or deforestation) on water resources, or providing security against floods and droughts (WMO, 1998b). Data requirements can thus differ significantly from one application to the next. For example, in flood forecasting, real-time data at a fine temporal, almost minute-by-minute, resolution is needed, whereas for water resources planning, daily, or monthly, data would suffice.

Every hydrological analysis depends on the acquisition of relevant data. This is best achieved by first establishing the data requirements of the study and producing data requirement specifications to serve as a key reference document for the entire study.

The time taken to correctly specify data requirements at the beginning of a study can yield considerable savings, in terms of time, effort and money, during subsequent data acquisition and validation as attention focuses only on relevant data. Although there are no rigid rules governing data requirement specifications, generally, a specification should include sufficient information to establish criteria for the selection of data likely to be needed in the analysis. Typically, the document describes the following:

(a)   The purpose and context of the study, including background information, the target audience, the purpose of the analysis, and how the results will be used;

(b)   The objectives and expectations of the study, detailing the required output (results or deliverables), the acceptable level of uncertainty in the results, and the timescale, or deadline, for their delivery. Uncertainties inevitably pervade all aspects of hydrological analysis and the quality, and meaningfulness, of results is highly dependent on the quality and accuracy of the original data. The recommended accuracy of a range of hydrological data types is provided in the WMO Guide to Hydrological Practices (WMO-No. 168). For streamflow data, the recommended accuracy is typically in the order of ±5 per cent at the 95 per cent confidence interval (WMO, 2008a, Table I.2.5). These stated accuracies may be assumed to be the most stringent of recommendations, which may not be achievable for many specific applications. The purpose and constraints of a study ideally should determine the necessary accuracy of data (Stewart, 1999);

(c)   The resources available for the study, which dictate what can realistically be achieved. A study, and the quality of its results, is as much constrained by budget, timescales, software and staff capability as it is by its data. However, since a study's outcomes rely on the data it uses, sufficient resources should be allocated to the initial task of data collection and preparation to prevent an ultimately unsatisfactory result;

(d)   The geographical extent (area, scale and complexity) of the study. This, in turn, determines the necessary spatial resolution of data, which, for the time series of point measurements (for example, river flow, precipitation), may imply a minimum station density, or, for spatial data (for example, physiographical or climatological data), specifies the necessary scale (for example, 1: 50 000, 1: 250 000) of maps or the spatial resolution for raster, or gridded, data (for example, 1 km digital elevation model);

(e)   The temporal framework of the study, denoting the time domain (for example, long-term, standard period) and the minimum require-

ments for time-series data in respect of duration (length of record), frequency (temporal resolution of values) and completeness (acceptable number of missing values).

With regard to requirements for river-flow data in low-flow studies, given that the rate of change of flows tends to be relatively small from day-to-day during low-flow periods, daily resolution data (daily mean flow) are normally preferred, although weekly (7-day mean flow), 10-day and monthly (monthly mean flow) data are also used regularly. The time series should be as long as possible. Data of 30 years' duration or more is often recommended as a minimum record length (for example, Tallaksen and others, 2004). Pragmatically, hydrologists often have to manage with data of much shorter duration: a minimum record length of 5 years is commonly specified; however, data of fewer years' duration can sometimes be useful, especially if important events are captured in an otherwise undergauged region and if the data can be correlated with a longer time series from nearby gauging stations. Ideally, each time series should be a continuous, uninterrupted sequence of equally spaced flow observations and include data across the entire range of possible values, from highest to lowest flows. The time series should contain as few missing or truncated values as possible. While infilling methods can improve the utility of time-series data (see 3.3.4), it may not always be possible to determine realistic flows for lengthy sequences of missing values. Thresholds can be set arbitrarily to specify an acceptable level of completeness for a record, that is, the maximum number, or proportion, of missing values allowed. A threshold may be used to help decide whether to reject the whole record or just data from specific years. For the time series of daily mean flow data, it is not uncommon for an entire record to be rejected if, for example, more than 20 per cent of the values are missing. For a single year's daily data, thresholds of 5 per cent (more than 18 days of data missing) or 10 per cent are often used. The chosen threshold should always be determined according to the objectives and circumstances of the individual study. It should be noted, however, that this approach is not always appropriate because many of the missing or truncated values may have occurred during periods of high flows, which would not necessarily invalidate the record from a low-flow analysis perspective. Before rejecting a record, or any part thereof, on the basis of completeness, the timing of the missing values should be carefully considered: a seemingly unacceptably incomplete record may still prove to be valuable, if significant low-flow events have been captured.

Many statistical methods used in low-flow analysis require time series that are homogeneous, that is, data free from discontinuities and non-stationarities. A record is considered stationary if there is no systematic change in mean (no trend) or variance and if periodic variations have been removed (Chatfield, 2004). In reality, the time series of river flows are never strictly stationary and, over the period of a record, inhomogeneities may have occurred due to many factors, including changes in the measurement method, gauge re-location, the build-up and/or removal of weeds, ice or other debris, backwater effects, river training, variations in upstream water use, land-use changes or climate change. Requiring predominantly natural catchments with minimal human or artificial influences is often the easiest way of avoiding the most common sources of inhomogeneities in flow records (that is, the effects of human activity). However, few catchments are unaffected by human activity, and, for low-flow studies, an acceptable degree of artificial influence must be defined, for instance, some proportion (for example, 5 or 10 per cent) of the 95th percentile flow. In catchments where an accurate record of upstream artificial influences exists, it may be possible to reconstruct the "natural" from the "influenced" time series. This process, known as "naturalization", is described in the following sections, as are other methods to examine and correct inhomogeneities in flow data.

To carry out meaningful analysis, and indeed data correction, hydrologists require access to information (metadata) that describes the derivation of the time series. This includes details on the gauging station, hydrometric practices, the accuracy and sensitivity of measurements at low flows, the quality control measures applied to the data and local site conditions (weed growth, bed conditions, backwater effects). The interpretation of data is also assisted by knowledge of the upstream catchment, including information on catchment descriptors, upstream water uses and diversions and how these have changed over the measurement period. Such metadata are especially useful during data validation and should, therefore, always be demanded in the data requirements.

3.3.2 Data acquisition and storage

Once a study's data requirements have been established, the next step is to acquire the necessary data. Hydrological data can be obtained from many different sources. Some data providers are commercial enterprises, which generally charge a fee for their products and services; many others are non-profit-making organizations, which

may provide data free of charge, or for a small fee to cover the cost of the distribution media and handling. The budget available frequently determines the data source and quantity that can be obtained.

Knowledge of potential sources, and the data they possess, is invaluable for any study. This knowledge can be obtained from research (for example, Web-based searches, technical reference documents) or personal contacts. Some familiarity with the study area itself is useful, as is establishing good working relationships with the local organizations responsible for hydrological data collection and management. The WMO INFO-HYDRO Manual (WMO-No. 683) provides a useful listing of hydrological data providers and availability internationally and in 178 countries around the world. Some additional sources are helpfully given in WMO report, Hydrological Data Management: Present State and Trends (WMO-No. 964).

Data providers are increasingly disseminating data over the Internet. Their Websites can offer a range of options for accessing data, from simple e-mail requests to World Wide Web downloads and interactive Web services, which allow dynamic connections with host databases. As well as Internet-based file transfer, digital data are still commonly distributed on physical media, such as CD/DVD-ROM, memory sticks, and on magnetic tape or disk. Although data may still be distributed in hard copy (on paper), it is becoming a rarity. Despite the technological progress of recent decades, large amounts of potentially valuable hydrological data remain stored on paper charts or sheets, in yearbooks or notebooks, or on microfiche, in many archives and libraries around the world. Such data, if they can be found, must be digitized or intelligently scanned to be of use.

Digital data are supplied in a variety of file formats: as plain text, in fixed, character-delimited (for example, comma delimited), marked-up (for example, HTML, XML), or system-specific formats (for example, Microsoft Excel spreadsheet, ArcGIS Export, ESRI shapefile, AutoCAD drawing). Many formats can easily be compressed using public domain software (for example, pkzip or gzip). Of course, recipients should possess the relevant software to interpret the data locally. All data should be supplied with appropriate information (metadata) that adequately describes the format of the files and the data within (for example, definition of variables, units of measurement and projection parameters (for spatial data)).

Most data will be subject to copyright and intellectual property rights, which are normally retained by the data provider. These rights, and conditions of use, are usually detailed in the licence agreements that prospective recipients would ordinarily be required to accept before data are released. A licence agreement (or conditions of use) will stipulate whether the data can be used freely, without restriction of application, reuse, distribution or resale. Products derived from the data are often subject to the original provider's copyright and intellectual property rights; care must be taken, therefore, not to infringe these conditions with the subsequent use of a study's outcomes.

Data should be stored locally in a manner that makes them readily accessible and convenient to use. Streamflow and other time-series data may be stored as simple text files, in a spreadsheet (for example, Microsoft Excel), in a database (for example, ORACLE, Microsoft Access, MySQL, PostgreSQL), or in some other proprietary, or bespoke, hydrological data management software system (for example, ADAM, HYDATA, WATSTORE) (WMO, 2003). Spatial data generally would need to be stored in a GIS (for example, ArcGIS, MapInfo) or engineering drafting package (for example, AutoCAD).

All data should be labelled within the chosen storage system such that every data value can be uniquely identified and correctly retrieved. For streamflow data, this typically means all data in a single time series being given a unique number, or label, that allows it to be associated with the relevant gauging station, for example, by defining a unique gauging station number, or station identity. To distinguish between data within a series, each value could be given a unique date and time stamp. If two or more data values have the same station identity and date/time stamp (for example, when a monthly and daily value have the same date), a third identifier (for example, data type) would be needed to uniquely identify each data value. All supporting metadata (for example, river name, site name, map coordinates, catchment area, catchment characteristics, gauging history, factors affecting flow, and so on) should also be referenced by the relevant station identity.

Once stored in a usable format, time-series data may be analysed by a variety of statistical analysis tools or packages that may either be inherent to (built-in) the storage system or available through external software (for example, MATLAB, S-Plus, SAS).

3.3.3 Data examination and validation

Data must be examined or validated before being applied in analysis. All too often, hydrologists assume that they have "good" data and proceed with analysis without rigorously checking data quality, which results in erroneous conclusions being drawn from "bad" data. The axiom, "garbage in, garbage out", is as true in the context hydrological analysis as it is in any other. This section considers the examination of streamflow data only, which, it is assumed, has already been subjected to initial, or primary, hydrometric data-processing procedures by the relevant measuring authority and is provided as a time series of flows in an appropriate unit of measurement (for example, m³/s). Further detailed information on primary hydrometric data-processing methods and procedures may be found in the WMO Guide to Hydrological Practices (WMO-No. 168) or Herschy (1995).

The aim of the data examination and validation process is to assess whether the available data are suitable for analysis. During this process hydrologists must carefully review the data, using their expertise and judgement to decide how to address inhomogeneities, such as trends, step changes, errors, outliers or missing values, detected in the data. With the objectives of the study in mind, the hydrologist should decide whether the data should be rejected or corrected (infilled). Reference should always be made to relevant metadata during validation: key catchment descriptors (elevation, land use, presence of forests and lakes), details of station history and descriptions of the factors affecting runoff are all particularly useful for explaining problems and inhomogeneities. A variety of methods can be used to examine and validate streamflow data; some of the most common ones are described below.

Hydrograph inspection, visual inspection of a time-series plot (a hydrograph), is arguably the most effective method for validating streamflow data. To assess the quality of the low-flow data in particular, the hydrograph should be viewed with a logarithmic scale on the vertical y-axis. A logarithmic scale is used because it gives greater prominence to variations in the low-flow range. It should be noted, however, that the use of a logarithmic scale can result in unrealistic-looking recessions at very low flows.

Another useful technique, which helps draw attention to exceptional flows, is to plot the hydrograph within an envelope of corresponding long-term daily maximum and minimum flows (Figure 3.1).

The hydrograph of the entire record period should be plotted to check for any visible trends or discontinuities in the data. Statistics derived from data that contain trends, seasonality or some other systematic components can be seriously misleading (Chatfield, 2004). Close inspection of the whole time series helps reveal non-stationarities in the flow regime, such as regular changes in the magnitude, frequency or timing of peaks and minima (possibly caused by climatic change or instrument drift), or discontinuities that could be caused by a change in land use or observation method or a discrepancy in the unit of measurement used (for example, mm instead of m³/s), which sometimes occurs when new data is appended to an existing record. Further guidance on the treatment of trends and discontinuities is given later and in section 3.3.4.

The hydrograph should also be examined on a year-by-year basis, ideally alongside hydrographs for other sites upstream, downstream or in adjacent catchments and a hyetograph (rainfall plot) from a nearby raingauge (Figure 3.2). Examining recession for different low-flow events at the same gauging station can also be very revealing. Multiple hydrographs should be plotted in units of specific discharge (m³/s/km² or mm) if respective catchment areas are significantly different. For catchments affected by snow or ice, a temperature plot from a temperature gauge (or thermograph) in the vicinity of the catchment should be plotted. Flows in such catchments would normally be low during cold, winter months and expected to increase sharply as temperatures rise and the thaw begins in spring. The comparison of time plots between sites provides a useful consistency check of the data, with any discrepancies or diverging behaviour being readily identified. Some of the problems commonly observed during the inspection of hydrographs are outlined in Table 3.1 and illustrated in Figure 3.1.

An annual variation plot, a graph of successive annual averages (for example, annual mean flow), is a useful, and relatively simple, approach for identifying trends in data with seasonal variation.

A double-mass curve, which plots the accumulated values of two time series against each other, is another graphical method for examining flow data (Figure 3.3). A double-mass curve, constructed from the contemporaneous records of two gauging stations of hydrologically similar catchments in the same proximity, should approximate as a straight line. A sudden diversion from the straight line indicates a possible step change
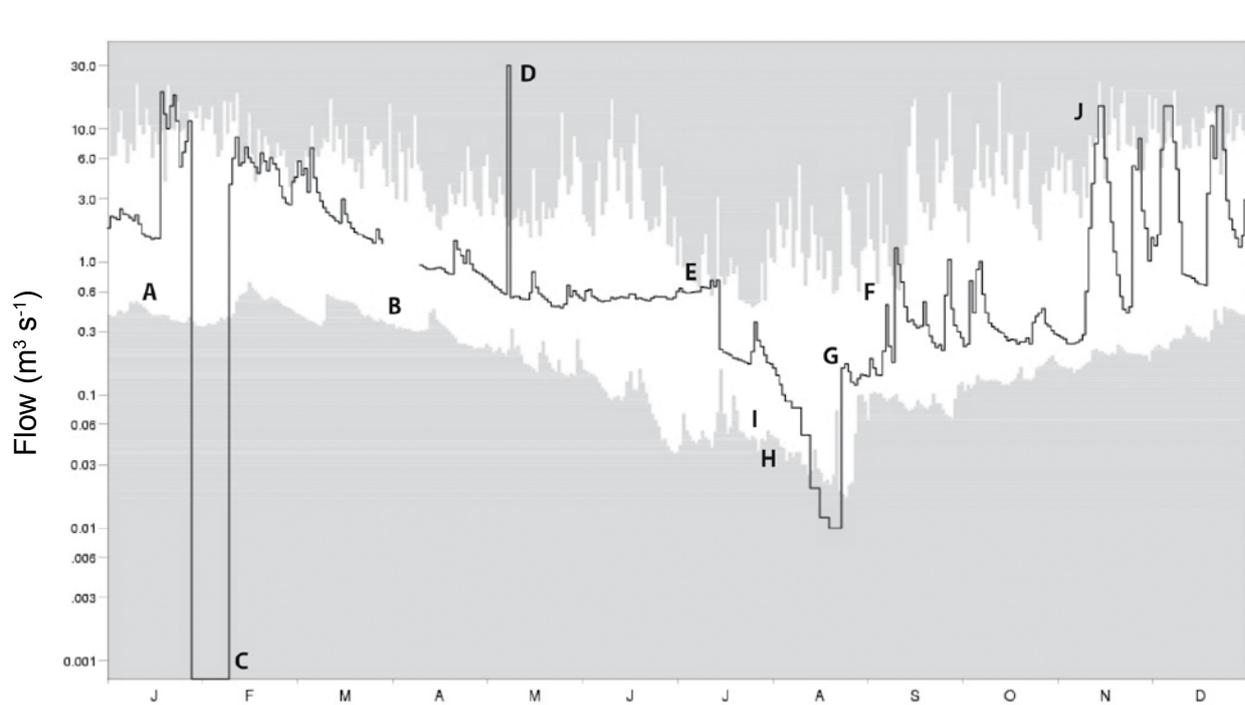
Figure 3.1 *Hydrograph analysis (Table 3.1 provides an explanation of the lettering)*

or some systematic change in either time series, possibly due to a change in the measurement method, the introduction of a new abstraction/discharge upstream, or a significant change in land use in one of the catchments. A double-mass curve can also help confirm whether an apparent trend in either time series is a consequence of global (for example, climate) change (no diversion) or can (diversion present) be attributed to local factors. The two time series used in a double-mass plot need not necessarily be of the same variable type. For instance, data from a nearby raingauge may sometimes be helpful to check a flow record.

A residual-mass curve is similar to the double-mass curve, yet it plots accumulated departures of two time series from some datum (normally the mean). Such a curve, constructed from records of two hydrologically similar catchments, should approximate a straight line, with any sudden diversion indicating a potential problem.

The comparison of catchment areal rainfall (estimated or derived from observations at several local raingauges) and runoff on a seasonal basis should show rainfall generally exceeding runoff as well as consistent behaviour between the two quantities from year to year.

Spatial consistency checking uses a map plot of a suitable flow statistic (for example, monthly runoff in mm), either as a colour-coded point value or an interpo-

lated surface (for example, inverse distance weighting), to reveal if observed flows are consistent with others in the area.

The application of the above methods is adequate to detect most inhomogeneities in streamflow data. However, it is sometimes necessary to apply more statistically rigorous and formal methods to detect nonstationarity (trends, step changes and changes in distribution) in data. There are many different types of statistical tests to detect change in data, and choosing the appropriate test depends on the type of change of interest (for example, trend or step change), whether the time of change is known and on the necessary rigour, or power, of the test (Robson and others, 2000). Tests to detect step change include the median change point test (the Pettit test for detecting change), the Wilcoxon-Mann-Whitney test, the cumulative deviation test and the Worsley likelihood ratio test. Tests for trend include Spearman's rho, the Mann-Kendall test and linear regression. The WMO report Detecting Trend and other Changes in Hydrological Data (WMO/TD-No. 1013) provides details of the various methods.

3.3.4 Data correction and editing
Few of the data available for hydrological analysis are free of errors, missing values or other inhomogeneities. The nature of the data queries and problems should be considered carefully, and, if possible, the time series should be corrected, or edited. Normally, it is best to

Table 3.1 Data quality problems detectable by hydrograph analysis	
Problem	**Possible causes**
A Discontinuity or step change	Recalibration or change in instrumentation Change in stage–discharge relation Change in the river cross-section Change in the unit of measurement Introduction of an artificial influence upstream
B Missing data	Measurement not taken Equipment failure Maintenance downtime
C Missing data entered as zero flows	Data-processing error
D Isolated, erroneous peaks (outliers)	Data-processing error
E Gradual increase in flow followed by sudden decrease	Flow computation based on rating curve. Weed growth or other obstruction (for example, debris- or ice-jams), followed by removal
F Sudden short-term increases and decreases in flow	Sluice-gate activity upstream
G Sudden change followed by prolonged increase, or decrease, in flow	Artificial influences upstream (surface water abstractions, discharges, reservoir operation)
H Unrealistic steepening of the recession (falling limb)	Unchecked extension to the rating curve
I Staircase effect	Limited stage resolution at low flows Insensitivity to stage changes at low flows Equipment malfunction
J Truncated flows	Upper- or lower-limit of measurement capability reached
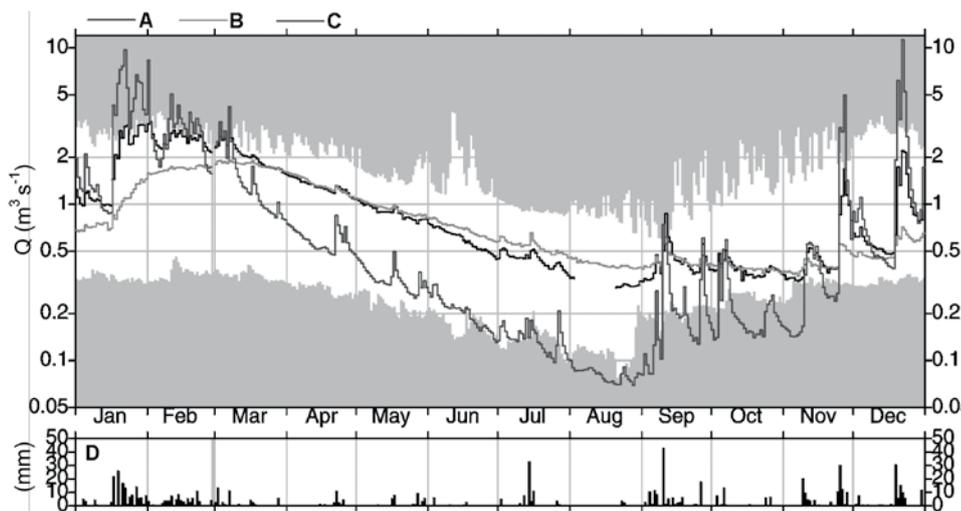
Figure 3.2

Comparison of hydrographs from adjacent catchments (A, B and C) and a hyetograph from a nearby raingauge (D) (note missing values in August)

focus available resources on the most notable anomalies, especially those in the extreme flow range.

Infilling missing data, modifying outliers and correcting errors

Missing data are a particular problem for low-flow analyses because they tend to cluster in the extreme flow ranges (Marsh, 2002). Even a small proportion of missing data can greatly reduce the ability to compile meaningful statistics (for example, annual 30-day minima). A variety of methods can be used to infill missing data and improve the utility of flow records. These vary from simple and manual visual adjustment to rainfall-runoff models and complex statistical analyses (Gyau-Baokye and Schultz, 1994). The methods can also be used to correct most of the other types of data problems, such as the modification of truncated values, outliers and spurious sequences. While it may not always be possible to obtain realistic flows for longer "problem" sequences, the inclusion of auditable and flagged estimates is often preferable to leaving gaps in the record.
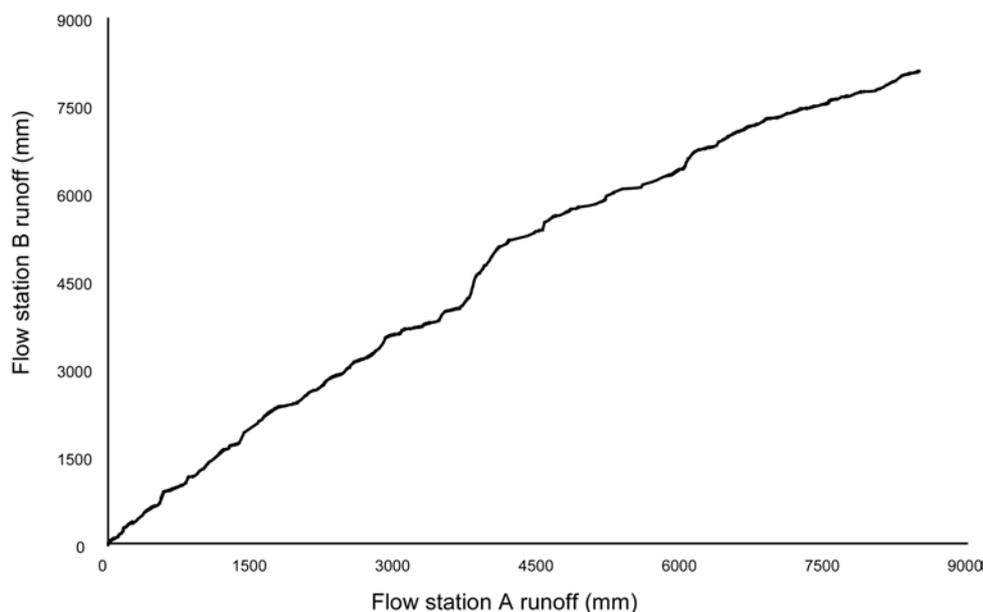
Figure 3.3
Double-mass curve constructed from adjacent catchments (A and B)

A quality control flag should be set against every edited data value to indicate when a correction has been made and the correction method used. Selecting the most appropriate infilling method depends on a number of factors, including the following:

- The nature of the site and characteristics of the upstream catchment;
- The degree of data fluctuation at the site;
- The size of the gap (number of missing data values);
- The length of the existing data record;
- The hydrological conditions at the site when the gap occurred (whether flow was rising, falling or peaking at the time);
- The availability of supporting metadata;
- The software tools available;
- The knowledge and expertise of the person responsible for correcting the data.

Some of the most common infilling methods are as follows:

Inference (manually by eye): This is applicable to short gaps, of a few days (~5 days, or longer where the flow regime is known to be stable) only in a daily flow record, during which there was no significant rainfall or flooding. Missing values are filled manually by inserting values that appear sensible when viewing the observed hydrograph. It is always useful when employing this method to compare the hydrograph being filled with that of another nearby (or analogue) gauging station, to

ensure that manually entered estimates are consistent with the observations at the other gauging station (Figure 3.2). To emphasize the low-flow data values, a logarithmic scale should be used when viewing the hydrographs. Where rainfall may be expected to influence the recession, or where artificial influences may be significant, the time series should be scanned for analogous flow sequences that would help to reconstruct the missing data. Manual infilling ideally should be conducted by someone familiar with the behaviour of the rivers and gauging stations concerned.

Serial interpolation: This is another means of infilling short gaps in low-flow data. This method is applicable only to periods without significant rainfall or flood events and should be used with great caution. Linear, polynomial or spline interpolation methods use existing data from the time series itself. Linear interpolation simply fits a straight line between the two data points immediately before and after the gap to determine intermediate values. Polynomial and spline interpolation, on the other hand, use several existing data points either side of the gap to generate a smooth curve that describes the missing values. Most statistical analysis packages, as well as hydrological data management software packages, provide such interpolation facilities. For further details of polynomial and spline interpolation see Atkinson (1988) or Wendroff (1966).

Interpolation from analogue gauging stations: This may be used for longer sequences of missing data by obtaining a relationship between the candidate time

series and the data from one, or more, analogue gauging stations. An analogue gauging station could be upstream or downstream of the (candidate) gauging station, in a nearby catchment, or a hydrologically similar catchment. One of the simplest approaches is to scale the relevant data values from an analogue catchment by some scaling factor, which is usually the ratio of the two catchment areas or the ratio of the respective mean flows. Another common approach involves calculating the flow percentile for each missing day from the analogue catchment's time series. The missing value is then assigned the flow value of the equivalent percentile from the existing candidate time series. This latter method, sometimes referred to as the equipercentile approach, requires both time series to be of long (≥ 5 years) or similar duration. Analogue methods benefit from a high correlation coefficient between the candidate and analogue time series over an identical period. The following additional factors should be considered in order to select suitable analogues:

(a) The geographical proximity of the catchments, to ensure that the catchments are climatologically similar;

(b) The similarity of catchment physiography (catchment area, elevation range and topographical relief, soil and hydrogeological conditions, proportions of lakes, forests, wetlands, moorland or cultivated land);

(c) The similarity of hydrological response, as indicated by recession analysis or the base-flow index (Chapter 5);

(d) The absence of significant artificial influences (river regulation, sewage or industrial effluent, or intakes for irrigation or other needs).

Hydrological (rainfall-runoff) modelling: This is another approach for infilling longer sequences of missing data. It uses models capable of describing the hydrological response (runoff) of a catchment, given certain specified time series inputs, primarily rainfall, or precipitation, but often also potential evaporation, temperature and other meteorological variables. Catchment response is characterized by model parameters, which can be calibrated, or tuned, according to previous observations.

A large variety of models exist (Chapter 9), from purely empirical black-box techniques, which make no attempt to model the internal structure of a catchment, to complex hydro-dynamical models, which involve complex systems of equations based on the physical laws that govern hydrological processes (WMO, 2008a, 1975). A detailed description of different modelling approaches may be found in Beven (2001).

Irrespective of the infilling method used, great care and judgement is required to prevent misleading, or erroneous, flow estimates from being stored. For instance, although outliers are often clearly visible and dealt with easily for the most part, caution should be exercised since the outlier may be a genuine extreme value and not an error. In such circumstances, referring to data from nearby gauging stations or raingauges would provide guidance.

Flow naturalization
Deriving a natural time series from an artificially influenced flow record is called naturalization. The process is usually conducted only where there is an insufficient number of good quality flow records for an analysis to proceed. Naturalization involves the adjustment of the observed flow record according to known artificial influences upstream. A systematic record of the influences is required, including times, rates and durations of abstractions, discharges and compensation flows. The data should be in compatible units and suitable for disaggregation into the necessary temporal resolution (for example, from monthly to daily). The natural flow on any day is simply approximated by adjusting the observed flow by the corresponding net upstream artificial influence. Such approximation has a high degree of uncertainty: while there may be an error of ±5 per cent in the observed flow, the error associated with the artificial influence can be around ±40 per cent, or higher.

Adjustment for trends, seasonality and discontinuities
Many low-flow analyses require data to be stationary, with all non-stationary components (trends, seasonality and discontinuities) removed. In some studies, however, interest focuses specifically on detecting the presence of trends and analysing their characteristics. Trend detection methods were mentioned earlier (see also WMO, 2000), and several further methods are available for describing and removing trends (Chatfield, 2004) and include: linear fitting (trend represented by a straight line or sequence of straight lines), curve fitting (trend represented by a polynomial curve), filtering (for example, linear filter, moving average, smoothing) and differencing (Box-Jenkins procedure). The methods

effectively model the trend, with residuals representing the local variation of the stationary series.

Streamflow data, like many other types of hydrological data, usually exhibit seasonal characteristics, which are consistent from year to year and, if seasonality is of interest, are easily estimated. If seasonal effects are not of interest, data can be deseasonalized by selecting a suitable adjustment or transformation function (for example, seasonal adjustment, seasonal differencing, autoregressive integrated moving average). Various seasonal adjustment methods and their applicability are described in den Butter and Fase (1991).

A step change, or discontinuity, detected by visual inspection or statistically, can sometimes be corrected if the time and magnitude of the change are known. Flows can be adjusted, either by addition (or subtraction), if a simple systematic shift has occurred, or by re-scaling if, for example, the data has been expressed in incorrect units.

References

Atkinson, K.A., 1988: An Introduction to Numerical Analysis (second edition). John Wiley and Sons.

Barnes, S.L., 1973: Mesoscale objective map analysis using weighting time series observations. NOAA Technical Memo ERL NSSL-62, US Department of Commerce.

Beven, K.J., 2001: Rainfall-Runoff Modelling: The Primer. John Wiley and Sons Ltd.

Champion, R., C.T. Lenard and T.M. Mill, 1996: An introduction to abstract splines. Mathematical Scientist, 21: 8–26.

Chatfield, C., 2004: The Analysis of Time Series – An Introduction (sixth edition). Texts in Statistical Science, Chapman & Hall/CRC, London.

den Butter, F.A.G. and M.M.G. Fase, 1991: Seasonal Adjustment as a Practical Problem. Elsevier, Amsterdam.

Dingman, S.L., D.M. Seely-Reynolds and R.C. Reynolds, 1988: Application of kriging to estimate mean annual precipitation in a region of orographic influence. Water Resources Bulletin, 24: 329–339.

Food and Agriculture Organization of the United Nations (FAO)/United Nations Educational, Scientific and Cultural Organization (UNESCO), 1981: Soil Map of the World. UNESCO, Paris.

Geological Survey of Canada, 1995: Generalized Geological Map of the World and Databases (CD-ROM). Geological Survey of Canada, Ottawa, Ontario.

Gyau-Baokye, P. and G.A. Schultz, 1994: Filling gaps in runoff time series in West Africa. Hydrological Sciences Journal, 39(6): 621–636.

Herschy, R.W., 1995: Streamflow Measurement. E and FN Spon, London.

— (ed.), 1999: Hydrometry Principles and Practices (second edition). John Wiley and Sons Ltd., Chichester, England.

International Organization for Standardization (ISO), 1981, 1982: Liquid Flow Measurement in Open Channels. Part 1: Establishment and operation of a gauging station, ISO 1100-1; Part 2: Determination of the stage-discharge relation, ISO 1100-2, ISO, Geneva.

—, 1988: Guidance on the sampling of groundwater. ISO/TC147, ISO, Geneva.

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

Rees, G., T.J. Marsh, L. Roald, D. Demuth, H.A.J. van Lanen and L. Kasparek, 2004: Hydrological data. In: Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater (L.M. Tallakesn and H.A.J. van Lanen, eds). Developments in Water Science, Elsevier, Amsterdam, the Netherlands, pp. 99–138.

Robson, A., A. Bardossy, D. Jones and Z.W. Kundzewicz, 2000: Statistical methods for testing for change. In: Detecting Trend and other Changes in Hydrological Data (Z.W. Kundzewicz and A. Robson, eds). WMO (WCDMP-45, WMO/TD-No. 1013), Geneva, pp. 49–85.

Singh, P. and V.P. Singh, 2001: Snow and Glacier Hydrology. Water Science and Technology Library, 37, Kluwer Academic Publishers, Dodrecht/Boston/London.

Stewart, B.J., 1999: The need for hydrological and related data. In: Extended Abstracts: Proceedings of the International Conference on Quality, Management and Availability of Data for Hydrology and Water Resources Management, Koblenz, Germany, 22–26 March 1999. Bundesanstalt für Gewässerkunde, IHP/OHP-Sekretariat, pp. 17–20.

Tallaksen, L.M., H. Madsen and H. Hisdal, 2004: Frequency analysis. In: Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater (L.M. Tallakesn and H.A.J. van Lanen, eds). Developments in Water Science, Elsevier, Amsterdam, the Netherlands, pp. 199–271.

Thiessen, A.H., 1911: Precipitation for large areas. Monthly Weather Review, 39: 1082–1084.

Wendroff, B., 1966: Theoretical Numerical Analysis. Academic Press, New York.

World Meteorological Organization, 1958: Design of Hydrological Networks (M.A. Kohler). Technical Note No. 25 (WMO-No. 82.TP.32), Geneva.

—, 1975: Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting. Operational Hydrology Report No. 7 (WMO-No. 429), Geneva.

—, 1980: Manual on Stream Gauging. Operational Hydrology Report No. 13, Volume II – Computation of Discharge (WMO-No. 519), Geneva, 258.

—, 1982: Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use (B. Sevruk). Operational Hydrology Report No. 21 (WMO-No. 589), Geneva.

—, 1985a: Use of Radar in Meteorology (G.A. Clift). Technical Note No. 181 (WMO-No. 625), Geneva.

—, 1985b: Casebook on Operational Assessment of Areal Evaporation. Operational Hydrology Report No. 22 (WMO-No. 635), Geneva.

—, 1992: Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture (B. Sevruk, ed.). Operational Hydrology Report No. 35 (WMO-No. 749), Geneva.

—, 1995: INFOHYDRO Manual (1995 edition). Operational Hydrology Report No. 28 (WMO-No. 683), Geneva.

—, 1998a: WMO Solid Precipitation Measurement Intercomparison: Final Report (B.E. Goodison, P.Y.T. Louie and D. Yang). Instruments and Observing Methods Report No. 67 (WMO/TD-No. 872), Geneva.

—, 1998b: WHYCOS: World Hydrological Cycle Observing System (WMO-No. 876, Geneva (see www.whycos.org).

—, 2000: Detecting Trend and other Changes in Hydrological Data (Z.W. Kundzewicz and A. Robson, eds) (WCDMP-45, WMO/TD-No.1013), Geneva.

—, 2003: Hydrological Data Management: Present State and Trends (A. Terakawa). Operational Hydrology Report No. 48 (WMO-No. 964), Geneva.

—, 2006: Technical Regulations Volume III – Hydrology (WMO-No. 49), Geneva.

—, 2008a: Guide to Hydrological Practices. Volume I, sixth edition (WMO-No. 168), Geneva (Volume II in preparation).

—, 2008b: Guide to Meteorological Instruments and Methods of Observation. Seventh edition (WMO-No. 8), Geneva.

4.   Processes and Regimes

4.1   Introduction

Low flows occur after periods of low rainfall or when precipitation falls as snow. This results in a reduction in water stored in soils, aquifers and lakes and a decrease in the outflow to the river. The timing of depletion depends primarily on antecedent weather conditions. The rate of depletion depends on hydrological processes and the storage properties within the catchment.

This chapter presents a summary of how these factors control the spatial and temporal distribution of low flows. An understanding of these flow-generating processes can aid the following:

(a)   The establishment of data requirements for a low-flow investigation (section 3.3);
(b)   The assessment of the variability of low flows in a catchment;
(c)   The selection of the most appropriate low-flow analyses method from those described in this Manual;
(d)   The development of hydrological models;
(e)   The interpretation of results.

Figure 4.1 shows the model of a catchment that receives precipitation, which then recharges different catchment storages, that is, soil water, groundwater, snow, glaciers, wetlands and lakes. The outflow from each of these storages contributes to river flow.

4.2   Processes causing low flows

4.2.1   Climate drivers

Catchment inputs originate from rainfall or snowmelt; thus, decreases in input can be caused by either:

(a)   An extended dry period leading to a climatic water deficit when potential evaporation exceeds precipitation; or

(b)   Extended periods of low temperatures during which precipitation is stored as snow.

Low flows usually occur during a long spell of warm, dry weather typically associated with high pressure systems and subsiding air. High temperatures, high radiation input, low humidity and wind increase evaporation and transpiration rates. Snowfall and snow storage result from temperatures continuously below freezing which are often associated with cold, polar air masses and/or decreasing temperatures at higher altitudes. In the absence of snowmelt, precipitation will accumulate and this will lead to a reduction in low flows.

In many regions, one or both situations occur annually. In mid- and high-latitude climates, low flows are often described by the season of occurrence, namely "summer low flow" and "winter low flow" (Figure 4.2). In low latitude climates, there may be one or more dry season and, consequently, one or more distinct low-flow period. As a result of constantly high evaporation rates, the climatic water deficit from the dry season may persist
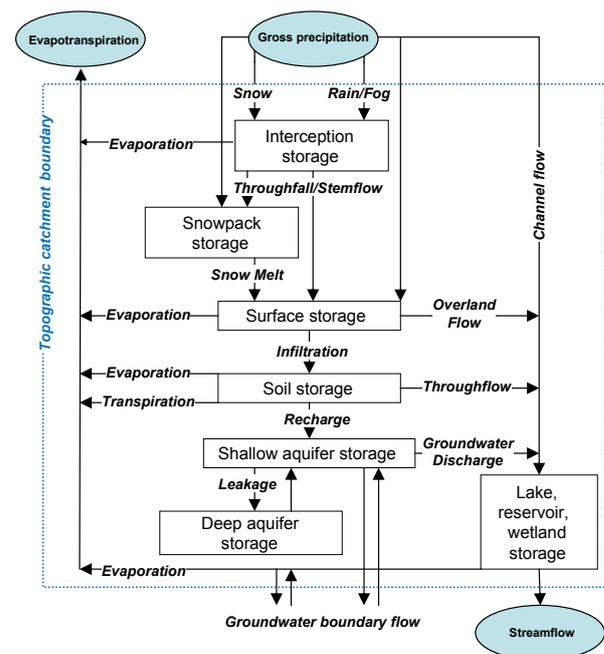
Figure 4.1 Hydrological processes and catchment storages (modified from Tallaksen and van Lanen, 2004)

Figure 4.2 *Summer and winter low flows*
(left: Dreisam River, Freiburg, Germany, August 1998; right: Columbia River, Golden, Canada, February 2007)

into the wet season. In arid and semi-arid climates, the combination of low precipitation and high evaporation results in minimal river networks and ephemeral rivers. These typically have prolonged periods of zero flow over several months or years and episodic high flows often in the form of flash floods.

Climate determines the magnitude and variation of temperature, precipitation and potential evaporation over the year. Climate diagrams and maps provide a valuable source of information for assessing the climatic drivers and the expected timing of low flows. However, climate varies spatially, particularly in mountain regions where there are strong altitude-dependent temperature and precipitation gradients. High precipitation (as rain or snow) in mountainous areas is often critical for providing the source of downstream low flows in arid or semi-arid areas. Climate also varies temporally at inter-annual, decadal and even centennial timescales. Long-term trends and changes in the climate system will result in changes to the low-flow regime.

4.2.2 Catchment processes and storage
While climate controls may lead to a climatic water surplus in one season and a deficit in another, catchment processes determine how these surpluses and deficits propagate through the vegetation, soil and groundwater system to streamflow. An understanding of these processes is a key component in developing and understanding the results of hydrological models (Chapter 9) and in interpreting how changing climate or land use will have an impact on the duration, frequency and magnitude of low flows. Of particular importance are soil moisture and groundwater storage, aquifer properties and the hydraulic resistance between aquifers and rivers (Figure 4.1). The continuous monitoring of catchment storages, for example, soil moisture, groundwater and lake level, provide valuable data for interpreting the results of low-flow studies (section 3.2). The key catchment processes which influence low flows are summarized below.

Precipitation input may be stored in micro-depressions; once these have been filled, water may flow to the stream as overland flow (Figure 4.1). This process tends to occur on impermeable urban surfaces and non-vegetated, sloping land with compacted topsoil or exposed rock. Overland flow rates depend on rainfall intensities and whether they exceed infiltration rates to the soil, which are lower on a clay soil than sandy soil. During freezing periods, precipitation is stored as snow and ice.

When temperatures rise above freezing, liquid water from the snow cover melts and either infiltrates into the soil or flows over frozen ground to the stream as overland flow.

As soil moisture is replenished, soil moisture content increases and water may flow vertically downward to an aquifer to recharge groundwater storage, or move laterally as throughflow towards the stream along a permeable soil layer. The available soil moisture capacity (amount of water that can be stored in the soil) may vary between a few tens to over several hundred millimetres water depth. A large soil moisture capacity provides a store to support high annual transpiration. Water can also recharge aquifers or flow laterally to the stream without fully replenishing soil moisture. This usually occurs via preferential flow paths such as cracks, macropores and pipes in the soil. In semi-arid and arid climates, a major part of aquifer recharge occurs through the river beds of ephemeral rivers. This indirect recharge often originates from high precipitation in mountainous regions upstream (see 4.2.1).

In response to recharge, aquifer storage increases as groundwater levels rise. The groundwater gradient and the transmissivity of the aquifer (saturated thickness multiplied by hydraulic conductivity) govern the groundwater discharge to the stream (Figure 4.1). If data on storativity, transmissivity or hydraulic conductivity are not available, these parameters can be estimated from hydrogeological or hydrological classifications of soils and bedrock material (WMO, 2008). When there is no recharge, groundwater discharge will continue owing to the depletion of storage. In hilly or mountainous regions, discharge from shallow aquifers of weathered hard rock often provides an important source of low flow during dry periods. In lowland areas (for example, deltas, coastal plains), deep aquifers typically exist beneath shallow aquifers, often separated by a semi-permeable layer (Figure 4.1). This may reduce storage changes and outflow characteristics of the deep aquifer. In lowland areas or large valleys, aquifers act as large storage systems and are able to feed rivers during prolonged dry conditions.

A river receives water from one or more of three different flow paths: overland flow, throughflow and groundwater discharge. Overland flow and throughflow respond quickly to rainfall or melting snow, whereas groundwater discharge responds slowly with a time lag of several days, months or years. If groundwater discharge comes from shallow saturated subsurface flow, then it responds quickly (hours or days) to rainfall or melting snow. Catchments dominated by overland flow, throughflow and/or shallow saturated subsurface flow are therefore classified as quickly responding or "flashy" catchments. Catchments fed primarily by groundwater discharge are classified as slowly responding catchments with a high base flow. Hydrograph separation techniques can be used to divide the total streamflow into a quick and a delayed component (section 5.2) The delayed flow component, commonly referred to as the base flow, represents the proportion of flow that originates from stored sources. A high base-flow proportion would imply that the catchment is able to sustain river flow during dry periods. Base-flow indices are generally highly correlated to the hydrological properties of soils and geology and the presence or absence of lakes in a catchment.

A catchment with a fast/slow response to rainfall usually has fast/slow recession behaviour (section 5.3). This is demonstrated in Figure 4.3, in which the streamflow for a quickly responding and a slowly responding catchment is shown (Tallaksen and van Lanen, 2004). Streamflow simulations were conducted for a temperate humid climate (Figures 4.3(A) and 4.3(B)) and a semi-arid climate (Figures 4.3(C) and 4.3(D)). The recharge inputs for the two different climates differ, but are similar for the two different response cases within each climate. Similarly, the aquifer characteristics of the quickly responding cases (Figures 4.3(A) and 4.3(C)) and the slowly responding cases (Figures 4.3(B) and 4.3(D)) are identical.

Low flows in the quickly responding catchments are lower than in the slowly responding ones (compare graphs 4.3(A) with 4.3(B) and 4.3(C) with 4.3(D)). For example, in the temperate, humid climate the low flows for the quickly responding catchment are regularly lower than 10 mm per month, whereas in the slowly responding catchment they are never below 15 mm/month. Low flows in the slowly responding catchments are more persistent (multi-year effects) than in the quickly responding catchments. These differences are a clear illustration of the influence of hydrological processes and storages on low flows. There is also significant climate control, with more prolonged low flows in the semi-arid climate than in the temperate, humid climate (compare graphs 4.3(A) with 4.3(C) and 4.3(B) with 4.3(D)).

Lakes and reservoirs usually have a large impact on downstream low flows. Lakes in a moist and cool
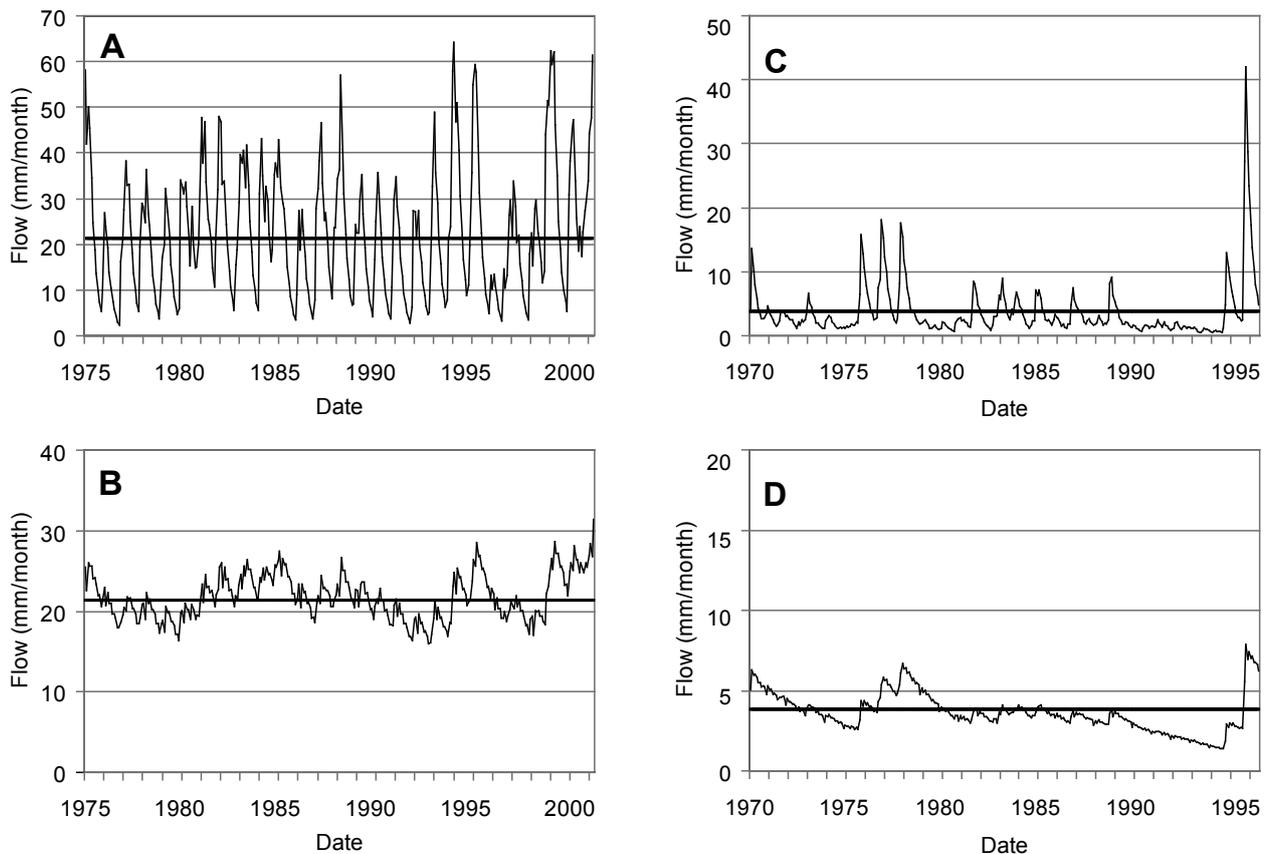
Figure 4.3 Simulated flow to a stream in catchment: (A) temperate, humid climate and quickly responding; (B) temperate, humid climate and slowly responding; (C) semi-arid climate and quickly responding; and (D) semi-arid climate and slowly responding (straight line represents mean flow)

climate provide additional catchment storage to maintain low flows during dry periods. In a semi-arid climate, however, downstream low flows may be smaller than those upstream of a lake due to high lake evaporation losses outweighing any increase in low flows caused by the regulatory impact. The effect of reservoirs on low flows is mainly determined by their operation and normally results in a reduction in discharge below the reservoir. Direct artificial influences on low flows are discussed in Chapter 10 and include the abstraction of water from rivers, lakes and groundwater, and the discharge of effluents into the channel. Human influences can also indirectly affect low flows through a change in land use, such as deforestation, afforestation or urbanization, and the impact of global warming on changing precipitation regimes, or that of temperature increase on deglaciation. The relationship between hydrological process and low flows and the impact of human influences on droughts are reviewed by Tallaksen and van Lanen (2004). For a comprehensive description of catchment processes, readers are referred to Dingman (2002).

4.3 Low flows in different hydrological regimes

4.3.1 Regime distinction
A monthly streamflow regime may be calculated from several years of streamflow data (section 3.3). The regime illustrates the seasonality of river flows and hence the typical duration and timing of low flows. The following sections illustrate some examples of how climate-driven seasonal hydrological regimes are modified by catchment processes. This type of analysis should be undertaken before embarking on a national or regional low-flow study to ensure that the key processes causing low flows are understood. A distinction is made between rain- and snow-dominated regimes (section 4.2). The former are further subdivided by the presence or absence of a distinct annual dry season. Glacial regimes are discussed separately.

4.3.2 Rain-dominated regimes
Climates with no distinct dry season
Rivers in tropical or temperate climates with no distinct dry season are mostly perennial, that is, they flow all year.

The seasonal distribution of rainfall will determine whether there are distinct low-flow periods. In temperate climates, the most common time for low flows to occur is towards the end of the warm season, when dry weather patterns may persist for several weeks.

Figure 4.4 shows the hydrological regimes from two small catchments in the Netherlands. The slowly responding Noor brook drains the south-eastern part of a chalk plateau and has a thick unsaturated zone and a multilayered aquifer system with substantial deep storage. Owing to these large stores, the hydrograph of the Noor does not show a strong low-flow season (see also the same watershed in Figure 4.3(B)). The quickly responding Hupsel is a catchment where a sandy shallow (2 to 8 m) aquifer overlies impermeable clay. The Hupsel

hydrograph shows a more pronounced low-flow season in the summer months from May to August, when transpiration is high and storages are depleted (see also Figure 4.3(A)), and its quick response to rainfall also shows a much wider range of daily flows.

Climates with a dry season (tropical and temperate)
Rivers in all climates with a distinct dry season show a strong seasonality, with the streamflow cycle following the precipitation cycle. Amplified by high transpiration, the dry season flows are generally very low, unless the catchment has significant aquifer or lake storage. Streams draining small catchments will often be dry for pronged periods. Dry season climates are commonly similar from year to year and, as a result, the interannual variation in low-flow discharge is dependent primarily

Figure 4.4 Rain-dominated hydrological regimes in two streams in the Netherlands
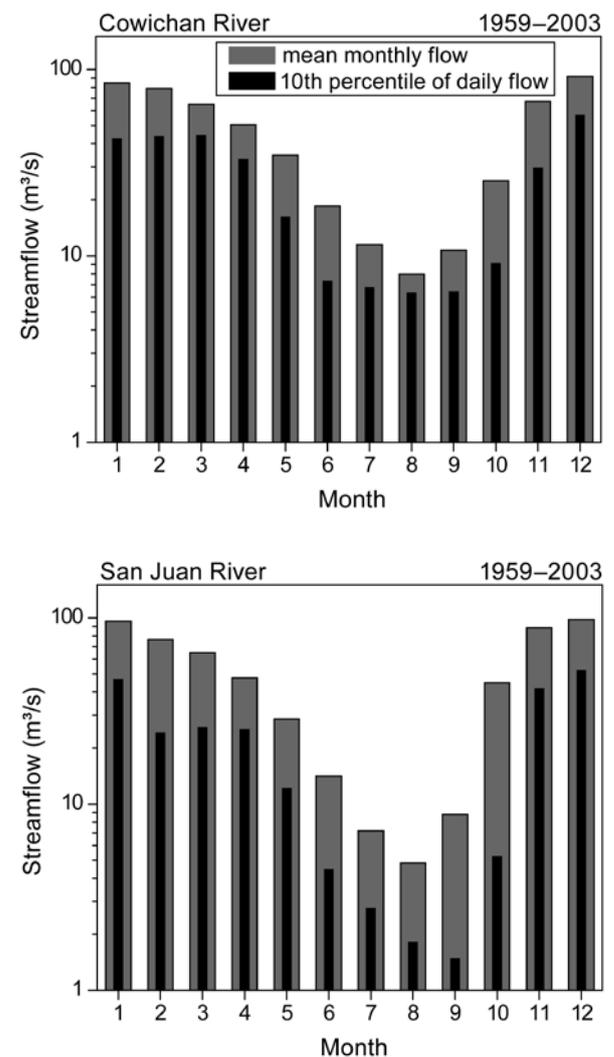
Figure 4.5 Two rain-dominated hydrological regimes with a summer dry season in south-western Canada (Source: Water Survey of Canada)

on the groundwater storage at the beginning of the dry season. Reservoirs (for public water supply and irrigation) are common in these regions and significantly influence downstream river flows.

Figure 4.5 shows the regimes of two rivers on Vancouver Island (British Columbia, Canada). The region has a Mediterranean climate with a dry season from June to September. Owing to the large range of flows, a logarithmic scale is used in the figure (section 3.3).

While Cowichan River (top) has a lake with a regulated outlet (during the summer months), San Juan River (bottom) has no lakes or wetlands in its catchment. Summer average and low flows in the San Juan River therefore drop to lower levels.
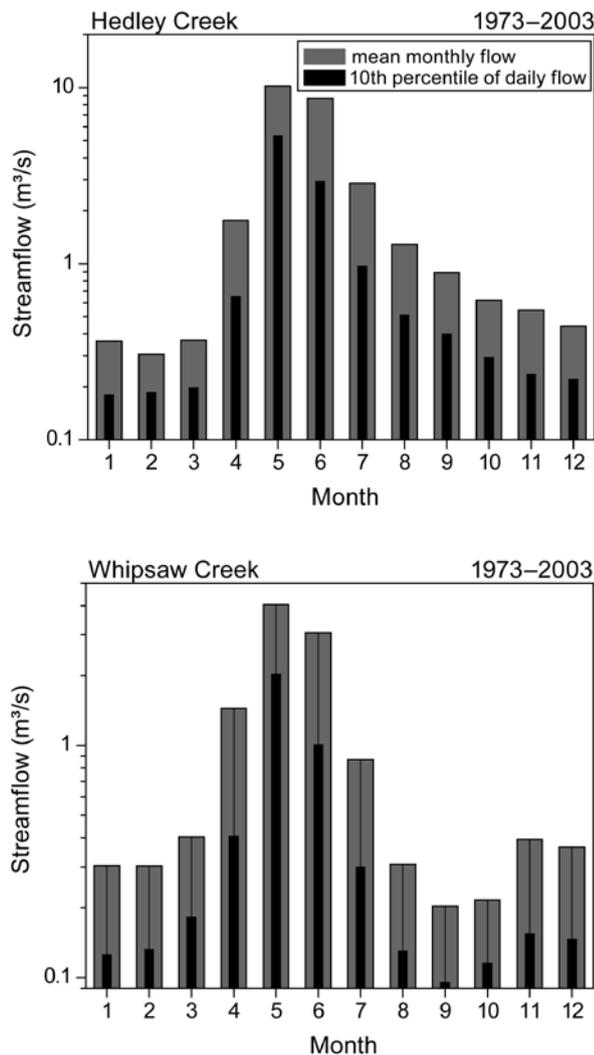
Figure 4.6 *Snow-dominated regimes in British Columbia*
(Source: Water Survey of Canada)

Dry climates
Streamflow in arid and semi-arid climates is intermittent or ephemeral, that is, the rivers are dry during part or most of the year. Low-flow studies are of less relevance than understanding how occasional flood events recharge groundwater systems, how water can be conserved and in estimating reservoir yield in these systems with high interannual flow variability (McMahon and Mein, 1978).

4.3.3 Snow-dominated regimes
Snow-dominated climates are found not only at high latitudes, but also in mountain regions worldwide. They are part of the headwaters of most large river systems which eventually flow through warmer climate zones. The most important difference of snow-dominated regimes compared with rain-dominated regimes is that they do not follow the annual precipitation cycle given that precipitation is stored as snow. Low flows therefore primarily occur during the cold season (Figure 4.6). Streamflow increases with rising temperatures and increasing snowmelt. A secondary low-flow period can occur, depending on the precipitation during the warm season and the meltwater component of flow. In continental interiors and high mountains, very low temperatures during a long winter may cause soil and surface water to freeze, resulting in very low base flows. Although some water usually flows beneath river ice, in small catchments, or during extreme cold periods, streamflow may cease.

In regions with low relief, or in small mountain catchments, spring snowmelt occurs over a short period of time (days to weeks). In larger mountainous catchments, snowmelt gradually migrates from lower to higher elevations and produces a longer snowmelt period. When snowmelt ceases, streamflow recedes. The rate depends on the additional rainfall input and the storage characteristics of the catchment. In the absence of aquifer or lake storage, a second low-flow period is common.

Figure 4.6 shows examples of two snow-dominated regimes from the mountains of British Columbia in Canada. While the snowmelt peak in both creeks is very similar, the recession period in Hedley Creek (top) is slower. Hedley Creek spans a larger elevation range than Whispsaw Creek (bottom) and water is released gradually from various storages, including several small lakes in the basin's headwaters. Therefore, Hedley Creek does not show the secondary low-flow period during the summer dry season which is typical of Whipsaw Creek. Hedley Creek also maintains a somewhat higher base-flow level during the winter.

4.3.4 Glacial regimes

During the cold season and the transition season, hydrographs from glacierized catchments are similar to those of snow-dominated catchments. They are dominated by winter low flows. Spring snowmelt, however, tends to start later and lasts longer into the warm season. High elevations and extensive glaciers delay melting. The main difference between the hydrographs of glacierized and non-glacierized catchments occurs after the snow has melted. With increasing temperatures, glacier melt increases after the snow has melted from the glacier surface, while, in a non-glaciated catchment, streamflow recedes to a secondary low-flow season. This augmentation of streamflow during the warm, dry season depends on the glacier coverage in the catchment (Figure 4.7). The regime of the Blue River (top) with only 6 per cent glacier coverage strongly resembles a snow-dominated regime with a secondary summer

low-flow period, while that of Canoe Creek (bottom) with 25 per cent glacier cover maintains high streamflows throughout the summer season. Streamflow in a glacierized catchment is generally less variable from year to year as it is less dependent on the annual variability of precipitation input.

In many mountain regions of the world, low flow caused by glacial meltwater is an essential water resource. It is of particular importance in dry regions in the lee of mountain ranges (the eastern slopes of the American Cordillera), or in areas where high population density renders glacial meltwater essential (the Himalayas). Most mountain glaciers are currently receding, and this deglaciation is predicted to continue because of global warming. Depending on the climate and glacier history in a region, meltwater may increase initially as rising temperatures increase the ablation rate of a glacier. In the long term, however, the reduction in glaciated area will lead to a reduction in glacial meltwater (compare the two regimes in Figure 4.7) and hence a transition to a snow- and rain-dominated regime. This may lead to a reduction in low flows during the critical dry season.

Figure 4.7 *Regimes of two glacierized rivers in British Columbia (Source: Water Survey of Canada)*

References

Dingman, S.L., 2002: Physical Hydrology. Second edition, Prentice Hall, Upper Saddle River, NJ, United States.

McMahon, T.A. and R.G. Mein, 1978: Reservoir Capacity and Yield. Developments in Water Science, 9, Elsevier, Amsterdam, the Netherlands.

Tallaksen, L.M. and H.A.J. van Lanen (eds), 2004: *Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater*. Developments in Water Science, 48, Elsevier, Amsterdam, the Netherlands.

World Meteorological Organization, 2008: *Guide to Hydrological Practices*. Volume I, sixth edition (WMO-No. 168), Geneva (Volume II in preparation).

5. Low-Flow indices

5.1 Introduction

There are a number of different ways of analysing the time series of daily flows to produce summary information that describes the low-flow regime of a river. The proliferation of methods is a result of the following:

(a) The different definitions of a low-flow event. For example, an event can be expressed as annual minima, a threshold discharge, the time during which the discharge is below a threshold (Chapter 8) or the rate of recession;

(b) The different methods of expressing frequency. The frequency may be expressed as a proportion of time during which a discharge is exceeded, for example the flow-duration curve (Chapter 6), or as a proportion of years during which a given low flow occurs, for example, extreme value analysis (Chapter 7);

(c) Different durations or averaging periods. Many applications require information over a set period, such as seven or thirty days.

In this Manual, the term "low-flow indices" is used for specific values derived from an analysis of low flows. The first two indices in this chapter describe the proportion of base flow in a river and the recession constant. They are followed by three flow statistics, the mean, the mean annual minima and the 95 percentile exceedance discharge (Q_{95}). Many decisions on the design or management of water resources are based on these indices. Examples include using recession analysis for low-flow forecasting and using Q_{95} for preliminary assessment when establishing water abstraction licences.

5.2 Base-flow index

Hydrograph separation techniques generally divide the total streamflow into a quick component and a delayed component. The delayed flow component, commonly referred to as the base flow Q_b, represents the proportion of flow that originates from stored sources. A high index of base flow would imply that the catchment is able to sustain river flow during extended dry periods. Base-flow indices are generally highly correlated with the hydrological properties of soil, geology and other storage-related descriptors, such as lake percentage. The base-flow index (BFI) is presented below, and a review of alternative automated separation procedures can be found in Nathan and McMahon (1990).

The BFI is the ratio of base flow to total flow calculated from a hydrograph separation procedure. It was initially developed in a low-flow study in the United Kingdom (Gustard, 1983; Gustard and others, 1992) for characterizing the hydrological response of catchment soils and geology. Values of the index range from 0.15 to 0.2 for an impermeable catchment with a "flashy" flow regime to more than 0.95 for catchments with high storage capacity and a stable flow regime. The index must be interpreted with care, for example, the BFI is heavily modified downstream of lakes and reservoirs. In tropical climates, the index is influenced by the seasonal climate regime, and high index values may be observed downstream of glaciers. Examples of base-flow separation for two United Kingdom catchments are shown in Figure 5.1.

The calculation procedure is as follows:

(a) Divide the time series of daily flows, Q (m³/s), into non-overlapping blocks of five days;

(b) Select the minima of each five-day period, Q_m;

(c) Identify the turning points in this sequence of minima (Q_m) by considering, in turn, each minimum and its neighbouring minima values. In each case, if 0.9 x central value ≤ adjacent values, then the central value becomes a turning point, Q_t;

(d) Join the turning points, Q_t, by straight lines to obtain the base-flow hydrograph;

(e) Assign a base-flow value to each day by linear interpolation between the turning points. The base flow is constrained to equal the observed hydrograph on any day if the base-flow hydrograph exceeds the observed flow;
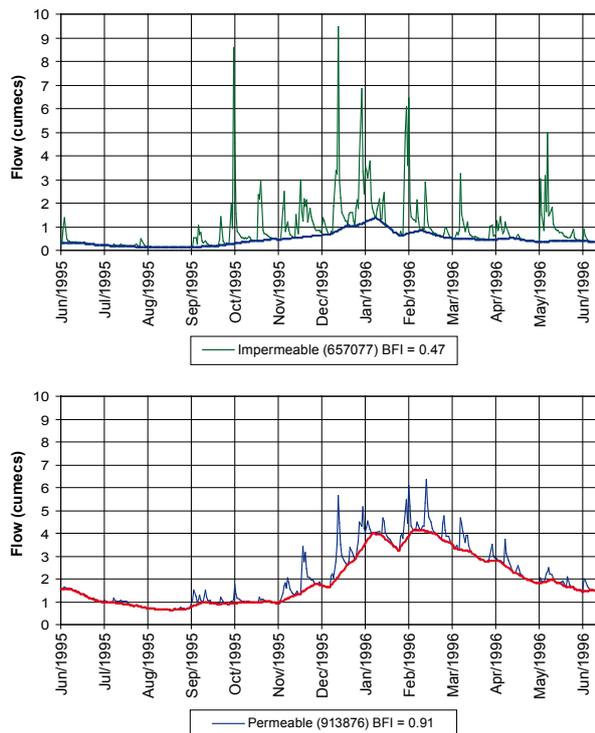
Figure 5.1 Base-flow separations for an
impermeable (top) and permeable catchment
(bottom) in the United Kingdom

(f)   Continue this procedure until the complete time series has been analysed;

(g)   The volume of water (m³) beneath the separation line (V$_{base}$) for the period of interest is simply determined as the sum of the daily base-flow values multiplied by the timespan in seconds per day. The volume of water beneath the recorded hydrograph (Vtotal) is calculated in the same way;

(h)   Lastly, BFI is determined as: BFI = V$_{base}$/V$_{total}$.

The BFI is sensitive to missing data (one missing day may result in several days of data being omitted from the base-flow separation). Therefore, missing periods should be infilled prior to the calculation (section 3.2). A detailed example and program for calculating the BFI can be found in Hisdal and others (2004).

It is recommended that the base-flow separation be computed for the entire record to avoid the loss of some days at the start and end of each year. The period of record BFI is then calculated as the ratio of the volume of base flow to the volume of total flow for the whole period. Annual BFI values can be determined by summing up the base-flow and total-flow volume separately

for each year, allowing also the annual variability in the index to be assessed.

The BFI procedure was developed for rainfall regimes with a typical streamflow response in hours or days. This is reflected in the choice of parameters: five-day blocks and a turning point factor of 0.9, which were determined by calibration and visual inspection of the base flow derived from over 100 catchments in the United Kingdom. In regions with long-duration floods, for example lake- or snow-dominated catchments, a turning point might be identified in the high-flow period, and the procedure thus fails to provide reliable results. In this case, as well as for catchments in other hydrological regimes, alternative parameter values may be chosen and the BFI calculated for each season separately. Seasonal calculations imply shorter observation periods, and longer records are necessary to obtain stable values (Tallaksen, 1987).

5.3   Recession analysis

The gradual depletion of the water stored in a catchment during periods with little or no precipitation is reflected in the shape of the recession curve, that is, the falling limb of the hydrograph (Figure 5.2). The recession curve describes in an integrated manner how different catchment storages and processes control the river outflow (section 4.2.2). Rivers with a slow recession rate are typically groundwater or lake dominated, whereas a fast rate is characteristic of flashy rivers draining impermeable catchments with limited storage. The quantification of the recession curve has proven useful in many areas of water resources management, including low-flow forecasting (section 11.2.2) and the estimation of low-flow variables at ungauged sites. In the latter case, the recession rate is used as an index of catchment storage, for example, in regional statistical procedures (section 9.3) and rainfall-runoff modelling (section 9.4).

The numerical estimation of recession indices involves the selection of an analytical expression to fit to the curve, the determination of a characteristic recession and the optimization of the recession parameters. A comprehensive review of recession analysis is provided by Hall (1968) and Tallaksen (1995).

The recession curve is modelled by fitting an analytical expression to the outflow function Q$_t$, where Q is the rate of flow and t time. The time interval Δt is normally in the order of days. If Q$_t$ is modelled as the outflow
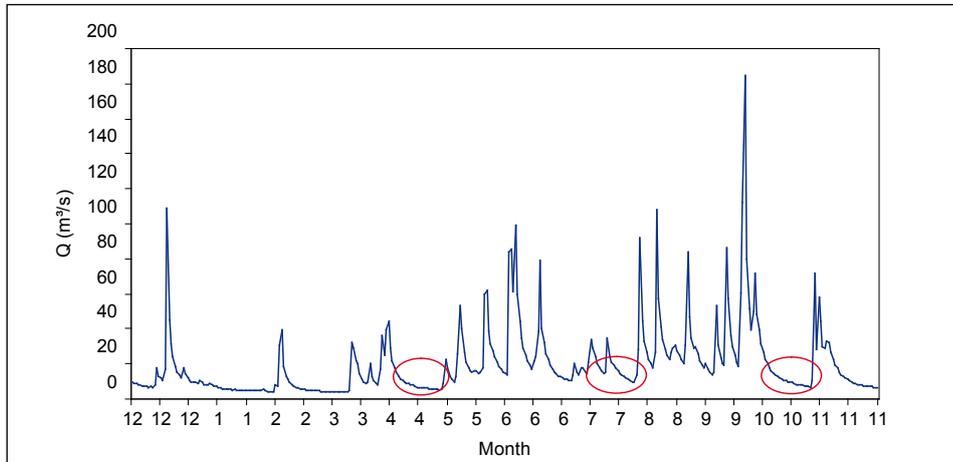
Figure 5.2

Identification of recession periods from a continuous streamflow record (data from one hydrological year 1969/1970; River Ngaruroro in New Zealand)

from a first order linear storage with no inflow, the recession rate will follow the simple exponential equation:

$$Q_t = Q_0 \, exp(-t/C) \qquad (5.1(a))$$

$$lnQ_t = lnQ_0 - t/C \qquad (5.1(b))$$

where Q_t is the flow at time t; Q_0 the flow at the start of the modelled recession period (t = 0); and C the recession constant (dimension time). The curve plots as a straight line of slope $-1/C$ on a semi-logarithmic plot of t against lnQ_t. The lack of fit of equation 5.1 for long recession segments has led to the separation of the curve into distinct components representing the outflow from a series of linear reservoirs; commonly two or three terms are adopted. Alternatively, non-linear relationships have been sought.

In a humid climate, rainfall frequently interrupts the recession period and a series of recession segments of varying duration results (Figure 5.2). The segments represent different stages in the outflow process and their characteristics also depend on the particular recession model and calculation procedure adopted. Seasonal variations in the recession behaviour further add to the variability in the recession rate. Steeper recession curves are generally found during periods of high evapotranspiration in the growing season commensurate with a decline in base flow. The high variability of recession rates has made it difficult to find a consistent way to select recession segments from a continuous flow record. As a result, various procedures have been developed to identify and parameterize the characteristic recession behaviour of a catchment. These can be classified into two main groups: those based on con-

structing a master recession curve (MRC) and those performing a separate calculation of parameters of individual recession segments (IRS). In both cases, the starting point is to define a set of criteria for selecting recession segments from a continuous record. It is common to disregard the first part of a recession period to exclude the influence of rapid response discharge following a rainfall event. A fixed or constant starting value restricts the recession to the range of flow below a predefined discharge, whereas a variable starting value can be defined as the flow at a given time after rainfall or peak discharge. Similarly, the length of the recession period can be a constant or a varying number of time steps. A minimum length in the order of five to seven days is, however, commonly used. The choice of recession model and calculation procedure depends on the purpose of the study and the nature of the region under study.

The MRC approach tries to overcome the problem of variability in individual segments by constructing a mean recession curve. In the correlation method, the data are pooled and the discharge at one time interval (Q_{t-1}) is plotted against discharge one time interval later (Q_t) and a curve fitted to the data points (Langbein, 1938). If the recession rate follows an exponential decay, a straight line results and the recession parameter can be estimated from the slope k, provided that the line is forced to intercept at (0,0):

$$k = Q_t / Q_t - 1 \qquad (5.2)$$

The recession constant C in equation 5.1 is then related to k as:

$$C = - \Delta t \, / ln(k) \qquad (5.3)$$
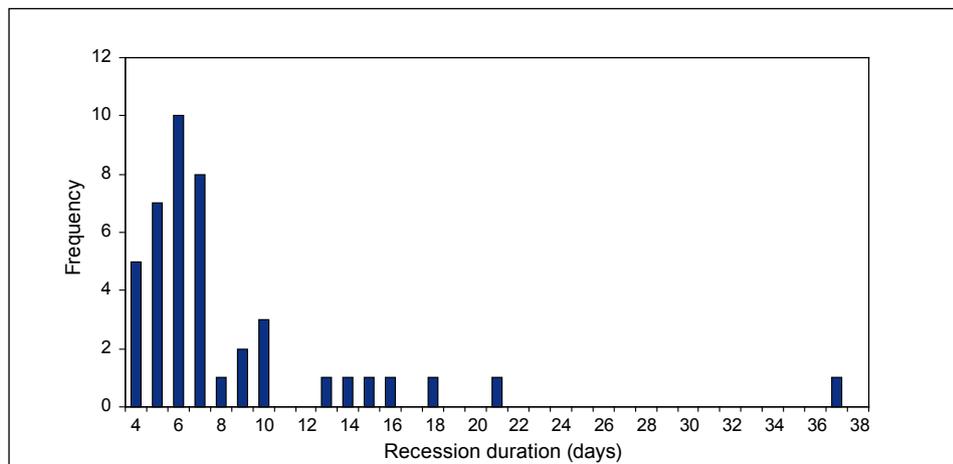
Figure 5.3
Histogram of recession length (duration) (data from Ngaruroro River in New Zealand)

More recent applications of the correlation method plot the rate of flow change, $\Delta Q/\Delta t$, against Q. The graphical analysis of the relationship is often performed by means of the upper and lower envelope of points, representing the maxima and minima observed recession rates, respectively (Brutsaert and Nieber, 1977). The correlation plot requires highly accurate low-flow measurements, and the quality of the low-flow data is often a limiting factor when the time interval is chosen (section 3.2).

In the IRS method, the variability in individual recession segments is explicitly accounted for by fitting a recession model to each segment. Sample statistics of the model parameters, for example mean and variance of the recession constant, can subsequently be determined to characterize the overall recession behaviour of the catchment. If a separate model is fitted to each recession segment by the least squares method, the average slope equals the arithmetic mean of the individual slopes, provided that the segments are of equal length; otherwise a weighted average must be calculated. The weightings are based on the length of the recession segments (Tallaksen, 1989). In Figure 5.3, the distribution of the length (duration) of the recession period below a given threshold (Q_{70} is used) is shown for a daily time series of streamflow for Ngaruroro River at Kuripapango (New Zealand). In the example, a minimum duration of four days is chosen. The distribution is clearly skewed towards higher values with a mean value of 8.4 days. The modal value is 6 days.

The two approaches for calculating recession characteristics, the MRC and the IRS method, are demonstrated below in a step-by-step manner using daily streamflow data from Ngaruroro River. The data cover the period 1963–1989.

1. In both methods, a fixed threshold level is chosen, namely, the starting point of the recession is set to be the first value below the Q_{70} threshold, at least two days after a peak flood discharge.

2. Longer duration segments commonly experience slower recession rates. The segments are therefore truncated at a given day so as to be of equal length. Figure 5.3 suggests that, for this river, the fixed length should be less than, or equal to, seven days (here, seven days are chosen) as there is a marked reduction in the number of segments for longer durations.

3. In the correlation method, the parameter C of the MRC is obtained by plotting pairs of Q_{t-1}, Q_t values in the same diagram before fitting a straight line (Figure 5.4). The values are derived from the set of recession segments selected following the criteria in step 1 and 2. The slope of the curve equals the recession rate as represented by k in equation 5.2. Here, k = 0.9602, which corresponds to a C value of 24.6 days (equation 5.3). By limiting the pairs of Q_{t-1}, Q_t values in the correlation plot to those below a fixed threshold and of a given duration, the variability encountered will be considerably less compared to using all pairs of $Q_t < Q_{t-1}$. It is therefore not necessary to consider envelope curves in this case.

4. In the IRS method, the parameter C of the recession curve is determined as the mean value of the C of individual segments. In our example, C_{mean} equals 26.6 days and as a measure of the variability the coefficient of variation is calculated,
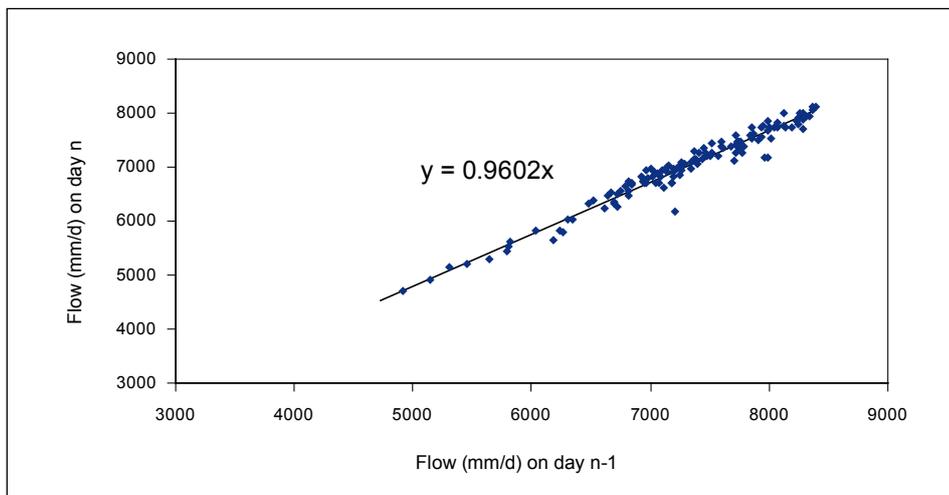
Figure 5.4
Recession rate
(k = 0.9602) determined
using the correlation
method for recessions of
7-day duration
(data from Ngaruroro
River in New Zealand)

C_{CV} = 0.92. The individual C values are obtained by fitting the recession equation to each selected recession segment using the criteria in step 1 and 2. This can be carried out using a programming tool or a spreadsheet function, for example in Excel.

5. Comparing the results of the two methods shows that the overall recession rate, C (in days), calculated using the MRC (24.6) and IRS method (26.6), corresponds well.

In the example above, the data used to determine the recession constant originate from recession segments of a fixed length. In low-flow forecasting (at-site analysis), on the other hand, long-duration recessions are the prime interest, and it is important to select the longest duration segments and an analytical expression that are able to model the lower end of the recession curve satisfactorily. Accordingly, more complex equations are generally required for this purpose. It is nevertheless important to account for the variability in the recession rate in the extreme lower range, by providing an estimate of the uncertainty in the forecasted low flow (section 11.2). An estimate of the uncertainty (for example, standard errors or confidence limits) can be determined by analysing the flow variability at a given number of days from the start of the recession forecast. In a regional study where the recession characteristics represent storage properties, it is the speed with which the low flow is reached that is important (Tallaksen, 1995). Accordingly, a simple expression is often sufficient to map regional differences, and both the IRS and MRC method can be applied using a fixed threshold level and recession length. In both cases, seasonal variations can

be accounted for by limiting the analysis to data from only the season of interest.

5.4   Low-flow statistics

5.4.1   Mean flow
The mean flow is one of the most commonly used statistics in hydrology and water resources planning. It can be estimated from a time series of gauged data by summing all daily discharges and dividing by the number of days in the record. It is normally calculated for complete calendar or hydrological years of data (section 3.2). It can also be calculated for specific months or seasons.

5.4.2   Ninety-five percentile flow: Q_{95}
This is one of the most common low-flow indices used operationally and is defined as the flow exceeded for 95 per cent of the time. It can be determined by ranking all daily discharges and finding the discharge exceeded by 95 per cent of all values. Chapter 6 describes in detail the 95 percentile exceedance discharge from the flow-duration curve. Q_{95} can also be derived from individual months, for groups of months or any specified periods. Other percentiles can similarly be derived from the flow-duration curve.

5.4.3   Mean annual minima: MAM (n-day)
Annual minima can be derived from a daily flow series by selecting the lowest flow every year and the mean of the minima calculated. Minima of different durations can be determined, with 1, 7, 10, 30 and 90 days being commonly used. The annual minima can be used to determine a distribution function for estimating the frequency or return period of low flows

(section 7.5). In temperate climates, the mean annual 7-day minima is numerically similar to Q_{95} for most flow records.

5.5   Operational applications

The BFI has been used primarily as a general index of catchment response. It has had its widest application in regional low-flow studies in the United Kingdom (Gustard and others, 1992), where it is now routinely calculated for over 1 000 gauged records published in the United Kingdom National Water Archive (CEH, 2003). The BFI has also been used to classify the hydrological response of soil types for regional flood studies (Boorman and others, 1995). Furthermore, it has been implemented as a general catchment descriptor for hydrological modelling (Chapter 9), as a tool for selecting analogue catchments, and for estimating annual and long-term groundwater recharge. The BFI has been used not only in the United Kingdom, but also in low-flow studies in mainland Europe, New Zealand, Southern Africa and the Himalayas. It has also had extensive use in Canada (Piggott and others, 2005), where it has been mapped in support of regional low-flow studies and used to map recharge and discharge zones, to investigate the impact of climate change on groundwater resources and also to relate flood response to soil type.

Recession indices are primarily used to give a lower bound to forecast (section 11.2) future flows 5, 10 or 30 days ahead. It is assumed that there is no significant effective rainfall contributing to streamflow during this period. This is often valid for catchments with a distinctive dry season, streams draining permeable catchments or, for example, in the dry season downstream of glaciers.

The mean flow provides an estimate of the total water resources available and is a key variable in all water resources assessment investigations. It is also used for initial investigations for run-of-river hydropower schemes when a percentage of the mean flow and the available head are used to give an estimate of the potential generating capacity of the scheme.

Low-flow statistics provide a valuable estimate of the conditions experienced during the dry season. For rapid assessment of the availability of water for abstraction in temperate regimes, simple flow statistics such as Q_{95} are often used to assess the amount of water available at low flows. For public water supply, a constant ab-

straction is often required, perhaps with seasonal variability. A second common application of both Q_{95} and the mean of the 7- or 10-day annual minima is that of irrigation scheme design. This involves estimating the potential area that can be irrigated by the supply river for schemes without storage. If there is a seasonal variability in irrigation demand, then flow statistics can be determined for specific months or groups of months. For preliminary design, Q_{95} is also used to assess the availability of water for the dilution of industrial or domestic effluents. Water quality models based on the rate and quality of the effluent and the flow and quality of the receiving stream are used to determine the frequency distribution of downstream water quality. Some of the above applications are described in more detail in Chapters 6 and 12.

References

Boorman, D.B., J.M. Hollis and A. Lilly, 1995: Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. IH Report No. 126, Institute of Hydrology, Wallingford, United Kingdom.

Brutsaert, W. and J.L. Nieber, 1977: Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resources Research, 13(3): 637–643.

Centre for Ecology and Hydrology (CEH), 2003: Hydrological Data UK: Hydrometric Register of Statistics 1996–2000, Wallingford, United Kingdom.

Gustard, A., 1983: Regional variability of soil characteristics for flood and low flow estimation. Agricultural Water Management, 6(2–3): 255–268.

Gustard, A., A. Bullock and J.M. Dixon, 1992: Low Flow Estimation in the United Kingdom. Institute of Hydrology Report No. 108, Wallingford, United Kingdom.

Hall, F.R., 1968: Base flow recessions – a review. Water Resources Research, 4(5): 973–983.

Hisdal, H., L.M. Tallaksen, B. Clausen, E. Peters and A. Gustard, 2004: Hydrological drought characteristics. In: Hydrological Drought Processes and Estimation Methods for Streamflow and Groundwater (L.M. Tallaksen and H.A.J. van Lanen, eds). Developments in Water Sciences 48, Elsevier B.V., the Netherlands, pp. 139–198.

Langbein, W.B., 1938: Some channel storage studies and their application to the determination of infiltration. Transactions, American Geophysical Union, 19: 435–445.

Nathan, R.J. and T.A. McMahon, 1990: Evaluation of automated techniques for base flow and recession analysis. Water Resources Research, 26(7): 1465–1473.

Piggott, A.R., S. Moin and C. Southam, 2005: A revised approach to the UKIH method for the calculation of baseflow. Hydrological Sciences Journal, 50: 911–920.

Tallaksen, L.M., 1987: An Evaluation of the Base Flow Index (BFI). Report Series in Hydrology No. 16, University of Oslo, Norway.

—, 1989: Analysis of time variability in recessions. In: FRIENDS in Hydrology (L. Roald, K. Nordseth and K.A. Hassel, eds), IAHS Publication No. 187, pp. 5–96.

—, 1995: A review of baseflow recession analysis. Journal of Hydrology, 165: 349–370.

6.   The Flow-Duration curve

6.1   Definition and derivation

The flow-duration curve (FDC) is a graph of river discharge plotted against exceedance frequency and is normally derived from the complete time series of recorded river flows. It is simple to construct and used in many different water resources applications over the entire range of river flows. The construction is based on ranking the data (normally daily discharge) and calculating the frequency of exceedance for each value. It effectively reorders the observed hydrograph from one ordered by time to one ordered by magnitude. The percentage of time that any particular discharge is exceeded can be estimated from the plot. Specific percentiles from the curve, for example, the flow exceeded for 95 per cent of the time, are often used. Comprehensive reviews of the FDC are given by Vogel and Fennessey (1994, 1995) and specifically in the context of low-flow hydrology in Hisdal and others (2004).

Figure 6.1 shows an example of the FDC for the Drammenselv at Fiskum in Norway. This FDC was determined using the following steps and an Excel spreadsheet:
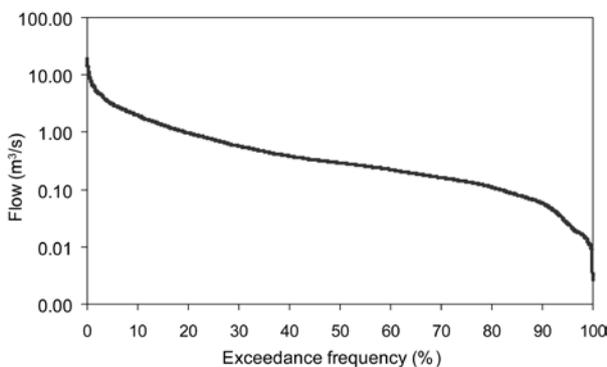
Figure 6.1 FDC for the Drammenselv at Fiskum in Norway

(a) Ten years of daily data are used. The total number of days and flow values, Q, are then 3653. Table 6.1 lists the first ten dates (first column) and corresponding flow values (second column);

(b) The FDC is constructed following the calculation steps given in the right-hand side of the table:
   (i)   The rank (i) (third column) of each value is calculated (using an automatic rank function in Excel) by sorting the values in descending order, where the ith largest value has rank i (that is, the highest discharge has rank 1 and the lowest rank 3653);
   (ii) The exceedance frequency EF_{Qi} is calculated as:
$$E_{Qi} = i/N$$

This gives an estimate of the exceedance frequency of the ith largest event. EF_{Qi} (fourth column) is the observed frequency when the flow, Q, is larger than the flow value with rank i, Q_i (Chapter 7 provides details of plotting position formulae);

(c) Tabulation of the FDC:
   (i)   Corresponding values of streamflow (Q in m³/s, second column) and exceedance frequency (EF_{Qi} in per cent, fourth column) are tabulated;
   (ii) The two columns are sorted by EF_{Qi} (using an automatic sort function in the spreadsheet);

(d) FDC plot: The sorted columns are then plotted (Figure 6.1). The discharge axis is logarithmic (a standard option in the spreadsheet), enables a wide range of flows to be plotted and ensures that the low-flow range is clear on the graph;

(e) Selected exceedance values: As an example, let us estimate the discharge corresponding to the 90 percentile (Q_{90}). This can be read from Figure 6.1. Alternatively, a sample of values in this range is shown in Table 6.2, and the 90 percentile flow value is estimated as 0.058 m³/s. If the required frequency is not given exactly, values can be obtained as the value of Q corresponding to the largest value of EF_{Qi} that is less than, or equal to, the required value of. EF_{Qi} Alternatively, if there are large differences between successive values, a linear interpolation can be used.

Table 6.1 Calculation of a daily FDC for Drammenselva at Fiskum in Norway			
Data (10-year series)		**Calculation of FDC**	
Date	Streamflow (m³/s)	Rank, i	Exceedance frequency EF_{Qi} (%)
1 Jan 1991	0.0083	3641	0.9967
2 Jan 1991	0.0095	3637	0.9956
3 Jan 1991	0.0081	3642	0.9970
4 Jan 1991	0.0056	3644	0.9975
5 Jan 1991	0.0039	3646	0.9981
6 Jan 1991	0.0019	3650	0.9992
7 Jan 1991	0.0027	3649	0.9989

Drammenselva at Fiskum has a distinct winter low-flow period because of precipitation being stored as snow. Table 6.1 shows that the first seven flows in January 1991 all have high exceedance frequencies and corresponding very low flows.

This chapter illustrates different methods and issues relating to the derivation of FDCs from a daily flow record. Example data series are used, and Table 6.3 provides summary information about their catchments. The record length required to determine FDCs with an acceptable sampling error will depend on the natural flow variability. In temperate climates, a 10-year period

Table 6.2 Extract of values corresponding to Q_{90}	
EF_{Qi} (%)	Q (m³/s)
89.98	0.0580
90.00	0.0579
90.00	0.0579
90.06	0.0578

or more is recommended. However, in most cases, it is better to estimate the FDC based on one or two years of record rather than to estimate it based on regional hydrological models. It is nonetheless important to be aware of the fact that the uncertainty in the FDC will decrease as the record length increases.

6.2 Standardization

To improve the readability of the curve, discharge is usually plotted on a logarithmic scale (Figure 6.1) and in some countries a normal probability scale is used for the horizontal frequency axis (Figure 6.2). If the logarithms of the daily mean flow were normally distributed, they would plot as a straight line with this log-normal transformation. This is approximately the case for many flow regimes, and such a scheme can enhance the ease of interpreting the curve and comparing curves from different catchments or different time periods. If log-normal graph paper is not available, it is possible to construct the curve by transforming the exceedance frequencies using the standard normal probability distribution function.

The FDC is frequently used to compare the regime of different basins and this is made easier by discharge standardization by the ratios of the average or median flow, or as flow per unit area. For example, Figure 6.2 shows the FDCs of two contrasting British rivers with the discharge on the vertical axis expressed as a percentage of the mean flow. The shape of the FDC reflects the combined effect of physiographic and climatic influences on river flow, and hence the catchment response. A time series with low variability is reflected in a flat curve typical of flow from a permeable catchment (Figure 6.2, Lambourne), or one with a strong regulatory influence caused by lake storage.

Table 6.3 Catchment and discharge characteristics for catchments with FDCs in Figures 6.1–6.4					
River	Station name	Area (km²)	Average annual precipitation (mm)	Mean flow (l/s/km²)	Q_{95} (l/s/km²)
Drammenselva (Norway)	Fiskum	50	800–850	15.8	0.5
Nigardselva (Norway)	Nigardsbrevatn	66	2 000–4 000	96	2.1
Honokohau, Hawaii (USA)	Maui	11	na	98	31
Lambourne (UK)	Shaw	234	805	7	2.2
Arroyo Seco, California (USA)	Soledad	632	800–865	8	0
Beult (UK)	Style Bridge	277	690	7	0.2
Måna (Norway)	Møsvatn	1 498	800–1 000	33	1.1

na: not available

A curve with a steep gradient has a high variability of daily flows and is typical of an impermeable catchment with little storage and a quick response to rainfall (Figure 6.2, Beult).

Flow [%MF]
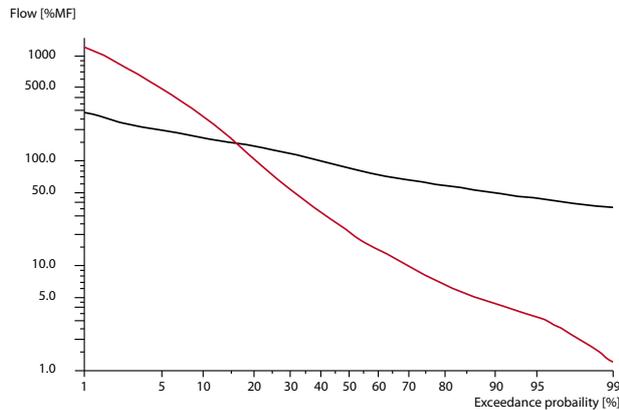
Figure 6.2 FDCs for contrasting flow regimes; Lambourne (black): permeable catchment; Beult (grey): impermeable catchment (Source: WHS HydroTools)

Figure 6.3 gives examples of FDCs from different climatic regions (Chapter 4). The Honokohau River at Maui (Hawaii) is in the tropics with a warm and humid climate where convective precipitation dominates and there is no distinct dry season. The FDC shows that this river is perennial, has a rather large variability in river flows and high low-flow values. For the temperate summer dry climates, for example, the Arroyo Seco at Soledad, California, precipitation shows high interannual variability, and in some years the river may run dry for several months. This is reflected in the steep FDC showing that about 15 per cent of all days have zero flow. The River Lambourne gauged at Shaw, in the United Kingdom, is located in a temperate maritime climate without a distinct dry season. Despite having very low effective rainfall in the summer due to high evaporative losses, the FDC shows that there is little variability in the streamflow. This is because summer low flows are supported by the outflow from a major aquifer maintaining base flow.

Nigardselva at Nigardsbrevatn in Norway has a cold climate with no distinct dry season. The catchment has 75 per cent glacier coverage and, following a snowmelt flood in the early summer, melt water from the glacier contributes considerably to the late summer flow. The FDC is rather steep, reflecting high-flow variability with high snowmelt floods and low-flow in the winter when precipitation is stored as snow and ice.

The FDC can also be valuable when studying the effect of anthropogenic influences in a catchment. Figure 6.4 shows the FDCs derived from the observed and naturalized (section 3.3.4) flow series downstream of Møsvatn in Norway, which is regulated for hydropower production. The anthropogenic impacts are large: floods are reduced, and for more than 80 per cent of the time the flow varies between only 20 and 80 m³/s; but, in this case low flows are not substantially changed.

Comparison of FDCs is also useful for selecting analogue catchments (section 9.2). If the FDC based on one or two years of record corresponds well with the FDC of a nearby catchment with a long and high-quality record, it can be assumed that the catchment and flow characteristics of the two drainage areas are similar.
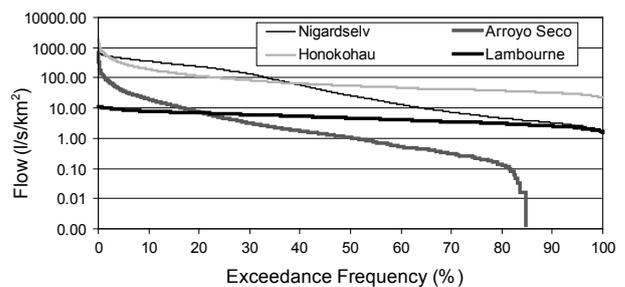
Figure 6.3 FDCs for different river-flow regimes
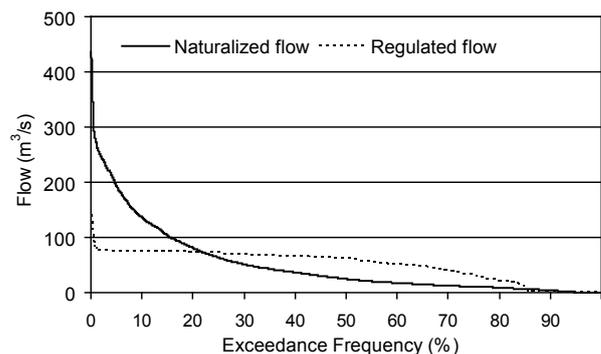
Figure 6.4 FDCs for the flow from Møsvatn in Norway; naturalized flow (solid line) and regulated flow (dotted line)

6.3   Durations and seasons

In the examples given in 6.1 and 6.2, the FDC is based on daily data. For some applications, it may be of interest to estimate the proportion of, for example, 10-day periods when the average discharge is greater than a

certain value. These curves can be determined by running a moving average filter of the appropriate duration through the series prior to constructing the FDC. A range of different durations, for example 7, 10, 30, 60 days, can be used. The longer the averaging period, the less steep the FDC, and this smoothing effect will be greatest for the most variable hydrographs. Although FDCs based on average daily flows are used most commonly, it is possible to construct them from mean monthly or mean annual flow data. Mean daily data will have much steeper curves than those derived from longer time resolution data. For low-flow investigations, curves based on monthly or annual mean flows are less useful, because the extreme flows are lost in the averaging process.

FDCs are normally derived from the total period of record, but this does not provide information on the year-to-year variability of curves, or the uncertainty in estimating the FDC from a given record length. Vogel and Fennessey (1994) suggest constructing separate FDCs for each year and then computing the median flow associated with each exceedance probability. The result is an FDC less influenced by the period of record. Based on these annual FDCs, it is also possible to construct confidence intervals and assess the uncertainty of the estimated median FDC. FDCs may be determined for particular periods (defined by days, months or a group of months) of the year. For example, for irrigation abstraction, the growing season for a specific crop type may define the most appropriate period for analysis.

6.4   Percentiles as low-flow indices

Low-flow percentiles from the FDC are often used as key indices of low-flow (Chapter 5), for example, the 95 percentile flow, or Q_{95}, the flow that is exceeded for 95 per cent of the period of record. This discharge will be exceeded on average for 18 days per year and is a useful general index of low-flow. The percentile used as a low-flow index depends very much on the type of river being studied.

For perennial rivers, Q_{90} or Q_{95} are typically applied. In semi-arid or polar regions, a larger percentage of zero values is often found in recorded flow series. If, for example, the river has zero flows for 50 per cent of the time, useful percentiles with non-zero discharges will be much higher, for example Q_{40} or Q_{30}. If the difference in discharge between different percentiles, for example, Q_{95}, Q_{90} and Q_{70}, is small, this indicates a flat FDC typical of a river with a low variance in daily flows.

6.5   Applications of the FDC

6.5.1   Water resources management in England and Wales

The FDC is a key tool for the sustainable management of water resources (Figure 6.5). The management of abstractions normally requires estimating the FDC from gauged data or, at ungauged sites, from statistical or simulation models (Chapter 9) of the following:

(a)   The natural regime;
(b)   The historical regime which includes the impact of abstractions and discharges returned to the river;
(c)   A target regime that maintains the ecology of the river at an acceptable level.

Determining these FDCs (Figure 6.5) enables the regulatory authority to estimate an "abstractable volume" and a "hands-off flow". The abstractable volume is the maximum volume of water that can be abstracted from the river without resulting in an unacceptable deterioration in instream ecology or an adverse impact on downstream water users. The hands-off flow is the discharge at which abstraction must cease. For example, in England and Wales, the management of abstractions is legally binding and controlled through a licence to abstract water, which limits the total amount of water abstracted, the maximum rate and the time frame (usually seasonal).
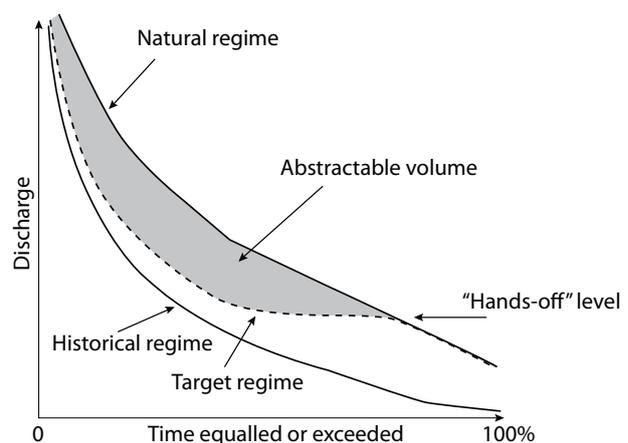

Figure 6.5 *River abstraction concepts based on the FDC*

Water resources management at the catchment level in England and Wales is undertaken by the Environment Agency through the Catchment Abstraction Management Strategies (CAMS), as reported by the Agency in 2002.

There are 129 CAMS areas in England and Wales. Each catchment is divided into Water Resource Management Units, comprising the surface waters upstream of a specified assessment point and the associated Groundwater Management Units. With regard to the ecology of a river, an assessment is made of the sensitivity of each river reach to abstraction. A naturalized FDC for the river is produced and used with an "environmental weighting" for the river in order to determine the ecological river flow objective (ERFO), in terms of a target FDC. The methodology seeks to retain a range of flows, rather than a single minimum flow. Comparing the actual FDC (assuming that the maximum permitted licensed abstractions are occurring) with the actual abstractions (usually much less), allows the river to be divided into one of four categories: water available, no water available, overlicensed or overabstracted. (further details are given in the case study in Chapter 13). The difference between the naturalized FDC and the ERFO curve provides a basis for estimating the amount of water that can be licensed for abstraction.

6.5.2 Public water supply

The requirements for low-flow information for water supply normally fall into two categories: those with reservoir storage, and those without. For river systems without storage, the FDC is commonly used for the preliminary design of simple abstraction schemes in order to estimate the percentage of the time that a given abstraction can take place. Following an initial feasibility study, a more detailed simulation of the hydrology and resources system will be carried out. However, for small local abstractions, the FDC may be sufficient for creating the final design.

6.5.3 Agriculture

The primary application of water for agricultural use is to supply water for irrigation. A key element of the planning for proposed schemes is an assessment of water availability for defining the potential area that can be irrigated by the supply river. The assessment is carried out by identifying the critical periods of the year, as determined by the seasonal irrigation demand for different crops. Irrigation demand is calculated for each period and crop type from rainfall, evaporation and crop water requirement data. To account for water losses associated with water supply inefficiencies, irrigation demand is multiplied by an efficiency factor to calculate the diversion requirement.

These are calculated for each phase of the cropping calendar, normally expressed as a diversion requirement

per hectare of irrigable crop. Seasonal FDCs can then be used to compare potential demand with available water.

6.5.4 Fish farming

In England and Wales, the abstraction of water from rivers for fish farming requires a licence. This often involves the analysis of FDCs at gauged and ungauged sites to determine how much water can be abstracted. Although flow-frequency analysis may be used to determine a licence, this is normally stated in flow units. This helps the abstractor to understand and comply with the licence. Although the following is an example of a licence to abstract water for a fish farm, the principles apply to licences for other purposes. In the given example of a fish farm (Figure 6.6), the licence states the following:

(1)   When the flow is at, or greater than, $0.130 \, \text{m}^3/\text{s}$, a minimum flow of $0.030 \, \text{m}^3/\text{s}$ shall remain in the watercourse below the abstraction point.

(2)   When the flow is less than $0.130 \, \text{m}^3/\text{s}$, a minimum flow of $0.010 \, \text{m}^3/\text{s}$ shall remain in the watercourse below the abstraction point.

These conditions are set once the environmental impact of the abstraction and the potential impact on downstream abstractors have been considered.
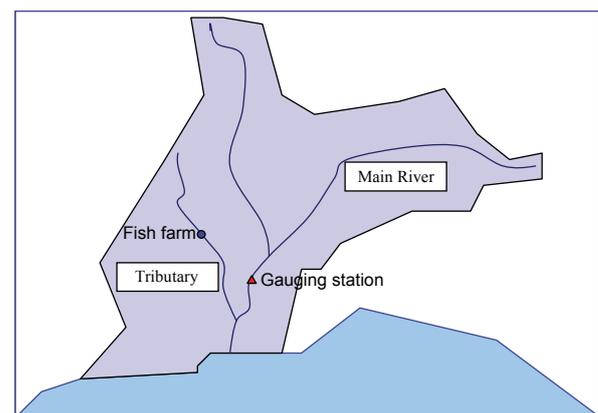
Figure 6.6 *Location of fish farm and gauging station*

Having set the licence conditions, a second issue is that of ensuring that the minimum flow is always maintained below the abstraction point during the two different flow conditions. It is prohibitively expensive to install a gauging station at this (and many other) abstraction location. The gauging station discharge equivalent to a flow of $0.130 \, \text{m}^3/\text{s}$ at the fish farm was calculated by

relating spot flow measurements (Chapter 9) at the fish farm to the measured discharge at a nearby gauging station (Figure 6.6). The FDC at the gauging station was used to ensure that an adequate range of flows between Q_6 and Q_{60} was measured at the fish farm. The spot flow measurements at the fish farm were then regressed against the daily mean flow at the gauging station. This enabled the prescribed flow at the fish farm to be converted into an equivalent flow at the gauging station, and this was used as a further condition of the licence that read:

"It should be noted that a flow of 0.130 m³/s [at the abstraction point] is equivalent to a flow of 1.454 m³/s in the river at the Agency's Gauging Station. The Licence Holder shall request river flows at the Gauging Station from the Agency at relevant flow levels to ensure compliance with the conditions (1) and (2) above."

6.5.5 Water quality

The FDC is also used to estimate the dilution of domestic or industrial discharge destined for a river. Legal consent is frequently required to discharge a pollutant into a river. Water quality models based on the rate and quality of the discharge and the flow and quality of the receiving stream are used to determine the frequency distribution of downstream water quality. The cumulative distribution function of receiving river flows or Q_{95} are the most commonly used flow variables to simulate downstream water quality distributions and to determine the constraints on a discharge consent. This planning or design application contrasts with the real-time application of assessing the impact of specific pollution incidents, for example, an oil discharge following an industrial accident. Flow rates are then required to estimate the dispersion rate and travel time. The latter is required to warn public water-supply abstractors downstream to stop abstracting.

6.5.6 Hydropower and conventional power

Small-scale hydropower schemes generally have no artificial storage and thus rely entirely on the flow conditions of the river to generate electricity. In small-scale hydropower design, the conventional method for describing the availability of water in a river is the FDC. The design must accommodate fluctuating power demands and protection of downstream abstractors' interests and ecosystem health. A case study of small-scale hydropower design is presented in detail in Chapter 12. The FDC is also used in the design of more complex large-scale hydropower systems involving reservoirs, lake impoundments and major river diversions between catchments.

In Norway, the Norwegian Water Resources and Energy Directorate, an agency of the Ministry of Petroleum and Energy, is responsible for licences to regulate rivers and build hydropower plants. Important hydrological information that must be included in a licence application concerns the low-flow conditions, including estimates of Q_{95} for the summer season (1 May–30 September) and winter season (1 October–30 April). As an example, the Directorate received a request for hydrological information on the River Flisa from a hydropower developer. There was a daily flow record for the period 1917–2005 from a gauging station at Knappom (catchment area of 1625 km²). The catchment has a cold climate with two low-flow periods: one in the winter caused by precipitation being stored as snow, and one in the summer caused by low net rainfall (precipitation minus evaporation). There is a snowmelt flood in the spring and a second high-flow period in the autumn caused by high rainfall levels. The FDCs for the summer and winter season were calculated separately based on the whole period of record (Figure 6.7). The Q_{95} for the winter period (2.2 l/s/km²) was lower than Q_{95} for the summer period (3.0 l/s/km²). These values were used to determine the residual flow requirements in the licence.

The FDC is also used to estimate the frequency of the availability of cooling water for large thermal (coal, oil, gas, nuclear) power stations. Low-flow design seeks to ensure that sufficient cooling water is available and that the increase in downstream water temperature, due to the return of warmer water to the river, does not damage aquatic ecosystems.
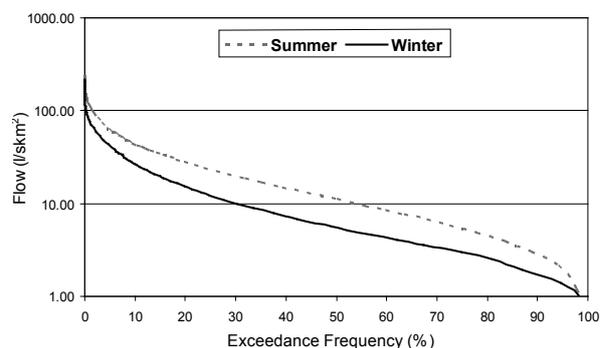
Figure 6.7 FDCs for the summer season (dotted line) and winter season (solid line) for Flisa at Knappom in Norway

6.5.7 Navigation

River systems provide an important transport facility for both industrial and leisure navigation. Navigation is interrupted during periods of low-flow because the

water depth in natural river systems cannot accommodate vessels and the water available is insufficient to supply the upstream and downstream movement of vessels through locks. If the discharge at critical navigation points is converted into a water depth, then the FDC can be used to estimate the percentage of time that the river is below a given depth. This enables the frequency of interrupted navigation for different sized vessels to be estimated and proposals can be made for improved channel design or dredging.

6.5.8   Ecosystem protection and amenities

Ecosystems are at their most vulnerable at times of low-flow because of a reduction in habitat availability, water temperature extremes, reduced dissolved oxygen, a deterioration in water quality (caused by reduced effluent dilution) and habitat fragmentation (caused by natural or artificial barriers to fish movement). A range of modelling techniques can be used for predicting and mitigating the impact of low flows on freshwater ecology. They range from simple methods based on low-flow indices often known as "standard-setting" methods to more complex habitat models. Percentiles from the FDC can be used to set a minimum flow in a river so that, when the discharge falls below this level, abstractions should cease (or be reduced). In addition to supporting complex

ecosystems, rivers are natural assets for sport and recreational activities, such as canoeing, fishing, ornithology and walking. Ensuring adequate water depth and/or velocity, even when flow rates are very low, can artificially enhance the natural attraction of such sites. The impact of all the above-mentioned abstractions on ecosystems and amenities would be a key component of a water resources study.

References

Hisdal, H., L.M. Tallaksen, B. Clausen, E. Peters and A. Gustard, 2004: Hydrological drought characteristics. In: *Hydrological Drought Processes and Estimation Methods for Streamflow and Groundwater* (L.M. Tallaksen and H.A.J. van Lanen, eds). Developments in Water Sciences 48, Elsevier Science Publisher, the Netherlands: 139–198.

Vogel, R.M. and N.M. Fennessey, 1994: Flow duration curves I: New interpretation and confidence intervals. *Journal of Water Resources Planning and Management*, 120(4): 485–504.

— , 1995. Flow duration curves II: A review of applications in water resources planning. *Water Resources Bulletin*, 31(6): 1029–1039.

7.   Extreme value analysis

7.1   Introduction

Most statistical methods are concerned with what happens in the centre of a distribution and seek robust methods that can adequately describe a dataset without being overly influenced by extreme values. There are situations, however, where the extreme values are the prime interest, as is the case for minima values in low-flow analysis. Estimates of the probability of occurrence of low-flow events can be derived from historical records using frequency analysis. The chapter starts by presenting two example Australian catchments and their low-flow data (section 7.2). This is followed by a general introduction to the concepts of frequency analysis (section 7.3), which involves the definition and selection of the type of hydrological event and extreme characteristics to be studied (section 7.4), the choice of probability distribution (section 7.5), the estimation of distribution parameters (section 7.6) and, lastly, the calculation of extreme quantiles or design values for a given problem (section 7.7).

The procedure is demonstrated using the Weibull distribution for estimating the T-year event for the two example catchments (section 7.8). The chapter closes with a brief introduction to regional frequency analysis (section 7.9). For a more general and detailed presentation of frequency analysis in hydrology, the reader is referred to Haan (1977), Stedinger and others (1993) and Tallaksen and others (2004). Frequency analysis of low flows is more specifically covered in the low-flow review by Smakhtin (2001) and the Institute of Hydrology (1980) report on low-flow prediction at the ungauged site.

7.2   Example data for at-site low-flow frequency analysis

In this chapter, two gauging stations from Eastern Victoria in Australia, namely, the Nicholson River at Deptford (Station 223204) and Timbarra River at Timbarra (Station 223207), are used to illustrate the calculation procedure for at-site low-flow frequency

Station 223207

Station 223204
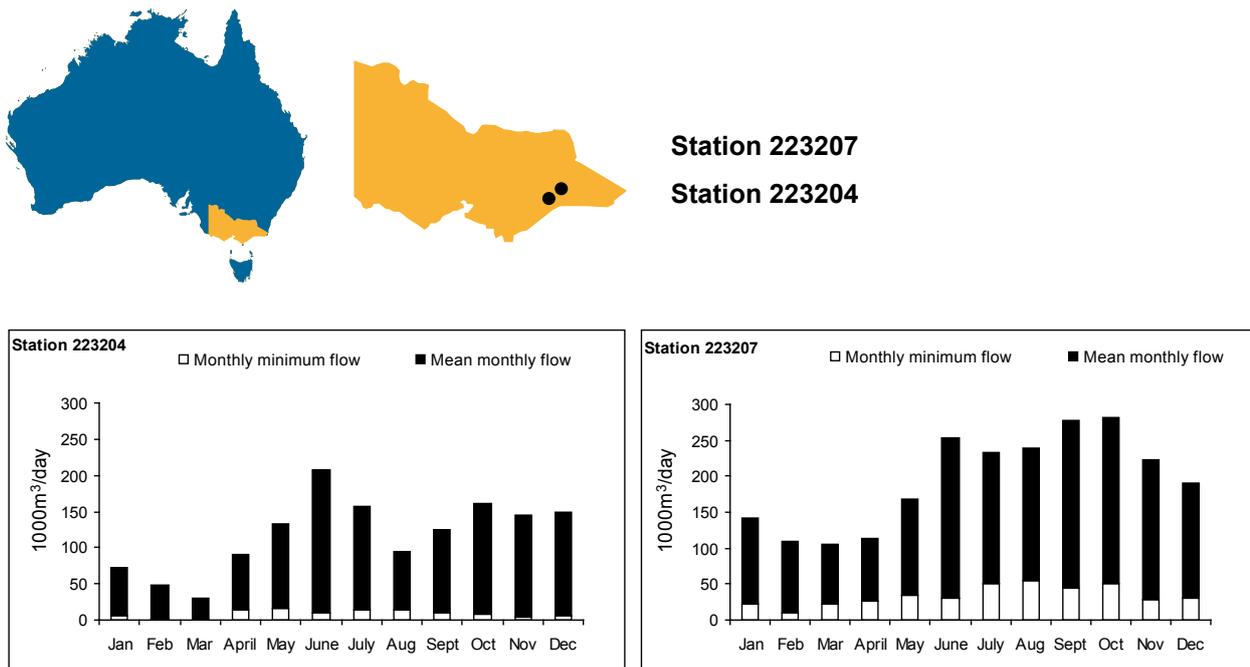
Figure 7.1 Location of example catchments in Australia and their hydrological regime

analysis and have catchment areas of 287 km² and 205 km², respectively. Both catchments are located at altitudes higher than 500 m.a.s.l. and are mainly covered by tall forest trees. The geology underlining the catchments are known as Palaeozoic igneous and metamorphic rocks.

The location of the two catchments is shown in Figure 7.1, along with plots depicting the hydrological regime of each station. The seasonal variation in mean monthly flow and monthly minimum flow shows that the lowest flows are found in late summer (January–March) for both stations. In our example, annual minima 7-day (AM(7)) series (section 7.4.1) are determined for a hydrological year starting on 1 August. Only Station 223204 experiences zero values (twice in the observed record). The derived low-flow values are listed below for Station 223204 and 223207, covering the period 1963–95 (n = 34 years) and 1959–83 (n = 25 years), respectively. Values are in 1 000 m³/d (equivalent to m³/s if divided by 86.4).

Station 223204: 8.0, 13.0, 2.0, 2.7, 9.1, 0.0, 0.7, 21.6, 35.1, 12.7, 1.3, 9.1, 26.0, 22.7, 21.3, 7.9, 23.0, 6.0, 3.1, 4.1, 0.0, 4.9, 2.3, 12.4, 4.4, 2.1, 3.1, 7.6, 9.0, 9.0, 20.4, 13.6, 3.3, 10.3

Station 223207: 27.3, 38.0, 72.9, 53.6, 45.7, 37.0, 21.7, 36.6, 43.1, 12.6, 20.7, 66.7, 76.6, 53.1, 15.7, 66.6, 78.0, 53.1, 62.6, 40.7, 51.6, 23.1, 23.4, 23.0, 6.0

7.3   Introduction to frequency analysis

Statistics are concerned with methods (estimators) for making conclusions about the properties of the population (true value) based on the properties of a sample drawn from the population. A given characteristic, for example, the mean value, computed by an estimator is called a sample estimate or statistic and is commonly denoted using the hat symbol (^).

Let X denote a random variable, and x a real number. The cumulative distribution function (cdf):

$$F_X(x) = \Pr\{X \le x\} \tag{7.1}$$

designates the probability P that the random value X is less than or equal to x, namely, the non-exceedance probability for x. The probability density function (pdf) is the derivative of the cdf and describes the relative likelihood that the continuous random variable X takes on different values:

$$f_X(x) = \frac{dF(x)}{dx} \tag{7.2}$$

The relation between f(x) and F(x) is shown in Figure 7.2, where F(x), the non-exceedance probability, equals the area under the curve for X ≤ x. The total area covered by f(x) is 1.

An exploratory data analysis, including a graphical display of the data, is generally recommended before performing a statistical analysis, as it might reveal and help to explore important characteristics of the time series. In Figure 7.3, the AM(7) flow values (in m³/d) for Station 223204 are plotted for each year in the record (data from Figure 7.2). The plot provides information on extreme values in the sample and their time of occurrence, possible trend in the series, spurious data, and so on. Although no clear trend can be identified in the data series in Figure 7.3, a sequence of wet and dry periods can be observed, that is, rather high low flows are found in the 1970s, indicating wet conditions as compared with the dryer values in the 1960s and 1980s.
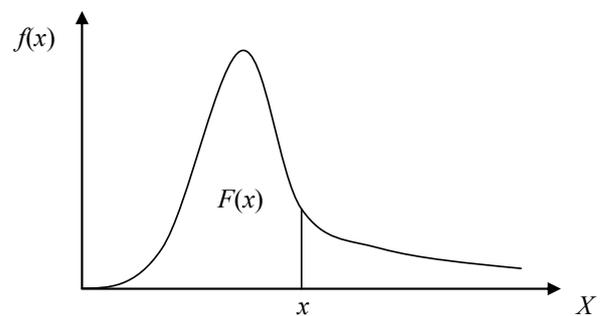
Figure 7.2 *Probability density function, f(x), and non-exceedance probability, F(x)*

The range of values observed within a sample can be displayed in a histogram, a plot of bars showing the fraction of the total sample which falls into different class intervals. The histograms of the low-flow series from the two Australian catchments reveal clear differences between the two stations (Figure 7.4). Station 223204 experiences zero values and the series is skewed towards higher values as compared with Station 223207, which has a more symmetrical distribution and thus lower skewness. Summary statistics such as the mean, standard deviation and skewness can be used to describe samples of a population (section 7.6.1). If the true distribution of the population is known, the sample statistics can be compared to the theoretical values (section 7.8).
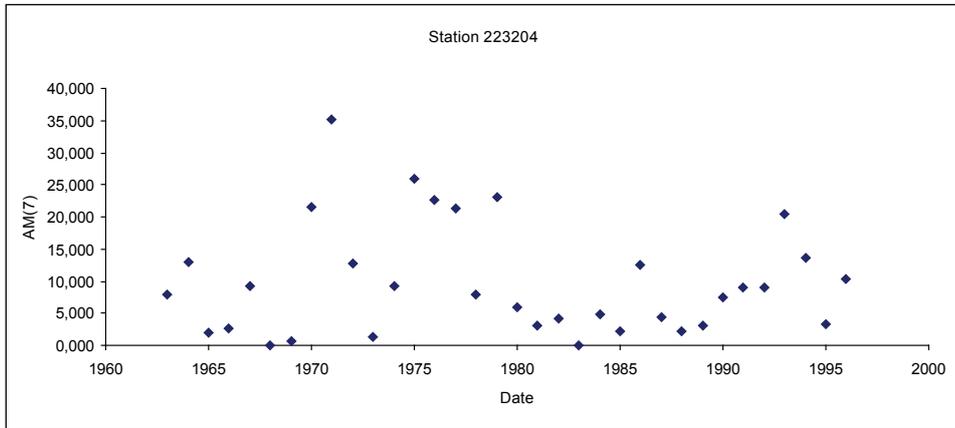
Figure 7.3
Time series of the AM(7)
flow for the Nicholson
River (Station 223204)

A probability plot is a special form of the quantile plot or flow-duration curve (section 6.1). The values are ranked similarly to the quantile plot method; however, instead of plotting the observed frequencies, the observations are now assumed to be independent and a probability is assigned to each value by using plotting positions (Cunnane, 1978).

Generally, plotting positions that attempt to achieve unbiased quantile estimates for different distributions can be written as follows:

$$p_i = i{-}a/(n{+}1{-}2a) \tag{7.3}$$

where p_i is a plotting position that gives an estimate of the non-exceedance probability of the ith smallest event and n the total number of events. Since it is not known if the largest or smallest population value is contained in the sample, plotting positions of 1 and 0 should be avoided.

Figure 7.4 Histogram of the AM(7) flow for the Nicholson
River (top) and the Timbarra River (bottom)
(values are in 1 000 m³/d)
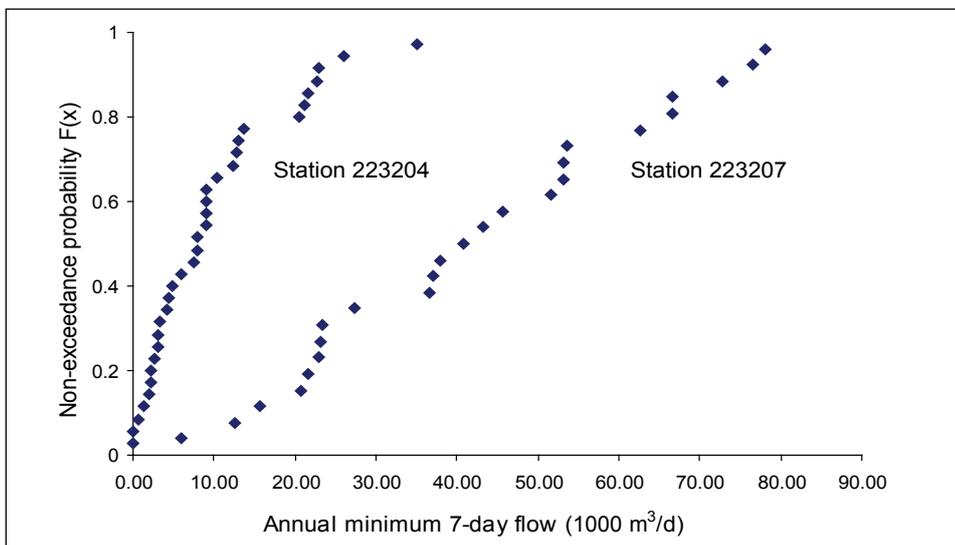
Figure 7.5
Probability plot
(empirical quantiles) of
the AM(7) flow for the
Nicholson River (Station
223204) and the Timbarra
River (Station 223207)

A well-known example is the Weibull formula (a = 0 in equation 7.3), which gives an unbiased estimate of the non-exceedance probability for all distributions and is therefore often recommended (for example, Haan, 1977; Stedinger and others, 1993). In the probability plot in Figure 7.5, the Weibull formula is used to determine the empirical distribution of the sample low-flow series of the Australian catchments. Probability plots are commonly used to compare sample data (empirical quantiles) to a theoretical distribution (distribution quantiles) as demonstrated in 7.8.

7.4   Extreme value selection

For frequency analysis purposes, the data must be independent and identically distributed. Identically distributed (or homogeneous) implies that the data selected should be from the same population, that is, the same generating processes have caused the extreme events. Independent events have no serial correlation (short-range dependence) or long-term trend in the time series (stationary flow regime). The presence of serial correlation in the time series is often referred to as persistence and occurs as a result of a memory in the hydrological system caused by large storages, such as extensive groundwater reservoirs or lakes. Persistence influences precision in the estimated statistics because the series contains less information as compared with a series of independent observations (for example, Tallaksen and others, 2004). Time series that are independent and identically distributed have the same population characteristics independently of time, that is, there is no seasonality in the series.

A pronounced seasonality implies that different types of weather conditions and hydrological processes dominate in different seasons (section 4.3). For example, in snow- and ice-affected regions, although low streamflow may occur during the winter and summer, it will be caused by different processes, that is, the data are non-homogenous. If the data can be divided into separate subsets, such as by calendar date, one extreme value series can be obtained for each season (process), and a frequency analysis can be performed for each series separately. Alternatively, a mixture of two distributions may be applied; however, moment expressions for mixed distributions tend to be complicated (Hosking and Wallis, 1997). A simple plot showing the time of occurrence of the extreme events selected for analysis can be useful to identify seasonal patterns, as demonstrated in Figure 7.6 for Station 223204. In this river, the majority of events occur during the summer months (December to

March), but the lowest flow can occur at any time of the year. There is, however, no need to split the events by season given that they originate from the same cause. Seasonal calculations are typically needed in regions with a seasonal snow and ice influence, as well as in regions with a marked wet and dry season (for example, monsoon climates). The low-flow time of occurrence will then be distributed in one or two clearly defined seasons.
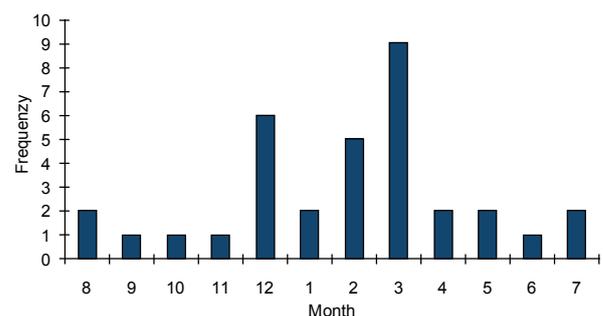
Figure 7.6 *Time of occurrence of the AM(7) flow for the Nicholson River (Station 223204)*

7.4.1   N-day minima

The most common approach to selecting extreme events from a time series is the annual minimum or maximum series (AMS) method. The AMS method is a special case of the block minima (maxima) model, which selects the smallest (largest) events within each time step, Δt. In the AMS, the block size selected is one year. Alternatively, it is possible to select the r-smallest (independent) events in each time step of equal size (block), for example, the two smallest events each year or every two years. However, the assumption of independent events argues for the use of a block size of at least one year due to the role of catchment storages in sustaining low-flow periods. An evaluation of the use of different block sizes in the extreme value modelling of maximum values can be found in Engeland and others (2004), whereas applications for low-flow values are not known and therefore not dealt with further in this chapter.

Traditionally, AM values have been selected for low-flow frequency analysis, that is, the lowest value is extracted for each hydrological year in the record. The hydrological year should be defined such that the low-flow season is not split between years. In the northern hemisphere, the calendar year is often used to select the AM flows as the low-flow period commonly occurs in late summer, namely, July–August. In our example, the

hydrological year is defined to start on 1 August as the catchments are located in the southern hemisphere, where the summer covers the December–February period (Figure 7.6).

The minimum values can be averaged over different durations to produce AM(n-day) series. The derived time series are the result of passing an n-day moving average through the daily data. Although it is common practice to consider 7, 10 or 30 days, values as high as 365 days have been reported (Institute of Hydrology, 1980). It is, however, important to avoid dependency (autocorrelation) in the time series when long averaging intervals are used. The autocorrelation depends on the averaging interval and the memory in the hydrological system, and large storages can cause even the AM(1) values to be correlated. In this chapter, the time series of the AM(7) flow are used for demonstration.

7.4.2 Censored series

Intermittent rivers regularly dry up during the dry season and the number of zero values can be considerable, particularly in semi-arid regions. Zero flows may, however, also occur during the dry season in temperate regions, particularly in quickly responding (headwater) catchments, karstic environments or during the winter in catchments affected by snow and ice (section 4.3). Care should be taken as streamflow may be recorded as zero for several reasons: the river has run dry, the discharge is below a recording limit, or missing observations are recorded as zero (section 3.2).

A conditional probability model is recommended for frequency analysis at sites whose record of AMS contains zero values (Stedinger and others, 1993). The parameter p0 describes the probability that an observation is zero (no flow), and a cdf, G(x), is fitted to the non-zero values of X. The unconditional cdf, F(x)*, for any value x > 0, is then:

$$F(x)^* = p_0 + (1 - p_0)G(x) \qquad (7.4)$$

The AM series may also contain events from rather wet years which might not be considered to belong to the extreme low-flow sample. A break in the probability plot of the AM n-day series has been reported accordingly (Institute of Hydrology, 1980; Nathan and McMahon, 1990). This problem can be addressed by choosing the r-smallest events in each time interval of equal size (block), for example, the smallest event (r = 1) in two years. Alternatively, an upper level or threshold can be introduced, below which only "true" low-flow values

are selected (censored series). In both cases, the proportion of "high" low-flow values will be reduced, but the sample or series will contain fewer values and thus less information. A truncated Weibull distribution was proposed by Gottschalk and others (1997) for samples determined with a constant upper threshold. Kroll and Stedinger (1996) suggested replacing the censored data with the threshold value as this resulted in less bias than discarding the data. Another option is to use LH- or LL-moments, which is a generalization of L-moments (section 7.6.2) developed to give more weight to the higher (Wang, 1997) and smaller values, respectively, in the sample (Durrans and Tomic, 2001; Bayazit and Önöz, 2002). LH-moments have also been used within low-flow analysis to fit the generalized extreme value (GEV) distribution (section 7.5) to negatively transformed minima series (Hewa and others, 2007). The method thus reduces the influence of rather wet years in a low-flow sample, but is sensitive to the size of the subsample selected.

The AM series may contain both zero values (zero-flow years) and years without events (non-drought years), and these values need special consideration as they represent the dry and the wet range of the observations, respectively. The conditional probability model and the plotting position method are considered to be simple and reasonable procedures when the majority of years (> 25 per cent) have observations (Stedinger and others, 1993). In arid and semi-arid regions, rivers are often intermittent or ephemeral (section 4.3) and the AM values may nearly all be zero. Under such circumstances, a traditional frequency analysis of AM flow is not applicable.

7.5 Distribution functions

Hydrological design may require extrapolation beyond the range of observations. This can be achieved by fitting a distribution function to the sample. There are, however, few observations in the tail of the distribution, which contains the extreme events. Estimates of events with high return periods will therefore depend on the behaviour of the tail of the fitted distribution. The prediction of return periods that do not greatly exceed the length of hydrological records is less sensitive to the choice of distribution function. The distribution functions presented in this chapter have been chosen based on their suitability to model minimum streamflow values. An extensive overview of distribution functions for low flows (minimum values) and hydrological drought (expressed as maximum values) is given in Tallaksen and

others (2004). It includes expressions for the pdf, the cdf, the extreme quantiles x_p or x_T, product moments (P-moments) and L-moments, and procedures for parameter estimation using P-moments, L-moments and maximum likelihood.

The GEV distribution is a general mathematical form that encompasses the three types of limiting distributions (Coles, 2001). Following the Fisher-Tippett theorem or limit laws for maxima (Fisher and Tippett, 1928), the GEV distribution can be defined by:

$$F_X(x) \;=\; \exp\left\{-\left[1 \;-\; \frac{\kappa(x-\xi)}{\alpha}\right]^{1/\kappa}\right\} \qquad (7.5)$$

The model has three parameters: a location parameter, ξ, a scale parameter, α, and a shape parameter, κ, which controls the tail of the distribution (Figure 7.7). When $\kappa = 0$ it reduces to the Gumbel distribution (EV I); for $\kappa < 0$ it equals the Fréchet-type distribution (EV II); and for $\kappa > 0$ it equals the Weibull-type distribution with a finite upper bound (EV III). The three types of extreme distributions can be compared on a Gumbel probability plot, which plots the observations (x) against the Gumbel reduced variate, y, where $y = -\ln(-\ln F(x))$. A reduced variate, y, substitutes the variable x in the expression for F(x) and is linearly related to x (here, $y = (x-\xi)/\alpha$). This implies that the Gumbel distribution (EV I) will plot as a straight line and EV II and EV III as curved lines (Figure 7.7).

The EV III distribution has a parent distribution that is bound in the direction of the desired extreme. If X is EV III distributed, –X is Weibull distributed, and the Weibull distribution can be fitted using the parameter expressions for the GEV distribution applied to –X. The Weibull probability distribution for minimum values is given as:

$$F(x) = 1 - \exp\left[-\left(\frac{x-\xi}{\alpha}\right)^{\kappa}\right] \qquad (7.6)$$

which for $\kappa = 1$ equals the exponential distribution. The value of ξ (lower bound) should be greater than, or equal to, zero. A two-parameter Weibull distribution (Weibull, 1961) is the EV III distribution for minima bound below by zero ($\xi = 0$). The flexibility of the Weibull distribution, its theoretical base and the fact that it has a lower bound has made it a favourite choice in low-flow studies around the world (Tallaksen, 2000).
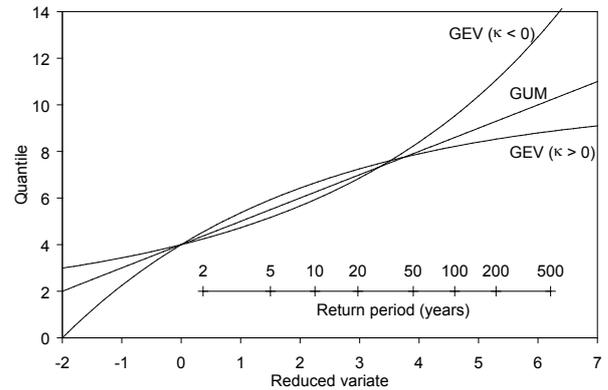
Figure 7.7 *The quantile, x_T, for the three types of GEV distributions plotted against the Gumbel reduced variate, y (from Tallaksen and others, 2004) (the return period is defined here as $1/(1 - F(x))$ as for the traditional case of annual maxima)*

Low-flow values generally show a range of skewness variations and are bound in the direction of the extreme. The distribution function should, accordingly, be skewed and have a finite lower limit greater than, or equal to, zero. When the true distribution has a lower bound that is closely approximated by the observed data, as is the case for low flows, it is advisable to fit a distribution capable of modelling bound data (Hosking and Wallis, 1997). If a low-flow distribution does not have a lower bound, negative estimation values may result. These are commonly treated as zero values or simply ignored. Apart from the Weibull distribution, the functions commonly applied in low-flow frequency analysis include the EV I distribution (Gumbel), the log-normal distribution and the Pearson Type 3 (P3) distribution. The EV I distribution cannot in general be recommended for analysis of minima values as it is not bound (in the lower or upper tail); thus, there is a probability of negative values in the lower range. Nonetheless, it often empirically fits AM well and can be used, provided that caution is applied when extrapolating to negative flows.

If the series is positively skewed, the logarithm can be described by a normal distribution ($Y = \ln(X)$), provided that the original series X is strictly positive. If a lower bound parameter is introduced ($X - \xi$), a three-parameter log-normal distribution results. The P3 distribution is bound below or above, depending on the sign of the scale parameter α. If $\alpha > 0$ and the location parameter $\xi = 0$ (lower bound), the P3 distribution reduces to the Gamma distribution. The Log-Pearson Type 3 distribution describes a random variable whose logarithms

are P3 distributed. Different forms of GEV (including the Weibull distribution), log-normal and P3 distributions have frequently been chosen for low-flow analysis based on goodness-of-fit tests and visual inspection (for example, Kroll and Vogel, 2002; Smakhtin, 2001; Zaidman and others, 2003). Gottschalk and others (1997) combined recession analysis with the frequency analysis of dry spells (derived distribution approach) to obtain a family of low-flow distribution functions, including the Weibull distribution. The results confirm the suitability of the Weibull distribution for low-flow frequency analysis.

7.6   Parameter estimation methods

Once the distribution function has been selected, the next step is to estimate the parameters of the distribution from the sample data. In this Manual, the method of moments, including P-moments and L-moments, is presented. For other methods, such as maximum likelihood methods and Bayesian inference, the reader is referred to common statistical literature (for example, Smith, 2001). In this section, the method of moments is used to estimate the parameters of a distribution; however, it can also be used to summarize the statistical properties of a probability function or an observed data sample, to test hypotheses about distribution form and to identify homogeneous regions.

The moment estimators of the parameters are obtained by replacing the theoretical moments for the specified distribution with the sample moments (for example, mean value, variance and skewness). Conventional P-moments, probability weighted moments (PWMs) (Greenwood and others, 1979) and L-moments (Hosking, 1990) can be used. L-moments are weighted linear sums of the expected order statistics and can be written as functions of PWMs. Procedures based on PWMs and L-moments are therefore equivalent.

7.6.1   P-moments
The first product moment about $X = 0$ is the mean, μ, or the expected value of X, $E\{X\}$. The second moment about the mean is called the variance, σ^2. The standard deviation, σ, is a measure of the spread around the central value and equals the square root of the variance. A relative measure of the spread is the dimensionless coefficient of variation, $CV = \sigma/\mu$. The third moment about the mean is a measure of the symmetry of a distribution, which is characterized by the dimensionless skewness ratio, γ_3. The fourth moment about the mean provides information about the thickness of the tail of

the distribution (peakedness), which can also be characterized by a dimensionless ratio called kurtosis, γ_4. Given a set of observations $x_1 \ldots x_n$, the first four estimators of the P-moments can be calculated as:

$$\hat{\mu} = \bar{x} \;=\; \frac{1}{n}\sum_{i=1}^{n} x_i \tag{7.7}$$

$$\hat{\sigma}^2 = s^2 \;=\; \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{7.8}$$

$$\hat{\gamma}_3 = \frac{\dfrac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3}{\left[\dfrac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{3/2}} \tag{7.9}$$

$$\hat{\gamma}_4 = \frac{\dfrac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4}{\left[\dfrac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{2}} \tag{7.10}$$

The first two moment estimators (equations 7.7 and 7.8) are unbiased and independent of the distribution and sample size, whereas the skewness and kurtosis estimator in equations 7.9 and 7.10 are, in general, biased. Corrections similar to those for the variance, namely, a factor like (n–1), can be introduced for higher order moments that generally reduce, but do not eliminate, the bias (for example, Stedinger and others, 1993).

7.6.2   L-moments
The Hosking (1990) method of L-moments has found widespread application in the statistical analyses of hydrological data. L-moments are weighted linear (the "L" is therefore introduced) combinations of the expected order statistics and are analogous to the conventional moments used to summarize the statistical properties of a probability function or an observed dataset. Let X be a real-valued random variable with the cumulative distribution function F(x), and let $X(1:n) \leq X(2:n) \leq \ldots \leq X(n:n)$ be the order statistics of a random sample of size n drawn from the distribution of X. The first four L-moments are then defined as:

$$\lambda_1 = E\left\{X_{(1:1)}\right\}$$

$$\lambda_2 = \tfrac{1}{2}E\left\{X_{(2:2)} - X_{(1:2)}\right\}$$

$$\lambda_3 = \tfrac{1}{3}E\left\{X_{(3:3)} - 2X_{(2:3)} + X_{(1:3)}\right\} \qquad (7.11)$$

$$\lambda_4 = \tfrac{1}{4}E\left\{X_{(4:4)} - 3X_{(3:4)} + 3X_{(2:4)} - X_{(1:4)}\right\}$$

The first moment equals the mean $(E\{X\})$, and the second moment is a measure of variation based on the expected difference between two randomly selected observations. It is common to standardize moments of higher order to make them independent of the measurement unit of X. The L-moment ratios, L-coefficient of variation, L–CV ($\tau2$), L-skewness ($\tau3$) and L-kurtosis ($\tau4$), are defined as:

$$\tau_2 = \frac{\lambda_2}{\lambda_1}$$

$$\tau_3 = \frac{\lambda_3}{\lambda_2} \qquad (7.12)$$

$$\tau_4 = \frac{\lambda_4}{\lambda_2}$$

The main advantage of L-moments is that they suffer less from the effect of sample variability compared with product moment estimators because the calculation does not involve squaring or cubing the observations. Sankarasubramanian and Srinivasan (1999) suggest that P-moments are preferable at lower skewness, particularly for smaller samples, while L-moments are preferable at higher skewness, for all sample sizes. Generally, L-moments are more robust to extreme values in the data and enable more secure inferences to be made from small samples about an underlying probability distribution (Hosking, 1990). The at-site sample variability is often high, and this supports the use of regional procedures given that less emphasis is then put on single observations. L-moment estimators have proven to be especially advantageous in regional frequency estimation (section 7.9).

7.7   Estimation of the T-year event

Percentiles or quantiles of a distribution are often used as a design quantity. The quantile, x_p, is the value with cumulative non-exceedance probability, p, that is, $F_X(x_p) = p$ (section 7.3). The expression for x_p is obtai-

ned by inverting the expression for $F_X(x_p)$ for a given value of p. The quantiles of the Weibull distribution (section 7.5) can be estimated from:

$$x_p = \xi + \alpha\left[-\ln(1-p)\right]^{1/\kappa} \qquad (7.13)$$

The focus of interest in low-flow analysis is the non-exceedance probability p, which is defined for any time interval Δt. The non-exceedance (p) and exceedance probability (1–p) is frequently expressed in terms of the return period, T, which for minimum values is defined as:

$$T = \frac{1}{p} \qquad (7.14)$$

where T is the mean time interval between occurrence of an event $X \le xp$ and the T-year event is given by the corresponding value for xp. Annual non-exceedance probabilities are defined for Δt equal to one year. The probability that a T-year event occurs in any one year is 1/T, for example, the probability of a 100-year event occurring in any year is 0.01. On average, a T-year event will occur once in a T-year period.

A simple measure of the precision in the T-year event is the variance of the quantile estimator, which equals the square of the standard error. Another measure is confidence intervals, which can be calculated using the standard error of the quantile. A 95 per cent confidence interval will, in repeated sampling, contain the parameter 95 per cent of the time.

Expressions for different distributions can be found in Stedinger and others (1993). Alternative methods for calculating uncertainty include Monte Carlo simulations and resampling methods.

Table 7.1 P-moments and L-moments for the AM(7) series of the example catchments (values are in 1 000 m³/d)						
Station	**P-moments**			**L-moments**		
	μ	σ2	γ3	λ1	λ2	τ3
223204;F(x)	9.765	8.68	1.149	9.765	4.721	0.273
223204;G(x)				10.375	4.670	0.276
223207;F(x)	41.977	21.05	0.146	41.977	12.305	0.045

7.8 Application of the Weibull distribution for low-flow frequency analysis

In this section, the Weibull distribution (section 7.5) is fitted to the AM(7) series of the example catchments presented in 7.2, following steps I to III. The sample P-moments (equations 7.7–7.10) and L-moments (equations 7.11–7.12) of the two series are given in Table 7.1. F(x) refers to all values in the series, whereas G(x) refers to non-zero values only (section 7.4.2).

The moments of the Weibull distribution can be calculated from:

$$\mu = \xi + \alpha \Gamma\left(1 + \frac{1}{\kappa}\right) \tag{7.15}$$

$$\sigma^2 = \alpha^2 \left[\Gamma\left(1 + \frac{2}{\kappa}\right) - \left[\Gamma\left(1 + \frac{1}{\kappa}\right)\right]^2 \right] \tag{7.16}$$

$$\gamma_3 = \frac{\Gamma\left(1 + \frac{3}{\kappa}\right) - 3\Gamma\left(1 + \frac{1}{\kappa}\right)\Gamma\left(1 + \frac{2}{\kappa}\right) + 2\left[\Gamma\left(1 + \frac{1}{\kappa}\right)\right]^3}{\left[\Gamma\left(1 + \frac{2}{\kappa}\right) - \left[\Gamma\left(1 + \frac{1}{\kappa}\right)\right]^2\right]^{3/2}} \tag{7.17}$$

where Γ is the gamma function; ξ is the location parameter; α is the scale parameter; and κ is the shape parameter. If ξ is known, the moment estimate of κ can be obtained by combining equations 7.15 and 7.16, which can be solved using Newton-Raphson iteration. The moment estimate of α is then given by:

$$\hat{\alpha} = \frac{\hat{\mu} - \xi}{\Gamma\left(1 + \frac{1}{\hat{\kappa}}\right)} \tag{7.18}$$

The L-moments of the Weibull distribution can be estimated from:

$$\lambda_1 = \xi + \alpha \Gamma\left(1 + \frac{1}{\kappa}\right) \tag{7.19}$$

$$\lambda_2 = \alpha\left(1 - 2^{-1/\kappa}\right)\Gamma\left(1 + \frac{1}{\kappa}\right) \tag{7.20}$$

$$\tau_3 = 3 - \frac{2\left(1 - 3^{-1/\kappa}\right)}{1 - 2^{-1/\kappa}} \tag{7.21}$$

If ξ is known, L-moment estimates of κ and α are given by:

$$\hat{\kappa} = -\frac{\ln 2}{\ln\left(1 - \frac{\hat{\lambda}_2}{\hat{\lambda}_1}\right)} \quad , \quad \hat{\alpha} = \frac{\hat{\lambda}_1 - \xi}{\Gamma\left(1 + \frac{1}{\hat{\kappa}}\right)} \tag{7.22}$$

If ξ is unknown, expressions for the parameters ξ, κ and α can be derived from the first three moments (P-moments or L-moments). For example, refer to Tallaksen and others (2004). Empirical quantiles are calculated below for the two example AM(7) series, and the Weibull distribution fitted using both P-moments and L-moments (Table 7.2). The results are plotted in Figures 7.8–10 (note that Station 223204 has zero values and therefore additional calculations are performed).

Table 7.2 Parameters of the Weibull distribution estimated using (P-moments) and L-moments						
Station	Method of P-moments			Method of L-moments		
	$1/\kappa$	κ	α	$1/\kappa$	κ	α
223204; F(x)	0.695	1.44	10.76	0.953	1.05	9.953
223204; G(x)				0.863	1.16	10.926
223207; F(x)	0.3265	3.06	46.96	0.500	2.00	47.365

Step I: Derivation of empirical quantiles
(a) Rank the AM(7) values in ascending order and give the smallest value rank 1 (i =1);
(b) Derive the non-exceedance probability, F(x) = p, for each value using the Weibull plotting position formula (equation 7.3 for a = 0);
(c) Plot the AM(7) values against F(x) in a probability plot (section 7.4).

Step II: Fitting the 2-parameter Weibull distribution by P-moments

(a) Calculate an estimate of the first two P-moments for the AM(7) series (Table 7.1);

(b) Combine equations 7.15 and 7.16 to obtain an estimate of κ, using a Newton-Rapshon iteration scheme. Alternatively, create a table (or plot) to depict the relationship between the skewness of the Weibull distribution (equation 7.17) and 1/κ, and use the table (or plot) to interpolate 1/κ corresponding to the sample skewness (equation 7.9) of the low-flow series;

(c) Estimate α by substituting the interpolated 1/κ into equation 7.18 for ξ = 0;

(d) Estimate F(x) as given by equation 7.6 (here, ξ is zero).

Step III: Fitting the 2-parameter Weibull distribution by L-moments

(a) Calculate an estimate of the first two L-moments for the AM(7) series, both with and without the zero values included (Table 7.1);

(b) Obtain an estimate of κ and then α from equation 7.22 for both F(x) and G(x), where G(x) is fitted to the non-zero values;

(c) Estimate F(x) (based on all values including the zero observations), G(x) and F(x)* as given by equation 7.4 (the percentage of zero values is six for Station 223204, that is, $p_0 = 0.06$).

Graphical methods that plot the empirical quantiles (observations) against the distribution quantiles can provide an important visual check on how well the distribution fits the data. The points should lie close to the theoretical curve (probability plot) or the unit diagonal (pp-plot for probabilities and qq-plot for quantiles), if the distribution is a reasonable model for the data.

The probability plots in Figures 7.8 and 7.9 clearly show that a better fit is obtained for the AM series using the Weibull distribution in combination with L-moments, as compared with P-moments. The asterisk in Figure 7.8 indicates that the estimate is obtained using the expression for F(x)* (equation 7.4). Indeed, a very good fit is obtained in the lower range using L-moments as confirmed by the qq-plot in Figure 7.10 (Station 223204 is used as an example). The results support the use of the Weibull distribution for the analysis of minimum flow values. Accounting for zero values has only a minor influence on the distribution form, as can be expected given the low percentage of zero values in the series.
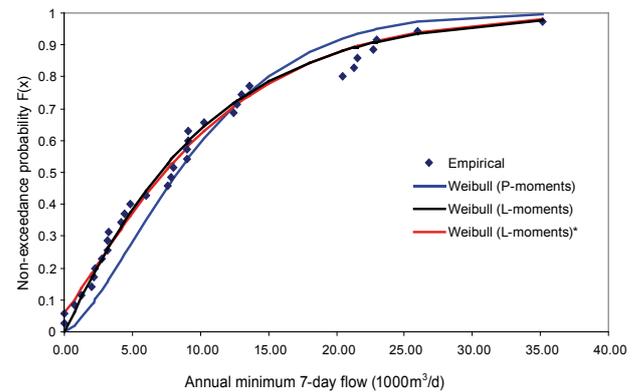
Figure 7.8 Probability plot showing the empirical quantiles (observations) against the Weibull distribution for the AM(7) flow series of the Nicholson River (Station 223204) (* the estimate is obtained using the expression for F(x)*)
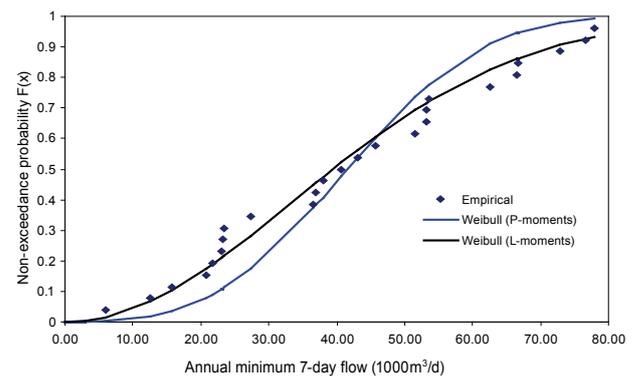
Figure 7.9 Probability plot showing the empirical quantiles (observations) against the Weibull distribution for the AM(7) flow series of the Timbarra River (Station 223207)

The low-flow quantile for the return period of interest can subsequently be derived from equation 7.13. A return period of T = 10 years corresponds to p = 0.10 (equation 7.14). Table 7.3 gives the 10-year low-flow value, xp = 0.1, estimated for the different parameter sets in Table 7.2. The notation F(x)* implies that zero values are explicitly accounted for following equation 7.4, which is also the recommended approach. The empirical values are obtained by linear interpolation between nearby observations. In general, lower (more extreme) values are found when L-moments are used. This is confirmed by the curve in Figure 7.8, which shows that the P-moment estimates generally overestimate the quantiles for F(x)>0.6–0.7, corresponding to a return period higher than one to two years.
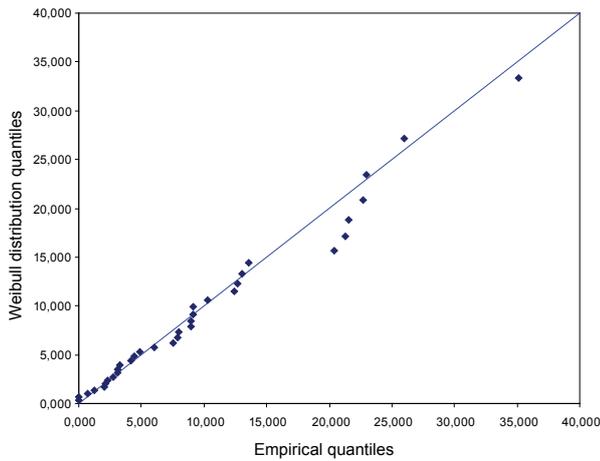
Figure 7.10 *qq-plot showing the empirical quantiles plotted against the Weibull distribution quantiles (fitted using L-moments) for the AM(7) flow series of Station 223204 (values are in 1 000 m³/d)*

The deviation between the observations and the estimated quantiles from a theoretical distribution can also be judged by a statistical test such as analytical goodness-of-fit criteria. The purpose is to evaluate whether the difference between the ordered observations and the estimated quantile from a given distribution is statistically significant. The chi-squared test statistic is based on a comparison of the number of observed and expected events in each class interval of a sample histogram, whereas the Kolmogorov-Smirnov test looks at the absolute deviation between the empirical and the cumulative distribution function. The conclusions that can be drawn from these tests depend on the level of

Table 7.3 Estimate of the 10-year event using the Weibull distribution			
Station	10-year event (1 000 m³/d)		
	Empirical	P-moments	L-moments
223204; F(x)	1.0	2.3	1.2
223204; G(x)			1.6
223204; F(x)*			1.5
223207; F(x)	14.1	22.5	15.4

confidence adopted; commonly, a 95 per cent level is chosen (Stedinger and others, 1993). In many cases, however, several distributions will provide statistically acceptable fits to the data, and goodness-of-fit tests fail to discriminate between the different distributions (for

example, Cunnane, 1985). Other more powerful tests (for a greater probability of correctly determining that a sample is not from a given distribution) include the probability plot correlation test, the L-moment and likelihood ratio tests, and the Akaike criterion as presented, for example, in Stedinger and others (1993) and Tallaksen and others (2004).

The more parameters a distribution has, the better it adapts to the sample data, including the tail of the distribution. Although it might therefore be tempting to select a distribution with a high number of parameters, the reliability in the parameter estimates will be more sensitive to sample variability. A larger sample size is thus required to give accurate parameter estimates. In hydrology, this generally implies that not more than two or three parameters are recommended for at-site frequency analysis. In regional frequency analysis (section 7.9), additional time series are introduced, and distributions with three or more parameters can be considered for the regional distribution. For example, the Wakeby distribution with five parameters is considered appropriate for most applications, provided that the sites in the region have an average record length of 20 years (Hosking and Wallis, 1997).

Although a distribution selected primarily based on theoretical considerations might not necessarily give the best fit to the data, it might still provide a better prediction of a future event (Tallaksen and others, 2004), the main reason for this being the great uncertainties inherently in conclusions that can be drawn by merely comparing the distribution fit to the observations. The assumptions underlying the extreme value theory may, however, not always be satisfied. It is therefore often recommended that the goodness-of-fit of an extreme value distribution be validated against that of other candidate distributions.

7.9 Regional frequency analysis

L-moment ratio diagrams are valuable for obtaining a general overview of the statistical properties of the sample observations and for investigating what families of distributions are consistent with a regional dataset. Figure 7.11 shows an L-moment ratio diagram where L-skewness is plotted against L-kurtosis for a selection of theoretical distributions. Two parameter distributions will show as points in the diagram (the normal, exponential and Gumbel distributions), whereas four parameter distributions are depicted as curves (the Weibull, lognormal, GEV and generalized Pareto (GP) distributions).

In addition, sample properties of AM(1) values calculated for the summer season of a Nordic dataset of 52 daily streamflow series are included in the plot.

The diagram shows that the Weibull and the log-normal distributions give the best overall fit to the data. In general, the GEV distribution has higher L-kurtosis than the sample dataset. Also included in the plot is the GP distribution, which is the limiting distribution for partial duration series, similarly to the GEV distribution for AMS. The observed data clearly do not fit the GP distribution, in accordance with the extreme value theory. It can be concluded that the Weibull distribution is a good choice for the low-flow data in the region. Ratio diagrams using L-CV and L-skewness can similarly be applied when choosing from two parameter distributions. Goodness-of-fit tests, including procedures based on L-moments, are commonly used to judge whether a particular time series is consistent with a regional distribution (Hosking and Wallis, 1997).

Regional frequency methods have been developed to improve at-site estimates and obtain more accurate estimates at sites with few or no observations. At-site procedures are sensitive to sample variability and model procedures, and more robust estimators would result if regional information was taken into account, particularly when estimating T-year events that largely exceed the length of observed record. A robust estimator should perform reasonably well for a wide range of catchments. This can be achieved by combining site-specific and regional information, provided that it can be assumed that the sites in the region have similar properties in terms of the variable being studied. The most common regional frequency method is the index method, first introduced for floods (index-flood method) and later successfully applied to drought studies (Clausen and Pearson, 1995; Madsen and Rosbjerg, 1998). The index method assumes that the data at different sites in a homogeneous region follow the same distribution, except for scale. The individual series are normalized by an at-site index parameter and then pooled to yield an estimate of the regional distribution parameters. The at-site T-year estimate is subsequently obtained by multiplying the normalized estimator by the at-site estimated index parameter. The mean value is often used as an index parameter, which, at an ungauged site, can be obtained using a regression equation.

The index procedure requires, among others, the classification of sites into homogeneous regions and the determination of a distribution function for each region. Hosking and Wallis (1993) developed procedures based on L-moment analysis for this purpose, and a general introduction to the topic is provided in Hosking and Wallis (1997). L-moment diagrams as described above are useful for identifying a regional distribution and can also provide an indication of the regional homogeneity by considering the dispersion of the points. The question is whether this dispersion is larger than the
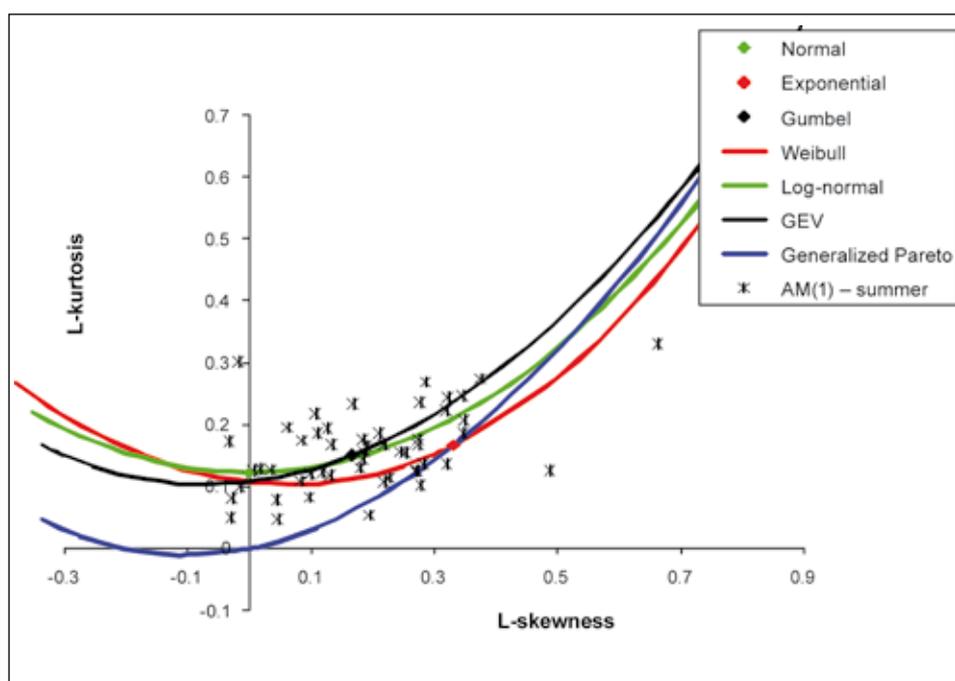

Figure 7.11
L-moment diagram of AM(1) flow series determined for a Nordic dataset of 52 discharge stations

expected variability as a result of sampling uncertainty. A statistics test based on L-moments is available for this purpose, namely, for testing the regional homogeneity of the sites. L-moments can subsequently be used to estimate the parameters of the regional distribution. Regional frequency analysis assumes that the station data are independent. The main effect of intersite dependence is to increase the variability of estimators, similarly to a reduced number of stations in the region. The effect is fairly small, however, for correlations that do not exceed 0.2 (Hosking and Wallis, 1997). A detailed example of regional frequency analysis elaborated for drought deficit volume and duration can be found in Tallaksen and others (2004).

References

Bayazit, M. and B. Önöz, 2002: LL-moments for estimating low flow quantiles. *Hydrological Sciences Journal*, 47(5): 707–720.

Clausen, B. and C.P. Pearson, 1995: Regional frequency analysis of annual maximum streamflow drought. *Journal of Hydrology*, 173: 111–130.

Coles, S., 2001: *An Introduction to Statistical Modeling of Extreme Values*. Springer Series in Statistics, Springer-Verlag, London.

Cunnane, C., 1978: Unbiased plotting positions – A review. *Journal of Hydrology*, 37: 205–222.

— , 1985: Factors affecting choice of distribution for flood series. *Hydrological Sciences Journal*, 30(1): 25–36.

Durrans, S.R. and S. Tomic, 2001: Comparison of parametric tail estimators for low-flow frequency analysis. *Journal of the American Water Resources Association*, 37(5): 1203–1214.

Engeland, K., H. Hisdal and A. Frigessi, 2004: Practical extreme value modelling of hydrological floods and droughts: A case study. *Extremes,* 7: 5–30.

Fisher, R.A. and L.H.C. Tippett, 1928: Limiting forms of the frequency distribution of the largest or smallest member of a sample. *Proceedings of the Cambridge Philosophical Society*, 24(2): 180–190.

Gottschalk, L., L.M. Tallaksen and G. Perzyna, 1997: Derivation of low flow distribution functions using recession curves. *Journal of Hydrology*, 194: 239–262.

Greenwood, J.A., J.M. Landwehr, N.C. Matalas and J.R. Wallis, 1979: Probability weighted moments: Definition and relation to parameters of several distributions expressible in inverse form. *Water Resources Research*, 15: 1049–1054.

Haan, C.T., 1977: *Statistical Methods in Hydrology*. The Iowa State University Press, Ames, United States.

Hewa, G.A., Q.J. Wang, T.A. McMahon, M. Peel and R.J. Nathan, 2007: Suitability of the generalised extreme value distribution estimated by LH-moments for low flow frequency analyses. *Water Resources and Research*, 43, W 06301, doi:10.1029, 2006WR004913.

Hosking, J.R.M., 1990: L-moments: Analysis and estimation of distributions using linear combinations of order statistics. *Journal of the Royal Statistical Society,* B 52(1): 105–124.

Hosking, J.R.M. and J.R. Wallis, 1993: Some statistics useful in regional frequency analysis. *Water Resources Research,* 29(2): 271–281. Correction in *Water Resources Research*, 31(1): 251, 1995.

— , 1997: *Regional frequency analysis: An approach based on L-moments*. Cambridge University Press.

Institute of Hydrology, 1980: *Low Flows Studies Report*. Three volumes, Institute of Hydrology, Wallingford, United Kingdom.

Kroll, C.N. and J.R. Stedinger, 1996: Estimation of moments and quantiles using censored data. *Water Resources Research*, 32(4): 1005–1012.

Kroll, C.N. and R.M. Vogel, 2002: Probability distribution of low streamflow series in the United States. *Journal of Hydrologic Engineering*, 7(2): 137–146.

Madsen, H. and D. Rosbjerg, 1998: A regional Bayesian method for estimation of extreme streamflow droughts. In: *Statistical and Bayesian Methods in Hydrological Sciences* (E. Parent, B. Bobee, P. Hubert and J. Miquel, eds). UNESCO, PHI Series, pp. 327–340.

Nathan, R.J. and T.A. McMahon, 1990: Practical aspect of low-flow frequency analysis. *Water Resources Research*, 26(9): 2135–2141.

Sankarasubramanian, A. and K. Srinivasan, 1999: Investigation and comparison of sampling properties of L-moments and conventional moments. *Journal of Hydrology*, 218: 13–34.

Smakhtin, V.Y., 2001: Low flow hydrology: A review. *Journal of Hydrology*, 240: 147–186.

Smith, R.L., 2001: *Environmental Statistics*. Lecture Notes for CBMS Course in Environmental Statistics. Available from: http://www.stat.unc.edu/postscript/rs/envnotes.pdf (accessed 27 October 2008).

Stedinger, J.R., R.M. Vogel and E. Foufoula-Georgiou, 1993: Frequency analysis of extreme events. In: *Handbook of Hydrology* (D.R. Maidment, ed.). McGraw-Hill, New York, 18.1–18.66.

Tallaksen, L.M., 2000: Streamflow drought frequency analysis. In: *Drought and Drought Mitigation in Europe* (J.V. Vogt and F. Somma, eds). Advances in Natural and Technological Hazards Research, 14, Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 103–117.

Tallaksen, L.M., H. Madsen and H. Hisdal, 2004: Frequency analysis. In: *Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater* (L.M. Tallaksen and H.A.J. van Lanen, eds). Developments in Water Sciences 48, Elsevier B.V., the Netherlands, pp. 199–271.

Wang, Q.J., 1997: LH moments for statistical analysis of extreme events. *Water Resources Research*, 33(12): 2841–2848.

Weibull, W., 1961: *Fatigue Testing and Analysis of Results*. Pergamon Press.

Zaidman, M., V. Keller, A.R. Young and D. Cadman, 2003: Flow-duration-frequency behaviour of British rivers based on annual minima data. *Journal of Hydrology*, 277: 195–213.

8. Streamflow deficit

8.1 Introduction

Streamflow deficits (Hisdal and others, 2004) are periods when the river is below a specific threshold that defines a drought or critical deficit. There are two main methods to select and characterize deficits, namely the threshold-level method and the sequent peak algorithm initially used for reservoir storage-yield analysis. In this chapter, only the threshold-level method is described. This method is used for providing estimates of the frequency of low-flow periods and for designing and operating regulating reservoirs where reservoir releases are made to support downstream abstractions. Examples of water use include those related to hydropower, public water supply and irrigation.

Figure 8.1 shows the definition of the timing, durations and volumes of deficits below a threshold discharge in a river. Streamflow deficits can also be characterized by intensity and spatial extent. The threshold-level method was initially named the "method of crossing theory" and is also referred to as "run sum analysis" because it generally studies runs below or above a given threshold. A detailed discussion of the method applied to a global dataset is given in Fleig and others (2006).
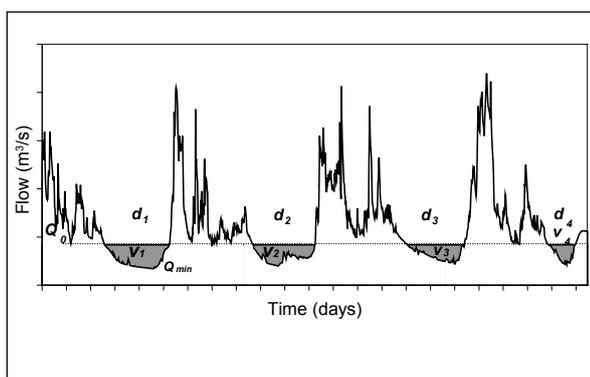
Figure 8.1 *Definition of deficit characteristics (modified from Hisdal and others, 2004; reproduced with Elsevier's permission)*

8.2 Definition and derivation

The threshold level Q_0 is also referred to as the truncation level and is used to define whether the flow in a river is in deficit (Figure 8.1). The deficit starts when the flow goes below the threshold and ends as soon as the flow returns above the threshold. Thus, the beginning and the end of a deficit period can be defined. In addition, the following deficit characteristics can be defined:

(a) The duration, which is the period of time where the flow is below the threshold level and is also referred to as drought duration, low-flow spell or run length (d_i, Figure 8.1);

(b) The volume or severity, which is also referred to as drought volume or run sum (v_i, Figure 8.1);

(c) The intensity, which is also referred to as deficit or drought magnitude, m_i, is the ratio between deficit volume and deficit duration;

(d) The minimum flow of each deficit event (Q_{min} in Figure 8.1);

(e) The time of occurrence, for example, the starting date, the mean of the onset and termination, or the date of the minimum flow.

Based on the time series of the deficit characteristics, it is possible to derive indices, such as the average deficit duration or average deficit volume.

Time resolution
Whether to analyse annual, monthly or daily discharge depends on the hydrological regime under study, the data available and the specific problem to be solved. In temperate climates a year might include severe short-duration deficits followed by periods of high flow, and therefore daily flow series would be required to identify deficit periods.

Deficits may last for several years in arid and semi-arid regimes, and monthly data may be sufficient. Different time resolutions might lead to different results regarding the selection of deficit periods.
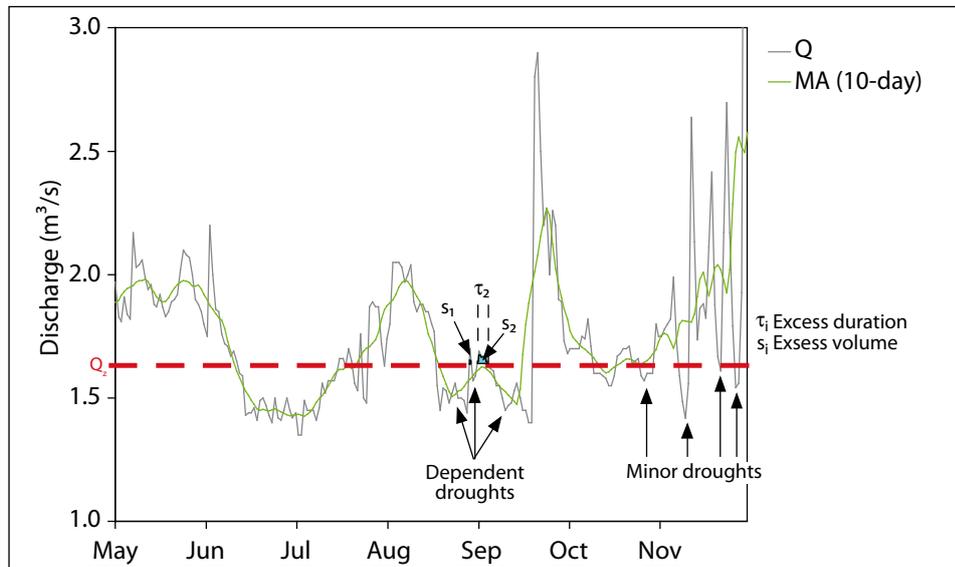
Figure 8.2

Illustration of pooling mutually dependent deficits and removal of minor deficits by an MA(10-day) filter (modified from Fleig and others, 2006; reproduced with the authors' permission)

The threshold-level method was originally based on analysing sequential time series with a time resolution of one month or longer. Daily data is now more commonly used. However, the use of daily data introduces the problems of dependency between deficits and minor deficits. During prolonged dry periods, the flow may exceed the threshold level for a short period of time, dividing a large deficit into a number of minor periods that are mutually dependent (Figure 8.2). This is inappropriate for extreme value modelling, which requires independent events. It is therefore recommended that pooling procedures be applied to define an independent sequence of deficits. A large number of minor events may also introduce bias in the extreme value modelling, and a procedure to remove such events may be required.

Pooling procedures include the moving average procedure (MA), the inter-event time (IT) and the inter-event time and volume criterion (IC). The MA procedure simply smoothes the time series applying a moving average filter. This is demonstrated in Figure 8.2, where a 10-day averaging interval has been used.

A study by Fleig and others (2006) found that the MA procedure is applicable to both quickly and slowly responding streams. The averaging interval can easily be optimized, and a filter width of around 7 days is appropriate for many hydrological regimes. An additional advantage of the MA pooling method is that it reduces the problem of minor deficits. A drawback is that the method modifies the discharge series and might introduce dependency between the deficit events, particularly for long moving averages.

The IT method pools mutually dependent deficits with characteristics (d_i, v_i) and (d_{i+1}, v_{i+1}) if they occur less than a predefined number of days, t_{min}, apart. The pooled duration and deficit volume can be defined as:

$$d_{pool} = d_i + d_{i+1} \qquad (8.1(a))$$
$$v_{pool} = v_i + v_{i+1} \qquad (8.1(b))$$

Fleig and others (2006) used the IT method and concluded that $t_{min} = 5$ days can be applied for perennial as well as intermittent streams if the stream is not very flashy when the method tends to pool too many events.

Tallaksen and others (1997) suggest the IC method, where two events are pooled if: (a) they occur less than a predefined number of days, t_{min}, apart (the inter-event time, τ_i, is less than t_{min}) and; (b) the ratio between the inter-event excess volume, s_i, and the preceding deficit volume, v_i, is less than a critical ratio, p_i. The pooled deficit is then pooled with the next one if the requirements of (a) and (b) are fulfilled, and so on. The pooled deficit characteristics can be calculated as follows:

$$d_{pool} = d_i + d_{i+1} + \tau_i \qquad (8.2(a))$$
$$v_{pool} = v_i + v_{i+1} - s_i \qquad (8.2(b))$$

The method was tested on two rivers with contrasting flow regimes and it was found that the optimal values of the pooling criteria were $t_{min} = 5$ days and $p_i = 0.1$. When the IT or IC method is used, minor deficits have to be excluded in an additional step by excluding deficits if the deficit volume or duration is smaller than predefined values.

Threshold selection

The choice of threshold is influenced by the purpose and region of the study and the data available. The threshold could, for example, be the amount of water required for a fish farm or for navigation or the abstraction rate downstream of a regulating reservoir. Alternatively, the purpose of the study may be of a more general character, for example, frequency analysis at a single site or a comparison of deficit characteristics at different sites.

A compromise may have to be made between including events that can really be regarded as significant deficits and including enough events for analysing their characteristics. When using monthly (or longer) data, typical threshold values are the mean or median flow or the mean minus one standard deviation (Dingman, 2002). It should be noted, however, that, if the median is used as a threshold, the streamflow is in a deficit situation for 50 per cent of the time.

Figure 8.3 *Illustration of threshold levels: fixed threshold (top); monthly varying threshold (middle); daily varying threshold (bottom) (modified from Stahl, 2001; reproduced with the author's permission)*

For studies of daily data, a percentile from the flow-duration curve (FDC) (Chapter 6) can be used as the threshold. For perennial rivers, relatively low thresholds in the range Q_{70} to Q_{95} are often used.

For intermittent and ephemeral rivers with many days of zero flow, higher percentiles will be required, for example, the median flow or even percentiles in the range Q_5 to Q_{20}. An alternative is to apply a variable threshold, for example, a percentile taken from a monthly FDC, or to calculate percentiles based on the non-zero values only.

In Figure 8.3 (top), a constant threshold Q_{90} from the FDC based on the whole period of record is used. If seasonal deficits are studied separately, the threshold can also be fixed, but based only on flow data from the relevant season studied. This is also illustrated in Figure 8.3 (top), with two seasonal thresholds for the summer and winter seasons. Variable monthly and daily threshold approaches are illustrated in Figure 8.3 (middle) and (bottom), respectively. To increase the sample size (if the flow record is short) and to obtain a smoother daily varying threshold, the exceedance percentiles for each day of the year can be calculated from an n-day moving average.

Studies of within-year deficits may impose restrictions on the use of very low threshold levels because this may lead to too many zero-deficit years resulting in very few events, or, for high threshold levels, the problem of deficits lasting longer than one year (multi-year deficits) may arise. Hence, a compromise must be found. The use of very low thresholds is also problematic in cases of short time series because the sample of derived deficits is too small for statistical analysis.

8.3   Application: Determination of streamflow deficit characteristics

In this example, a step-by-step procedure is used to derive and compare streamflow deficit characteristics from rivers in two contrasting river-flow regimes.

The calculations were programmed in C++ and the resulting time series of deficit characteristics were imported into Excel spreadsheets and plotted.

Data from the Drammenselv at Fiskum (Norway) and the Arroyo Seco at Soledad (United States) are used to demonstrate the procedure in the example below.

(a) Data: Drammenselva at Fiskum has a cold climate with no distinct dry season. Annual precipitation is between 800 and 850 mm. Winter precipitation falls as snow and there is a distinct snowmelt peak discharge in the spring. A second streamflow peak often occurs in the autumn, caused by rain. The river is perennial and the 30-year period from 1976 to 2005 is analysed. To be able to distinguish between summer deficits caused by a lack of precipitation and high evaporation losses, and winter deficits caused by precipitation being stored as snow, only the summer season (15 May – 15 October) is studied. Arroyo Seco at Soledad has a temperate climate with dry summers and wet winters. The annual precipitation is about the same as at Fiskum. However, the river is intermittent, that is, it has periods with zero flow and Q_{90} is zero. The complete 30-year period from 1968 to 1997 is studied and the whole year is analysed since temperatures never fall below zero;

(b) Parameter determination:
   (i) Threshold selection: A sequence of deficit events is obtained from the streamflow hydrograph by considering periods with flow below a certain threshold, Q0. The threshold level is obtained as an exceedance percentile from the FDC. In this example, to be able to compare the deficit characteristics from these two contrasting river-flow regimes, the same percentile, Q_{70}, is used as the threshold for both stations;
   (ii) Dependent and minor deficits: To reduce the problem of dependent and minor deficits, the MA procedure has been used with a filter width of 7 days;

(c) Calculation: The following deficit characteristics are calculated:
   (i) The start date, defined as the first day below the threshold;
   (ii) The end date, defined as the last day below the threshold;
   (iii) The deficit volume (1 000 m³), defined as the sum of the daily deficit flows multiplied by the duration in days;
   (iv) The deficit duration (days): A histogram of the deficit durations is shown in Figure 8.4. It can be seen that the two rivers have different deficit characteristics. The total number of deficit events at Fiskum is 59, on average almost two per year. Short-duration deficits dominate, with the average being 22 days. The most

severe deficit occurred in 1976 and lasted 90 days (from 6 July to 3 October). At Soledad, the deficits are fewer (38 in total) and last longer, with an average of 168 days. The sample is split into two. Except for one deficit lasting 42 days, there is one sample of less than 25 days and another with durations of more than 70 days. The longest deficit occurred in 1991/1992 with a duration of 245 days (from 2 June to 1 February); It should be noted that, because only summer deficits are studied at Fiskum, the maximum deficit duration is from 15 May to 15 October, that is, 154 days. Multi-year deficits cannot occur. In this example, none of the deficits starts prior to 15 May, but two deficits end on 15 October.

8.4 Definitions of low-flow and deficit characteristics: National standards in Germany

Some countries have developed national standards for deriving low-flow and deficit characteristics. One example is Germany, where the German Association for Water, Wastewater and Waste (DWA, formerly DVWK) has issued recommendations for statistical low-flow analysis and defined the following low-flow and deficit indices (DVWK, 1983, 1992):

NMxQ: Lowest arithmetic mean of n consecutive daily values of flow within the time period ZA during the reference period BZ (in m³/s). With BZ = ZA equal to one year, this is the annual minima of the n-day flow, AM(n-day) (Chapter 5).

MaxD: Longest period of non-exceedance of a threshold Q_0 within the time period ZA during the reference period BZ (in days). With BZ = ZA equal to one year, this is the annual maximum deficit duration.

SumD: Sum of all periods of non-exceedance of a threshold Q_0 within the time period ZA during the reference period BZ (in days). With BZ = ZA equal to one year, this is the sum of the deficit durations of all the deficit events within one year.

MaxV: Maximum deficit volume between the threshold, Q_0, and the hydrograph Q(t) within the time period ZA during the reference period BZ (in mm or hm³). With BZ = ZA equal to one year, this is the annual maximum deficit volume.
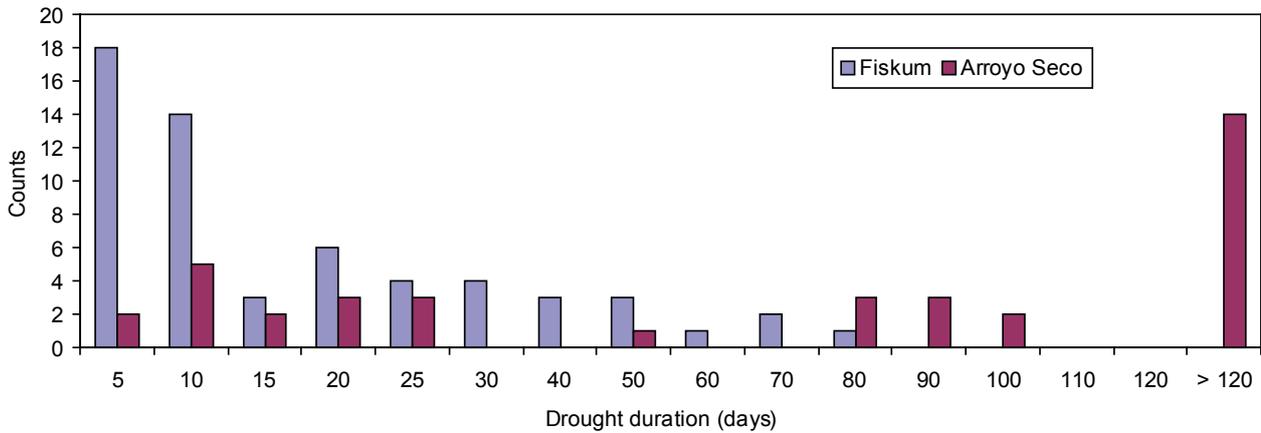
Figure 8.4 Histogram of drought duration for the Drammenselv at Fiskum (Norway) and the Arroyo Seco at Soledad
(United States); selection criteria: threshold level Q70 and MA(7)

SumV: Sum of all deficit volumes between the threshold, Q_0, and the hydrograph Q(t) within the time period ZA during the reference period BZ (in mm or hm^3). With BZ = ZA equal to one year, this is the sum of the deficit volumes of all the deficit events within one year.

BZ is a reference period that depends on the low-flow regime of the river under consideration; in a pluvial flow regime, the water year from 1 April to 31 March is used. ZA is the time period under consideration, for instance, the summer half-year, the water year, or the growth season. An illustration is given in Figure 8.5.

Practical studies define the threshold, Q0, by referring to flow minima that are either ecologically required or required by water resources management, reservoir operation and navigation. Regional comparisons are usually based on the mean low-flow. These definitions of low flow and deficit characteristics and the resulting statistics are used in Germany, Hungary and the Czech Republic.
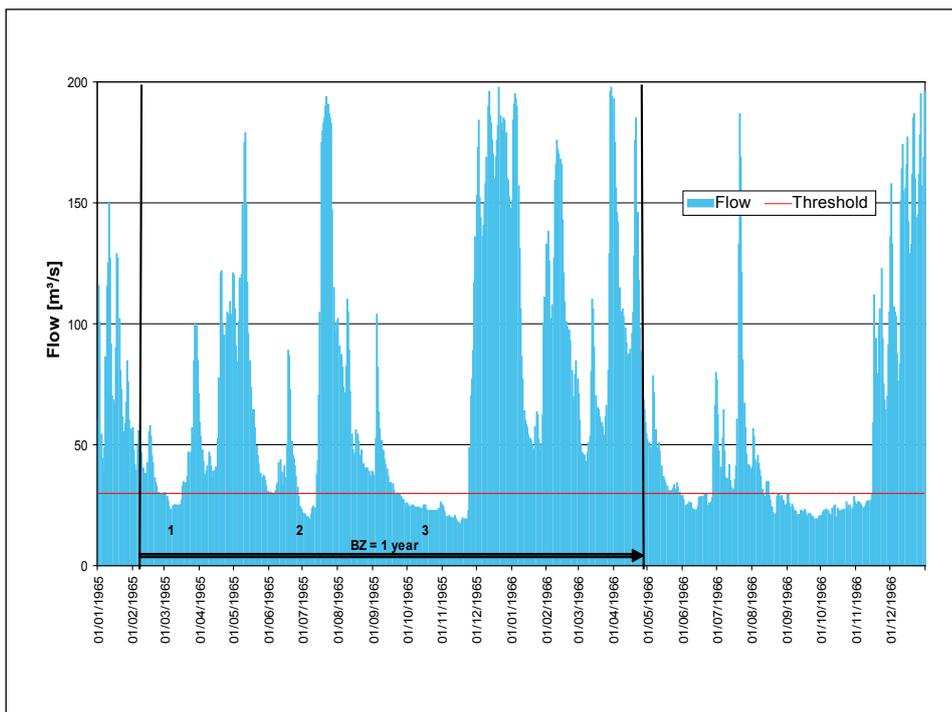
Figure 8.5

An illustration of deficit indices (BZ and ZA equal the water year). The 1965/66 year has three low flow events below a threshold of $Q_0 = 30$ m^3/s. The annual maximum duration (MaxD) and deficit volume (MaxV) are determined from event number 3. SumD and SumV are the sums of all three events.

References

Deutscher Verband für Wasserwirtschaft und Kulturbau (DVWK), 1983: *Niedrigwasseranalyse, Teil I: Statistische Untersuchung des Niedrigwasser-Abflusses. DVWK – Regeln 120*, Hamburg and Berlin.

— , 1992. *Niedrigwasseranalyse, Teil II: Statistische Untersuchung des Niedrigwasser-Abflusses. Regeln zur Wasserwirtschaft Nr. 121*, Hamburg and Berlin.

Dingman, S.L., 2002: *Physical Hydrology*. Second edition, Prentice Hall, New Jersey, United States.

Fleig, A., L.M. Tallaksen, H. Hisdal and S. Demuth, 2006: A global evaluation of streamflow drought characteristics. *Hydrology and Earth System Sciences,* 10: 535–552.

Hisdal, H., B. Clausen, A. Gustard, E. Peters and L.M. Tallaksen, 2004: Event definitions and indices. In: *Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater* (L.M. Tallaksen and H.A.J. van Lanen, eds). Developments in Water Science, 48, Elsevier Science B.V., Amsterdam: 139–198.

Stahl, K., 2001: Hydrological drought – A study across Europe. PhD thesis, *Freiburger Schriften zur Hydrologie*, Band 15, Institute of Hydrology, University of Freiburg, Freiburg, Germany.

Tallaksen, L.M., H. Madsen and B. Clausen, 1997: On the definition and modelling of streamflow drought duration and deficit volume. *Hydrological Sciences Journal,* 42(1): 15–33.

9. Estimating low flows at ungauged sites

9.1 Introduction

An understanding of river flows and a well-founded hydrological monitoring network are essential components for managing water resources. Data from these networks underpin physical and biochemical process studies, hydrological modelling, forecasting, the assessment of environmental change and water resources planning and operation. However, many management decisions are made in catchments for which measured data are rarely available. Furthermore, in many regions of the world hydrological networks (Chapter 3) have declined and the systems for collecting and managing water-related information are inadequate. This has led to the development of a wide range of techniques for estimating low flows at river sites without any recorded flow data, that is, ungauged sites.

Estimation methods can essentially be divided into three groups. The first group consists of empirical methods for the estimation of streamflow indices using simple mathematical equations. The equations developed do not explicitly describe physical, causal relationships (which are incorporated in deterministic or mathematical models), nor do they approximate estimation error. Nevertheless, empirical procedures attempt to account for the primary influences on streamflow in order to graphically or analytically estimate low-flow indices.

The second group is based on statistical models. Flow estimation at ungauged sites with the aid of multiple regression techniques has gained wide use in applied hydrology. This is largely because of the extensive application of research into hydrological design requirements. Although this approach is direct, objective and easy to handle, it has the disadvantage that the methods estimate specific low-flow indices rather than the full time series of river flows.

The third group contains rainfall-runoff models used to simulate the evolution of the time series of river flows within a catchment. These describe the interaction between catchment structure, rainfall inputs, evaporative outputs and streamflow outputs by representing hydrological processes by mathematical equations. The response of these models is controlled by model parameters. For application within an ungauged catchment, the model parameters may be derived from physical measurement or through relationships between model parameters and the physical, and sometimes climatic, characteristics of a catchment.

In practice, there may be short, or incomplete, local records of river flow within, or near to, an ungauged site. This local data may be used in conjunction with long continuous measurements from catchments with similar hydrological behaviour in order to reduce the uncertainty of flow estimation. Approaches to using local data as either an alternative to, or to complement, regional models are presented later (section 9.5).

If the accuracy of estimation using any of these techniques is considered unacceptable, then it is necessary to install a flow-measuring facility (Chapter 3). In practice, the flow regimes of many catchments are modified by human water-use activities. This chapter is limited to the estimation of natural flow regimes. Standard practice is to estimate the natural flow regime and then to superimpose the artificial influence of activities such as abstraction/diversion of river flow, the construction of impounding reservoirs and the discharge of wastewater. These artificial influences and how they might be accounted for in flow estimation are discussed further in Chapter 10.

9.2 Empirical methods

Owing to the large spatial variations in rainfall and hydrogeology in many countries, empirical transposition techniques all attempt to adjust the flow record for the analogue catchment for differences in hydrological scale (differences in rainfall and catchment area) between the analogue and ungauged catchments. An analogue catchment is one that is believed to have a similar hydrological response to precipitation and evaporation demand.

In the context of estimating the time series of river flows, it is also essential that the river flows within the ungauged and analogue catchments be synchronous, that is, with flows increasing and decreasing together. Accordingly, an analogue catchment is usually one that is:

(a) Geographically close to the ungauged catchment and hence has the same climatic regime;
(b) Hydrogeologically similar;
(c) Similar in size;
(d) Either a natural catchment or one that has a naturalized flow record.

Ideally, the analogue catchment should lie upstream or downstream of the ungauged catchment, that is, nested with the target ungauged catchment. In the case of a nested analogue catchment, there is a strong serial correlation between the flow measured at the analogue gauge and the flows at the ungauged site, given that the water flowing past both points has a common component. It is quite common for no connected analogue catchment to be available, and thus a catchment from an adjacent system or tributary for the same system is selected as the analogue for the ungauged catchment.

If there is a short period of local measured flow data at the target site, it is common practice to build these data into the transposition methods discussed in the section on the use of local data (section 9.5).

Streamflow estimation for ungauged catchments by transposing gauged streamflow data from an analogue catchment is a widely used technique requiring the re-scaling of the flow regime to the ungauged target catchment. These techniques all take the following form:

$$QX_T = fn\left(\frac{A_T}{A_A}\right)QX_A \qquad (9.1)$$

where:
QX_T = the flow in the target ungauged catchment T;
QX_A = the corresponding flow in the analogue catchment A;
A_T = the catchment area for the ungauged catchment T;
A_A = the catchment area for the analogue catchment A;
fn = a scaling constant or function.

Commonly, in simple area scaling, the scaling constant is set to 1. The simple scaling approach may be refined by introducing the ratio of average annual rainfall in addition to area to normalize for differences in average annual rainfall. If a short record is available for the target catchment, the scaling relationship can be optimized over the common period of record. Within the United Kingdom, the scaling function is often based on estimates of mean flow derived from the LowFlows 2000 software system (discussed further in the Low-Flows 2000 case study in Chapter 12), thus taking into account the non-linearity between rainfall and runoff within dryer areas.

Accuracy increases according to the similarity of the flow regimes of the rivers, particularly if the two catchments are nested. The greater the variation of the low-flow indices, the less reliable the transfer function. Accuracy can increase significantly if there is a short period of record for the target catchment which can be used to optimize the relationship through flow correlation. Often, a short record is not available and the practitioner must to decide whether the added accuracy of using the short record to optimize the relationship is worth the time and money required to carry out a period of measurement within the target catchment (for example, six months or more).

9.3 Statistical methods – regionalization

The technique of relating river-flow summary statistics to the physical and climatic descriptors of a catchment, or region, is commonly called regionalization. Regionalized models are used very widely for estimating low flows within ungauged catchments and have an advantage over simple empirical methods (section 9.2). Regionalized models for low-flow estimation can be broadly categorized into the regionalization of continuous simulation rainfall-runoff models, as discussed in section 9.4, and the regionalization of flow statistics, discussed within this section. Much of the conceptual thinking that underpins the development of regionalized flow statistic models also underpins the regionalization of rainfall-runoff models. The first step in developing such a model is to identify the facets of the low-flow regime that are of interest at the ungauged site and hence that are to be regionalized. The most commonly regionalized flow statistics are flow-duration statistics (Chapter 6), with others including the base-flow index (section 5.2), flow frequency statistics (Chapter 7) and recession parameters (section 5.3). For example, in the United Kingdom, the main focus of research on regionalized models has been the regionalization of flow-duration statistics as these statistics underpin both

abstraction licensing and the establishment of consents to discharge effluent into rivers.

Once the objectives for the regionalized model have been identified, the next step is to develop a conceptual model of the processes that control the spatial variation in the flow statistic of interest. The dominant influence is always scale. Rivers draining large catchments generally have larger flows than those draining small catchments, and it is very common to see poorly defined regional models published within literature focusing entirely on scale. These scale effects dominate goodness-of-fit measures that may be used to judge the quality of the simulation. The main issue with such models is that they cannot differentiate between the variation in low flows observed in catchments that are of the same size but that may have very different climatic and physical characteristics.

Low flows are influenced by a combination of the following: climatology, hydrogeology and soils, topography and land use (Chapter 4). The location determines which of these will be the dominant influences. For example, within the United Kingdom, the maritime climate is generally characterized by a lack of a marked seasonal variation in precipitation. In contrast, the hydrogeology of both major aquifers in the United Kingdom is complex, with hard rock and quaternary in one, and tertiary drift deposits of varying permeability in the other. Once normalized for hydrological scale (by dividing by the mean flow) the between catchment variation in flow-duration statistics is strongly influenced by hydrogeology (Holmes and others, 2002). This contrasts markedly with the Hindu Kush, where the onset and duration of the monsoon and elevation are the dominant influences on the variation of flow regimes within the region (Rees and others, 2005).

This conceptual understanding is gained through data analysis. The success or failure of a regionalization process depends greatly on whether an appropriate dataset is compiled to support the analysis procedure and subsequent model development. In essence, the dataset comprises a set of flow data from gauged catchments, with accompanying catchment descriptors that are representative of the hydrology of the region of interest. It is essential that the catchment descriptors adequately represent the influences on the variation in low flows that the model is to estimate. In many regions of the world, the appropriate mapping of these data is a limiting factor; however, advances in remotely sensed data continue to address this issue. Commonly, it may

be necessary to identify appropriate surrogate datasets. or example, location can be used as a good surrogate for more detailed information on the onset of the monsoon season within the mountainous Himalayan region of Hindu Kush (Rees and others, 2005). Croker and others (2003) used average annual rainfall as a surrogate for a true measure of the degree of stream ephemerality in a study that used the theory of total probability for predicting flow-duration statistics within ephemeral catchments in Portugal.

The flow data of a catchment must be of good hydrometric quality and relatively free of anthropogenic disturbance (for example, impounding reservoirs, abstractions and discharges), unless this disturbance is to be explicitly addressed within the model (this is rarely the case). Furthermore, the length of record should be sufficient to capture the natural variability of the system to minimize the influence of sampling error on the flow statistic of interest. The regionalization of hydrological variables that demonstrate significant trend through time should be attempted with care, if at all. The extensive quality assurance of data will strongly influence the outcomes of a study, and the importance of this step cannot be overly stressed. The development of a regionalized model for estimating low-flow indices can be summarized in the following five steps (see also Figure 9.1).

Step 1: Data acquisition
(a) The selection of the low-flow indices of interest, for example, the flow-duration curve (FDC);

(b) The selection of an appropriate set of gauged catchments across the region of interest on which to base the development and testing of the model;

(c) The acquisition and quality control of the river-flow data (Chapter 3) for these catchments. The following are basic considerations:
  (i) The period of measurement record should be long enough, and without significant gaps, to minimize the sampling error within the derivation of the low-flow index;
  (ii) The hydrometric errors in the measurements should be sufficiently small, such that the low-flow index is not sensitive to the magnitude of the error. For example, if low flows are of interest, the measurements should be both accurate and precise at low flows; but, the accuracy and precision at high flows may be of secondary importance;

(iii) The flow regime of the catchment should be essentially free of anthropogenic disturbance;

(d) The acquisition and quality control of physical and climatic descriptors of the catchment. These might include geology, soils, land use, topographic characteristics, average annual rainfall and seasonal rainfall;

(e) The partitioning of the catchment dataset into a model development dataset and a model validation dataset.

Step 2:   Model design

(a) The development of a conceptual model of the relationships between the low-flow index of interest and the physical and climatic characteristics collated under Step 1;

(b) The selection of an appropriate modelling framework (usually statistical) for developing predictive relationships between the flow indices from the catchment descriptors.

Step 3:   Model calibration

(a) The identification of significant relationships between flow indices and catchment descriptors;

(b) The development of predictive models considering issues such as covariance between catchment descriptors. It is strongly recommended that catchment descriptors be selected to minimize covariance. Good statistical textbooks (for example, Manly, 1986) give guidance on measuring covariance between datasets.

Step 4:   Model evaluation
The evaluation of the predictive performance of the model over the development catchment set and the examination of patterns in model residuals. Steps 3 and 4 are normally iterative, with the evaluation step leading to a recalibration of the model.

Step 5:   Model validation
(a) The evaluation of final model fit over the development catchment set;
(b) The evaluation of the reliability of the model over the independent catchment set.

Researchers have used many different techniques for developing regional relationships between flow statistics and catchment descriptors. It is beyond the scope of this Manual to detail all of these. Demuth (1993) gives a comprehensive review of the regionalization of low flows in western Europe. Smakhtin (2001) provides an
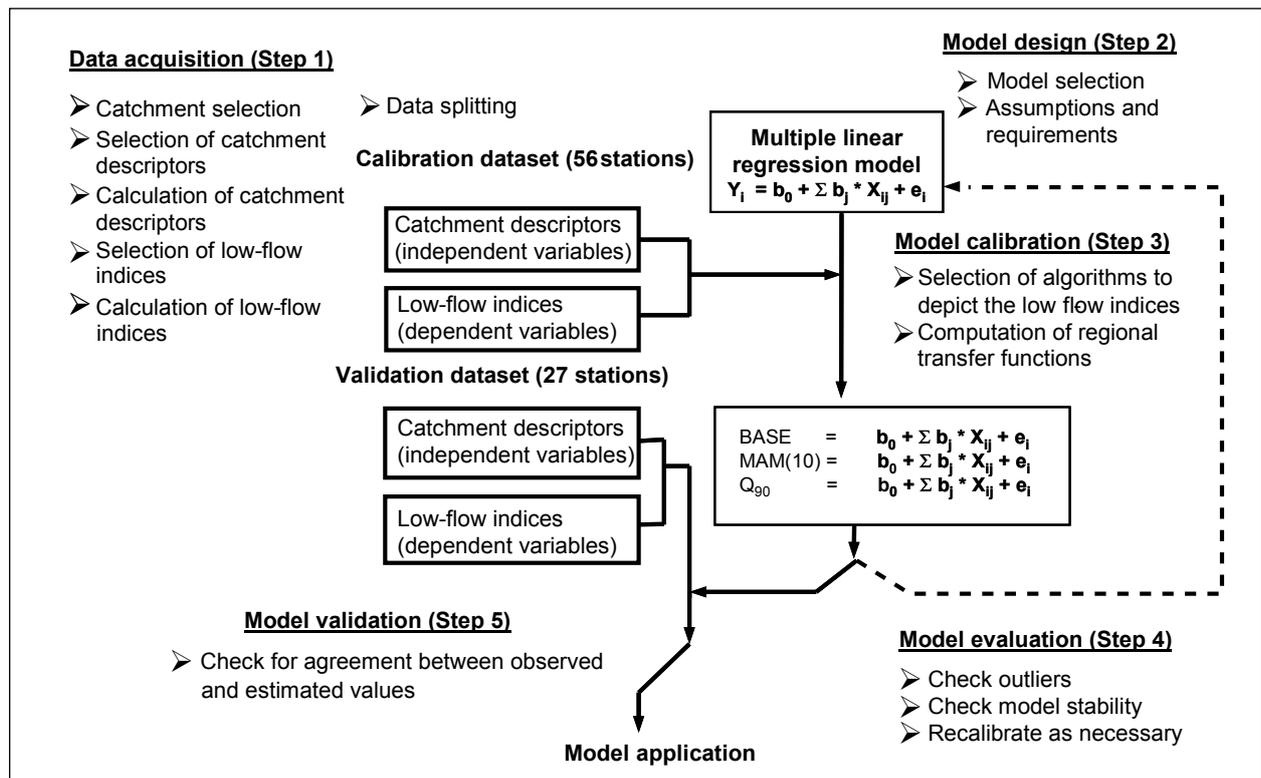

Figure 9.1 Regionalization procedure using multivariate regression (modified according to Demuth, 2004)

extensive review of low-flow hydrology, including the estimation of low flows at ungauged sites, while Young and others (2000) review the history of the regionalization of flow-duration statistics in the United Kingdom.

All techniques require the development of good, robust predictive models. The most widely used methods are based on multivariate regression. Within these models, it is often the case that non-linear transformations of either the flow data and/or catchment descriptors are required to optimize the models.

It should be recognized that these steps are very general and may vary in emphasis, depending on the nature of the analysis. Furthermore, the relationships between catchment descriptors and the low-flow indices of interest may not only be non-linear; they may also (in some cases) not be amenable to capture using classical statistical models.

It may also be necessary to subdivide a region into a number of fixed geographic regions in order to develop reliable models. This concept has been extended to the development of region-of-influence methods in which a dynamic pool of similar catchments to the ungauged catchment of interest is developed, and the estimate for the ungauged catchment is generated directly from observed data from the pool of similar catchments (Holmes and others, 2002).

Whatever approach is selected for developing regional models, great attention should be given to understanding model residuals; if these can be explained in terms of the limitations of the model, then the model can be improved.

In practice, users should always be aware of, and look to incorporate, local hydrometric data within the application of a regional model. Last, but by no means least, users should also be aware of potential anthropogenic influences (including discharges, abstractions and reservoirs) and take them into account when estimating within an ungauged catchment.

There are certain restrictions associated with multiple regression analysis. Although the procedure may be used to quantify the relationship between variables, it does not replace observations and experiments. Equations are based on correlation and not on the understanding of processes, which means that the models are not generally valid and cannot be extra-polated beyond their interval of validity.

9.4 Catchment modelling

9.4.1 Overview of rainfall-runoff models

Rainfall-runoff models are computer-based representations of catchment hydrology which are designed to transform the time series of meteorological inputs and outputs (precipitation, evaporation, temperature, and so on) into the time series of hydrological variables, typically streamflow, but also possibly other storages or fluxes within the drainage basin. Although there are many different ways of classifying models, most systems use a combination of the complexity of the model structure (and therefore the parameter set), the time interval (hourly or less, daily or monthly) and the spatial distribution system (lumped, semi-distributed or fully distributed). Beven (2001) provides a useful integrated guide to the principles and practice of hydrological modelling, as well as a large number of references to many of the issues associated with their use. One of the central issues is the choice of model structure and the level of complexity included. Available models vary from very simple mathematical transformation functions with few parameters, through conceptual models to complex physically based models. However, the distinction between these different types of models is not always clear. The "coefficients" of simple models and parameters of conceptual models are frequently considered to have some physical relevance, while the direct association between the parameters of physically based models and basin properties is often obscured by scale issues. The type of model structure has a large impact on the way in which a model is used, both in terms of calibration (establishing the parameter values for situations where observed streamflows are known) and application to ungauged basins.

Simple models with few parameters lend themselves to automated approaches to calibration, whereas this is more difficult with conceptual models because of the greater parameter space and the degree of interaction between parameters. The parameters of physically based models are intended to be quantified using measurable physical properties, avoiding the necessity of calibration against observed data. However, problems and difficulties exist with the parameter evaluation approaches of all three types of models and parameter quantification procedures. Many sophisticated mathematical methods have been designed to solve the problems of automatic calibration approaches and the determination of globally optimum solutions. However, it is always difficult to be sure that the calibrated parameters reflect the real signals in the data (runoff response

to rainfall), rather than the noise (errors in the input data). The same problem applies to manual calibration approaches, frequently used with conceptual models, which also suffer from potential bias related to the individual model user's calibration method. Some of the criticisms of physically based models relate to the extent to which laboratory-derived physical equations can be applied at the spatial scales typically used in practical modelling projects. A further problem lies in the ability of model users to measure appropriate physical basin properties and to covert these into model parameter values.

Most of the issues referred to in the previous paragraph can be evaluated when observed streamflow data are available. However, beyond the simulation of potential environmental change, the main practical use of hydrological models is to simulate flows where observed data are not available. This means that a method for estimating parameter values is required and that, ideally, the uncertainty associated with those estimates can also be quantified. Frequently used procedures for simple and conceptual models involve the development of regional relationships between model parameter values and measurable basin properties. Inevitably, the development of these relationships relies upon the availability of a sufficiently representative set of basins with observed streamflow data. They also rely upon access to appropriate (in terms of measured variables as well as the scale of measurement) physical basin property data. The application of physically based models in ungauged basins relies upon access to the same type of information and, in fact, may require more detailed data with a higher spatial resolution. In many data-poor regions, the lack of such data represents one of the major limitations to confidence in the results of streamflow simulations in ungauged basins, regardless of the type of model applied.

9.4.2   Application of physically based models with measured parameters

As discussed, the boundaries between model classification categories are not clearly defined. Many models are essentially hybrid, with constituent parts drawing from stochastic and deterministic components. If the deterministic components seek to describe the physics of the process represented, using differential equations that seek to conserve both mass and energy, the models are commonly referred to as being physically based. Physically based models are distributed, in that the model equations include space coordinates and are differential in nature (thus requiring the definition of

boundary conditions) as opposed to integral, as in the case of the conceptual rainfall-runoff models.

It is possible to argue that no model components are truly physically based. Any mathematical description of a process is an approximation of that process and is thus always a conceptualization. The preservation of the physicality of physically based deterministic model components is also called into question in the application of the model. While the process descriptions can model the transport of water under well-defined laboratory conditions, they may not do so when applied to the complexities of a real catchment. The scale of the spatial and temporal discretization of the model is extremely important. In practice, it is necessary to limit the resolution of distributed models to a grid scale that is commensurate with the input data describing catchment properties, climatological variations and available computing power. This lumping and the uncertainty in the input climatic data and field measurement of catchment properties (and hence parameter values) will generally mean that the model will require calibration to compensate for these uncertainties. Hence, the true physicality of the model is compromised. For a fuller discussion of the relative merits of this type of model compared with the simpler, integral conceptual class of deterministic models, the reader is directed to the work of Beven (2001), which provides an introduction to this topic.

Well-known physically based model codes include the SHE (Système Hydrologique Européen) model (Abbot and others, 1986) and the Commonwealth Scientific and Industrial Research Organisation TOPOG-DYNAMIC model (Zhang and others, 1999). Although these models are used for research applications, they are not widely used in operational practice for low flows because of application costs and limitations on data availability outside research catchments. The notable exception to this generalization is the use of linked surface water–groundwater modelling codes, in which the groundwater flow equations are generally solved on a finite difference scheme (such as the USGS MODFLOW model) or a finite element scheme. These modelling codes, linked to surface water codes, are being increasingly used to model the conjunctive use of groundwater and surface water resources within groundwater-dominated catchments.

9.4.3   Regionalization of conceptual models

Most conceptual models consist of components designed to represent the major storages (interception, soil

moisture, ground water, and so on) and fluxes (surface runoff, interflow, groundwater discharge, and so on) that exist within drainage basins and determine the nature of runoff responses to precipitation and other meteorological variables. In turn, the parameters of such models should reflect the operation of hydrological processes at the model spatial and temporal scale within a specific basin. The difficulty with applying such models is to translate the qualitative understanding of relationships between the parameters and basin processes into quantitative relationships that can be expected to generate streamflow simulation results with acceptable levels of uncertainty.

One of the simplest approaches to parameter regionalization is to calibrate the model using all available gauged data, identify regions of hydrological similarity (based on physical basin properties such as topography, soils, geology and vegetation cover) and assume that similar regions will have similar parameter values. Such a method formed the basis of the current national water resources database of South Africa, using simulated monthly flow time series (Midgley and others, 1994) and relied to a large extent on the establishment of an a priori calibration scheme. Unfortunately, the original study did not identify the degree of uncertainty associated with the approach's application.

A more quantitative approach is to attempt to determine relationships between appropriate measurable indices of basin hydrological response and model parameter values (Hughes, 1985; Fernandez and others, 2000; Yokoo and others, 2001; Young, 2006). The most commonly used approach is multivariate regression (discussed in the previous section), in which model parameters are treated as discrete entities. However, this approach ignores the issue of parameter interrelationships, which are generally accepted to exist to a greater or lesser extent in all rainfall-runoff models. Several approaches have been adopted to try to address this issue, including the use of sequential regression techniques (Lamb and others, 2000) and a region-of-influence approach based on canonical correlation analysis (Young, 2006). In an Austrian study, Merz and Blöschl (2004) found that the use of the average parameters of immediate upstream and downstream (nested) calibrated catchment models and regionalization by kriging both performed better than parameters predicted using regression relationships. As already mentioned, many of the problems are associated with a lack of access to quantified physical basin properties, a situation that is improving with advances in remote-sensing technology and

the availability of new data products (Biftu and Gan, 2001). An alternative approach is to interpret the model algorithms and associated parameter values in terms of the physical hydrological processes acting at the basin scale, applying probability distribution principles (Moore, 1985), and to attempt to estimate the parameters directly from a known or intuitive understanding of the operation of these processes. Such an approach may bridge the gap between conceptual models and more complex physically based methods.

9.4.4 Modelling future scenarios
One of the important applications of hydrological models is the estimation of water resources availability under future conditions, which may include changes to the basin response characteristics (land cover, and so on), changes to the forcing climate, changes to resources management (impoundments, abstractions, return flows, and so on) or a combination thereof. Some rainfall-runoff models contain components that allow relatively simple water resources development operations to be simulated, such as run-of-river abstractions, reservoirs with simple operating rules and artificial discharges (for example, industrial and domestic effluent). However, most rainfall-runoff models do not have the required components to simulate complex development impacts, and the use of water resources system models is more appropriate.

Land-cover changes can be simulated, given that the required modifications to the model parameter values can be identified and correctly quantified. This implies that the expected changes (to interception, evapotranspiration losses, surface runoff, and so forth) can be either explicitly or implicitly represented by changes in the model parameters. Physically based models can successfully simulate these impacts, given that the model formulation is truly representative of the real hydrological processes in the specific basin and that the parameters can be quantified with confidence. There is little doubt that conceptual-type models can also be used successfully; but, the parameter changes required for different land-cover change effects may require some form of calibration.

The common approach to simulating climate change effects is to substitute the historical time series of hydrometeorological forcing data with data simulated using a regional climate model to represent various possible future scenarios. However, this approach has the potential of ignoring other changes that may occur as a result of changes to the climate. While these may

take place over longer time scales than the climate changes, they may nevertheless be significant. This is particularly true of arid areas where, for example, surface vegetation cover can be highly dynamic, associated with recent climate events (of the past one to three years), and can have substantial impacts on runoff generation and groundwater recharge.

9.5   Use of local data

If the river-flow records within a catchment of interest are short or incomplete, it is always strongly recommend that these should be used to either improve or contrast the estimates generated using a regional model. The primary limitation of short-record data is that the data are unlikely to capture the natural variability of the catchment under investigation. The objective of most local data schemes is to reconcile the short-record data with this longer-term natural variability through comparisons with an appropriate long-record analogue catchment. The following subsections present commonly used approaches to collecting and using local data as either an alternative to, or to enhance, regional models.

9.5.1   Use of short records

If a short flow record exists for the catchment of interest and a suitable analogue catchment exists, with a long flow record overlapping the short flow record at the site of interest, then it is possible to synthesize a flow record at the site of interest from the long record. This is accomplished by developing a statistical relationship between the short and long record. Regression is commonly used, with the relationship being developed by regressing the short flow record against the flows at the long-term station using the overlap period and predicting a relationship between the two-flow series for this period. The so-developed regression equation can then be used to predict flows at the site of interest for periods outside the overlapping period, which can then be used to determine an FDC. A core assumption in this approach is that the flows within the catchments are synchronous (see section 9.2 for further details on selecting an analogue catchment). Short periods of record are used in order to establish a relationship between the flow in the target ungauged catchment (QX_T) and corresponding flow in the analogue catchment (QX_A).

$$QX_T = a + b \, QX_A \qquad\qquad (9.2)$$

where a and b are estimated by regression from the common record.

The flow axis of the long record FDC for the analogue catchment can then be transformed using this relationship.

Relationships thus developed often have significant associated uncertainties, which can be constrained by developing relationships within more than one suitable analogue catchment. Furthermore, if the emphasis is on simulating low flows, the dependence of the regression relationship on the high flow can be reduced by applying a logarithmic transformation to the data before developing the regression model and then taking the anti-logs of the resultant model.

9.5.2   Estimating the FDC using spot current metering

Flow-duration statistics can be determined by assigning exceedance percentiles to spot flow measurements. Measurement approaches include the use of an impeller-type or ultrasonic current meter or dilution gauging. Exceedance percentiles are derived from the flow percentile corresponding to the flow measured at a suitable gauged natural analogue catchment (section 9.2). Again, the flows at the two sites are assumed to be synchronous. To approximate the FDC, the flow measurements should be taken at a wide range of flows. However, if the specific design problem is in the low-flow range, then more metering should be carried out at low flows.

Once a suitable analogue catchment has been identified, the uncertainty associated with the estimation of the FDC is a function of the amount of spot current metering carried out for a specific percentile point. The method consists of the following steps:

1. Choose a gauged analogue catchment (A) with a well-established one-day FDC and similar catchment geology (see section 9.2 for guidance on the selection of analogue catchments).
2. Measure flow QX_T for the target ungauged catchment of interest (T) with a current meter. If a new programme of spot current meter reading is to be undertaken, then it is recommended that a sampling procedure be adopted based on the repeated independent measurement of flows corresponding to a given percentile flow within the analogue catchment. If historical data are to be used, this more rigorous procedure may not be possible, in which case assign QX_T a percentile, PX_A, (from the FDC for the analogue catchment) corresponding to flow QX_A at the analogue catchment on the same day.
3. Plot QX_T against PX_A.

An example of the approach using historical data is summarized in Table 9.1 for the Pang catchment (located in the Thames basin) using the Kennet catchment as the un-connected analogue catchment. The historical current metering, QX_T, for the Pang and the flows measured on the same day for the gauging station on the Kennet at Theale, QX_A, are shown in Table 9.1.

The flow measured with a current meter QX_T within the target catchment is plotted against percentile PX_A as demonstrated in Figure 9.2. An FDC constructed from the full measured flow record for the Pang is also shown in this figure for comparison purposes.

Three sources of error must be considered when using this method, as follows:

(a)   The hydrometric error associated with the current meter measurements within the ungauged catchment;

(b)   The assumption that the measurement is representative of the day's average flow;

(c)   The errors associated with assuming that the flows within the ungauged and analogue catchments are synchronous.

Figure 9.2 *Annual FDC for the Pang from current metering data*

Table 9.1 Current metering for the Pang catchment

Date of current metering	Current metering QX_T (m³/s)	Flow within the Kennet QX_A (m³/s)	Percentile on Kennet PX_A
1/5/Year	0.63	11.100	34
16/5/Year	0.67	9.630	39
1/6/Year	0.52	7.360	56
16/6/Year	0.30	6.460	63
1/7/Year	0.43	6.060	68
16/7/Year	0.34	6.060	68
1/8/Year	0.33	5.440	72
16/8/Year	0.30	4.870	80
1/9/Year	0.27	4.590	84
24/8/Year	0.30	5.420	78
16/9/Year	0.29	5.380	75
1/10/Year	0.24	4.420	88
16/10/Year	0.27	4.220	90

If good hydrometric practice is followed, the largest errors are associated with (c) at low flows. The errors have a random component and a systematic component. The random (sampling error) component can be reduced by repeated measurements.

However, systematic errors cannot be reduced. The origins of the systematic component can be best understood by considering the probability of occurrence of a specific flow percentile. If the target catchment is at the Q_{95} flow for the catchment, there is a 95 per cent chance that the flow within the analogue catchment will be equal to, or greater than, the Q_{95} per cent flow, and only a 5 per cent chance that it will be lower. At low flows, therefore, there is a systematic tendency for the low flows to be under-estimated. That is, if the true flow percentile is Q_{95}, the likelihood is that the flow within the analogue catchment will correspond to a less extreme flow percentile. At higher flow percentiles, the importance of the systematic error reduces, and at the Q_{50} flow it is negligible.

9.5.3   Spatial interpolation using FDCs

An alternative approach to developing relationships between short- and long-record time series of flows was developed by Hughes and Smakhtin (1996). This approach is used for "patching" or extending the time series of daily flow data using FDCs, which can also be used for generating time series of flow data at ungauged sites if combined with a regional statistical model for estimating the FDC. The approach is based on the assumption that hydrographs from rivers in a broadly climatically homogeneous region will have similar patterns of rises and falls. The actual flow values and rates of rise and fall will be related to basin response characteristics (determined by, among others, topography, soil, vegetation and geology), as reflected in the shapes of FDCs. The analysis procedures are simple, and are as follows:

(a)   Generate one-day calendar month FDCs for all observed flow data in the same climate area as the ungauged target catchment;

(b)   Generate equivalent FDCs for the ungauged target catchment using regional data (see Smakhtin and others, 1997, or the region-of-influence approach outlined in section 9.3);

(c)   For each day in the observed time series, find the exceedance percentile of the daily flow in the appropriate FDC and determine the ungauged site daily flow from the ungauged site FDC corresponding to the same exceedance percentile.

Where there is more than one time series of observed flow, the ungauged result will be a weighted mean of several estimates.

The method can also be used to simulate the impacts of some types of developments within a basin, assuming that the developments can be expressed as changes to the FDC characteristics. Examples might include run-of-river abstractions and land-use change effects. Although Smakhtin and Masse (2000) applied the same principle, they used the time series of smoothed rainfall data, instead of flow data, as the "observed" signal.
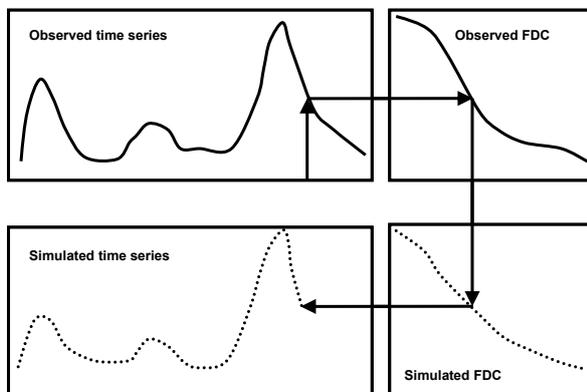

Figure 9.3 *Illustration of the "patching model" approach*

References

Abbot, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connel and J. Rasmussen, 1986: An introduction to the European Hydrologic System – Système Hydrologique Européen, "SHE" 2: Structure of a physically based, distributed modeling system. Journal of Hydrology, 87: 61–79.

Beven, K.J., 2001: Rainfall-runoff modelling: The Primer. John Wiley and Sons, Chichester, United Kingdom.

Biftu, G.F. and T.Y. Gan, 2001: Semi-distributed physically based hydrologic modeling of the Paddle River Basin, Alberta, using remotely sensed data. Journal of Hydrology, 244: 137–156.

Croker, K.M., A.R. Young, M.D. Zaidman and H.G. Rees, 2003: Flow duration curve estimation in ephemeral catchments in Portugal. Hydrological Sciences Journal, 48(3): 427–439.

Demuth, S., 1993: Untersuchungen zum Niedrigwasser in West Europa. Freiburger Schrifen zur Hydrologie, Institut fur Hydrologie Band 1.

Demuth, S., 2004: Self Guided Tour – Estimation of low flow indices at the ungauged site. In: Hydrological Drought Processes and Estimation Methods for Streamflow and Groundwater (L.M. Tallaksen and H.A.J. van Lanen, eds). Developments in Water Science, Elsevier, Amsterdam.

Fernandez, W., R.M. Vogel and A. Sankarasubramanian, 2000: Regional calibration of a watershed model. Hydrological Sciences Journal, 45(5): 689–707.

Holmes, M.G.R., A.R. Young, A.G. Gustard and R. Grew, 2002: A region of influence approach to predicting flow duration curves within ungauged catchments. Hydrology and Earth System Sciences, 6(4): 721–731.

Hughes, D.A., 1985: Conceptual catchment model parameter transfer investigations in the Southern Cape. Water SA, 11(3): 149–156.

Hughes, D.A. and V. Smakhtin, 1996: Daily flow data time series patching or extension: a spatial interpolation approach based on flow duration curves. Hydrological Sciences Journal, 41(6): 851–871.

Lamb, R., J. Crewitt and A. Calver, 2000: Relating hydrological model parameters and catchment properties to estimate flood frequencies from simulated river flows. Proceedings of the British Hydrological Society Seventh National Hydrology Symposium, Newcastle, September 2000, 3.57–3.64.

Manly, B.F., 1986: Multivariate Statistical Methods: A Primer. Chapman and Hall, London, ISBN 0412603004.

Merz, R. and G. Blöschl, 2004. Regionalisation of catchment model parameters. Journal of Hydrology, 287: 95–123.

Midgley, D.C., W.V. Pitman and B.J. Middleton, 1994: Surface water resources of South Africa 1990. Volumes I to VI, Water Research Commission, Pretoria, Report Nos. 298/1.1/94 to 298/1.6/94.

Moore, R.J., 1985: The probability-distributed principle and runoff production at point and basin scales. Hydrological Sciences Journal, 30(2): 273–297.

Rees, H.G., M.G.R. Holmes, A.R. Young, S.R. Kansakar, 2005: Recession based hydrological models for estimating low flows in ungauged catchments in the Himalayas. Hydrology and Earth System Sciences, 8(5): 891–902.

Smakhtin, V.U., 2001: Low Flow Hydrology: A Review. Journal of Hydrology, 240 (3–4): 147–186.

Smakhtin, V.U. and B. Masse, 2000: Continuous daily hydrograph simulation using duration curves of precipitation index. Hydrological Processes, 14: 1083–1100.

Smakhtin, V.U., E. Creuse-Naudine and D.A. Hughes, 1997: Regionalisation of daily flow characteristics in part of the Eastern Cape, South Africa. Hydrological Sciences Journal, 42(6): 919–936.

Yokoo, Y., S. Kazama, M. Sawamoto and H. Nishimura, 2001: Regionalisation of lumped water balance model parameters based on multiple regression. Journal of Hydrology, 246: 209–222.

Young, A.R., 2006: Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model. Journal of Hydrology, 320(1–2): 155–172.

Young, A.R., A. Gustard, A. Bullock, A.E. Sekulin and K.M. Croker, 2000: A river network based hydrological model for predicting natural and influenced flow statistics at ungauged sites. Science of the Total Environment, 251–252: 293–304.

Zhang, L., W.R. Dawes, T.J. Hatton, P.H. Reece, G.T.H. Beale and Z. Packer, 1999: Estimation of soil moisture and groundwater recharge using the TOPOG-IRM model. Water Resources Research, 35: 149–161.

10. Estimating low flows in artificially influenced rivers

10.1   Introduction

In natural rivers, the magnitude of low flows is determined by climate inputs and hydrological processes (Chapter 4). As a result of the development of rivers for public water supply, irrigation, power production, navigation and the dilution of domestic and industrial effluent and because of land-use change, few rivers now possess natural river-flow regimes. The impact of water resources development is most severe during periods of low flows when absolute volumes of water transfers represent a significantly higher proportion of the natural flow regime. The impact of artificial influences on natural low flows can be estimated either by analysing the time series of natural and artificial influences or by adjusting low-flow statistics with an estimate of the artificial component. This chapter outlines the approaches for estimating the impact of artificial influences on low flows. In addition, the chapter provides a basis for assessing the degree of artificial influence on measured river flows. This is an essential step in identifying which flow records should be rejected from studies when the objective is to relate low-flow statistics or parameters of hydrological models to catchment descriptors. When developing such models, it is clearly inappropriate to use data from rivers that are artificially controlled.

In highly developed catchments, the artificial component of flow may exceed the natural contribution, particularly at low flows. Information on the location, volume and timing of artificial influences is vital to enable water resources managers to allocate freshwater to users and preserve the ecological quality of rivers during periods of low flow or drought. The water user may sometimes monitor major abstractions and discharges on a daily or monthly basis. Access to these data is useful for identifying the effect of the artificial influences on the natural flow regime and for water resources management. In some countries, water use is regulated within a legal framework, where licences are issued to those who need to abstract water (from a freshwater body) or discharge effluent (into a freshwater body). Such licences

typically prescribe limits on the volume of water (or effluent) to be abstracted (or discharged) at a particular site on an annual or monthly basis. Users may be obliged to periodically provide the regulatory authority with information on the volume of water actually used. Similarly, reservoir operators are required by licence to follow a regime of regulated releases (compensation flows) to ensure that a minimum flow is maintained in the river downstream. They also periodically provide the regulatory authority with data on the releases. The information provides a good indication of past and future water use within a catchment and helps water managers to determine appropriate operational responses, or strategies, for maintaining supply.

10.2   Inventory of artificial influences

The principal artificial influences on low river flows are as follows:

- Abstractions from rivers;
- Abstractions from groundwater;
- Discharges into rivers;
- Reservoir storage;
- Land-use change.

To be able to incorporate the impacts of artificial influences into flow estimation, it is essential to quantify the major influences upstream of the site of interest (Bullock and others, 1994). The first step in any low-flow investigation is thus to produce a digital or hard-copy map of the catchment or region and to plot every artificial influence on the map. One of the major constraints of this task is that very few agencies routinely measure the influences on a daily, monthly or even annual time step. As a result, it is often necessary to make approximations of the magnitude of these inputs, storage changes and outputs and how they vary annually or seasonally. A second constraint is that the location of artificial influences is often not known, or, if they are known, the information is held by a large number of different agencies. It may be necessary to contact one or more of the following organizations to develop an inventory:

(a) Hydropower companies, for information on abstractions, diversions and change in reservoir storage;

(b) Power companies, for information on abstractions and returns from thermal power plants;

(c) Water utility companies, for information on reservoirs and river and groundwater abstractions;

(d) Water utility companies, for information on effluent discharges;

(e) Private companies, for information on industrial abstractions and discharges;

(f) Irrigation agencies, for information on river and groundwater abstractions and reservoir storage and the efficiency of irrigation schemes;

(g) Individual farmers, for irrigation data;

(h) Navigation agencies, for information on river diversions;

(i) Consulting companies which may have information on the design of water resources schemes;

(j) Government departments which may have inventories of major water resources projects;

(k) Agencies that have carried out previous low-flow investigations;

(l) Land-use survey agencies, including forestry departments and mapping agencies;

(m) Basin authorities which may hold all, or some, of the above information.

The recorded time series of artificial influences on low flows are ideal data. For major water resources schemes, these may be available. Examples include daily or monthly values of reservoir storage, reservoir abstraction, reservoir spill, reservoir compensation flow, river and groundwater abstractions, river diversions for hydropower schemes and effluent discharges from sewage treatment plants. In the absence of measured data, it is necessary to estimate artificial influences indirectly.

10.3   Artificial influences

10.3.1 River and groundwater abstractions

In the absence of measured data, and where there is a regulatory infrastructure responsible for controlling abstractions, abstraction licences can provide valuable information. However, a licence states only the legal limitations on abstractions. Operationally, abstractions may be significantly less than the legal abstraction regime, or, in some cases, greater than permitted.

The following sections are drawn from licensing policy in the United Kingdom. However, the key issues apply to countries with a different regulatory framework and the hydrological principles are generic and apply to countries where there is no licensing framework. A licence (for an example, see section 6.5.4) typically identifies the name and address of the abstractor, the location of the abstraction point and the permitted annual, seasonal and maximum abstraction rate.

Figure 10.1 illustrates two different abstraction patterns (constant and seasonal) and the impact on downstream river flows. A licence can contain information on multiple-abstraction locations, different purposes, and different seasonal abstractions and imposed licence conditions.
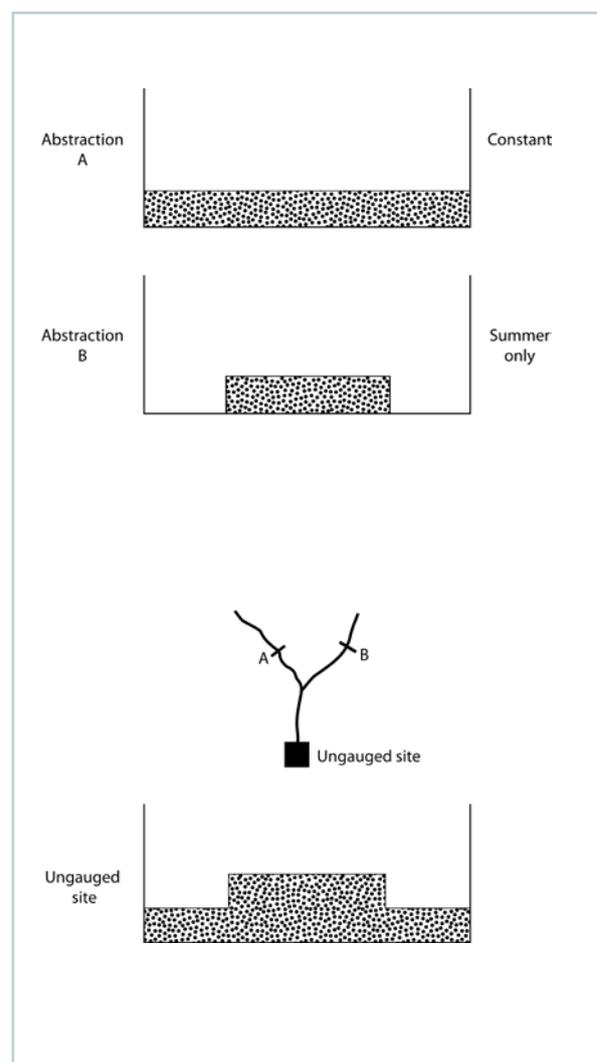
Figure 10.1 Impact of two abstractions at a downstream ungauged site
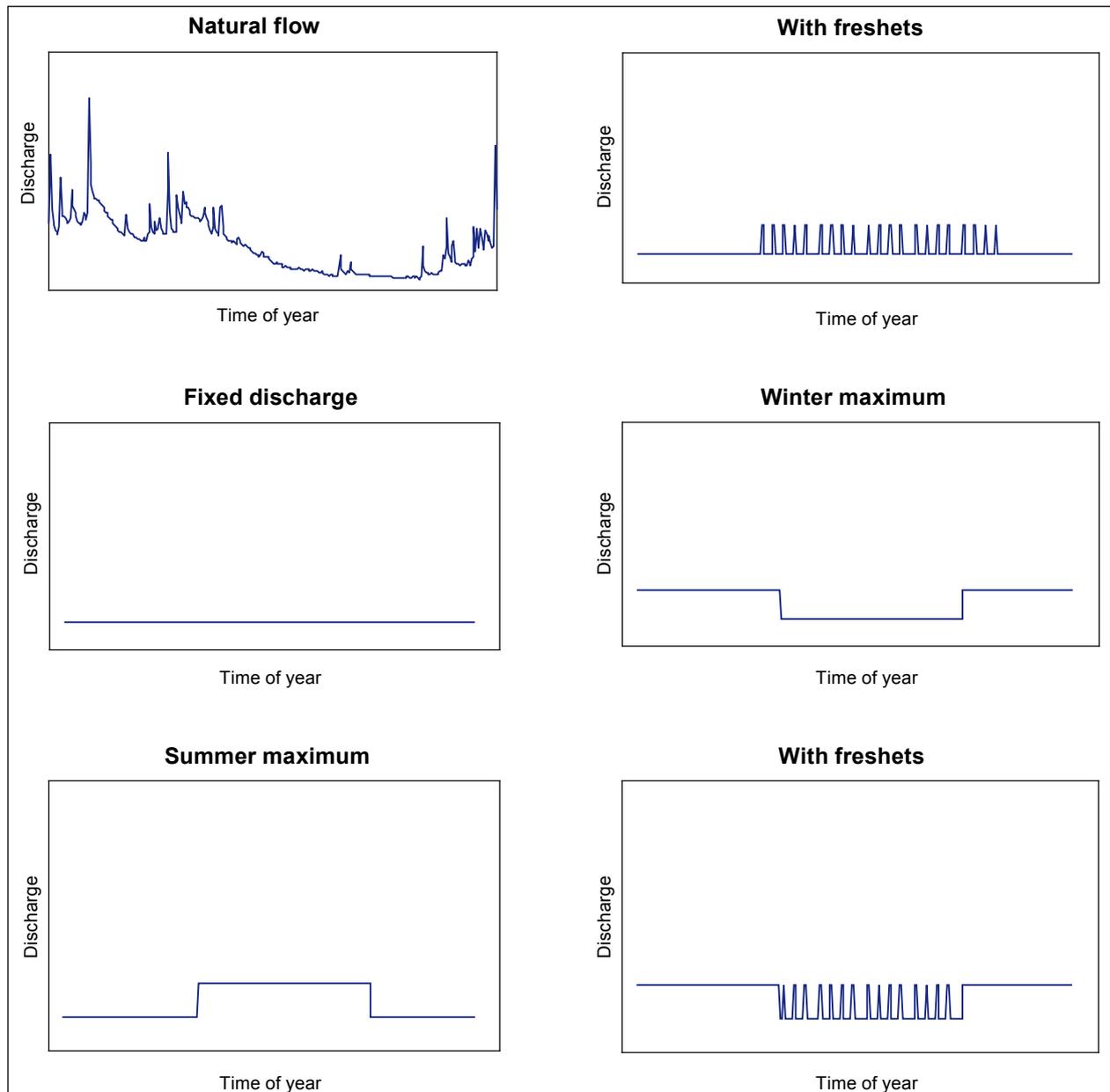
Figure 10.2 *Examples of reservoir release profiles (Source: Gustard and others, 1987)*

The following information is required (this may be specified in a licence):

(a)   Location and source: Water may be abstracted from groundwater or surface water from one or more sites;

(b)   Location: A river abstraction could be a reach of river covering several kilometres or, as is commonly the case for agricultural abstractions, from a number of watercourses. Groundwater abstractions are usually from a single borehole or a defined well field;

(c)   Location: A licence may integrate sites and specify individual abstraction rates;

(d)   Purpose: It is important to record the purpose of the abstraction. Irrigation abstractions are effectively lost to the river; however, an abstraction for public water supply is normally returned as effluent downstream or to an adjacent catchment. Although these key pathways are complex and rarely documented, they have major impacts on low flows;

(e)   Abstraction rate: The mean daily abstraction rate should be estimated;

(f) Seasonality of abstractions: This should be estimated and may follow a distinct seasonal pattern – for example, maximum rate during the dry season;

(g) Abstraction restrictions: Conditions may be imposed on the abstractor so that abstraction is ceased when certain conditions prevail – for example, the flow at a prescribed flow point (or groundwater level at a monitoring borehole) falls below a particular threshold;

(h) Measurement: The abstractor (licence holder) may be required to monitor the volumes of water actually abstracted (on a daily, monthly or annual basis);

(i) Water use: An estimate is required of the percentage of abstracted water that is returned – for example, cooling water losses from thermal power plants.

If there is no measured data or information from licences, then abstractions have to be estimated. This can be done through general knowledge or a site visit to the specific scheme. Estimates for irrigation abstraction can be based on crop area and crop water-use statistics and local advice on irrigation practices. For major irrigation schemes, areas can be estimated from remote-sensing data. Similarly, abstractions for public water supply can be estimated from per capita water consumption and an estimate of the population served. With regard to hydropower, approximate flow estimates can be derived from monthly or annual power production data and physical constraints on diversion schemes. Abstractions to pumped storage reservoirs can be estimated from pumping rates and the pumping period. In many situations, estimates can be made by combining a thorough understanding of the scheme with discussions with the scheme operator.

For regional studies, for example on the European scale, detailed information on water use is not available. Rees and Cole (1997) combined data based on geographic information systems (GIS) from Eurostat on the degree of urbanization (an index of population density) with average daily domestic consumption (1016 l/hd/d) and average daily industrial consumption (1016 l/hd/d). This enabled urban water demand to be compared with a range of annual and seasonal natural low-flow statistics such as the 90 percentile low flow. This was used to highlight areas of water stress across Europe using a consistent methodology. The main problem with this more generalized approach is that no account can be made of water returned to rivers in urban areas.

In many countries, irrigation is the dominant water use. For example, it accounts for 80 per cent of water demand in Greece and 65 per cent in Spain. Rees and Cole (1997) also developed a European model to estimate the spatial distribution of irrigation demand, again based on a GIS approach. The model combined estimates of the area of irrigated crops, an allocation model of crop-type distribution, a crop water requirement model and irrigation efficiencies to estimate irrigation demand across Europe. This enabled irrigation demand expressed as a proportion of mean annual discharge to be mapped across Europe. Although these approaches are not appropriate for detailed investigations, they provide a consistent method for estimating areas of water stress on a regional scale and contribute to large-scale environmental assessment (EEA, 1998).

10.3.2 Artificial discharge released into rivers

The following information is required on discharge released into rivers:

(a) The location of each discharge site;
(b) The average volume of discharge released into the river;
(c) The seasonal variability in discharge.

Obtaining measured data on actual discharge volumes is extremely problematical. Although measurements may be taken from large effluent treatment plants, discharge estimation must normally be carried out indirectly.

For example, the population served by a treatment plant can normally be used together with per capita water consumption or estimating the discharge returned to the river. This provides only an approximate guide to actual discharge volumes since it is difficult to quantify accurately the true population served by the works, the per capita water use and additional industrial effluent that may flow into a sewerage system.

10.3.3 Impounding reservoirs

To take into account the impact of reservoirs on low flows, it is recommended that the recorded daily or monthly time series of flow below the reservoir be used. If measurements are not available, then estimates of long-term mean monthly values of reservoir spill and compensation flows should be made. Figure 10.2 illustrates a range of typical release profiles. The impact of a reservoir on downstream flows depends on the reservoir type and the operating policy for managing the reservoir. Reservoirs can be divided into four main types as follows:

(a) Impounding reservoirs with a direct abstraction from the reservoir to supply a city or irrigation scheme. The downstream impact depends on the operation of the reservoir; however, it normally reduces peak flows and replaces the natural low-flow variability by controlled releases (compensation flow) from the dam;

(b) Regulating reservoirs, which regulate the river flow at an artificially high level to support an abstraction downstream. Again, the impact is generally that of reducing peak flows and replacing the natural low-flow variability by controlled releases. Given that water is not abstracted at the dam and is allowed to flow down the river, the impact is generally less than that of impounding reservoirs;

(c) Pumped-storage reservoirs, where water is pumped from a river to a reservoir. The impact is the same as that of direct abstraction from a river;

(d) Multi-purpose reservoirs – normally impounding or regulating – which are used for more than one purpose, for example, supporting abstraction, generating hydropower, flood control.

10.3.4 Groundwater abstractions

Abstractions from groundwater sources do not have an immediate impact on the flows in rivers because of the complex response of stream flow to the pumping of water from an unconfined, or semi-confined, aquifer (Chapter 4).

For an individual well, the impact of abstraction on river flow is complex and depends upon the following:

- Aquifer hydrogeology;
- Distance from the stream;
- Seasonality of pumping;
- Pumping rate;
- The degree of hydraulic connection between the aquifer and the stream.

The options for estimating the impact of groundwater abstraction on low flows include the following:

(a) To assume that groundwater abstraction has a direct impact on river flow. This approach tends to overestimate the impact at extreme low flows because the storage properties of the aquifer are not taken into account. However, this simple approach may

be appropriate where the abstraction is close to the stream, where the groundwater abstraction is known to be a small proportion of low flow in the river, or where a preliminary estimation is required;

(b) To use an analytical solution for calculating the impact of groundwater pumping from a single borehole or a group of boreholes on an adjacent stream. The Theis (1941) model is the simplest of the analytical models available and requires a minimum amount of input data for describing the aquifer. It has been implemented on a regional scale for estimating the impact of abstraction on low-flow statistics (Bullock and others, 1994). The principal assumptions and simplifications within the Theis model are as follows:

(i) The aquifer is isotropic, homogeneous and infinite in areal extent;

(ii) The borehole is screened over the entire depth of the aquifer;

(iii) The pumping rate is constant with time;

(iv) Water is released instantaneously from storage in the aquifer;

(v) Water-level variation in the stream caused by changes in discharge is neglected;

(vi) The stream represents the sole source of recharge, and, accordingly, recharge from infiltrated precipitation can be ignored;

(vii) The stream fully penetrates the aquifer;

(c) To use physically based groundwater models (section 9.4.2), which model the impact of groundwater pumping on local water tables, the movement of water through the aquifer, the hydraulic connection between the aquifer and the stream, and the impact on river flow. Detailed measurements of aquifer properties and the hydraulic connectivity between the aquifer and the river and the time series of precipitation, evaporation, groundwater level and river flow are required to develop these models. They will, however, provide the most accurate estimates of the impact of groundwater pumping on low flows and are recommended where this is a primary and significant impact (Tallaksen and van Lanen 2004).

10.4   Estimating artificially influenced low flows

10.4.1 Gauged flow data

If continuous flow measurements have been taken at, or close to, the ungauged site, this data can be used to determine the flow indices and statistics described in this Manual. However, care must be taken over the interpretation and extrapolation of these data, because the impact of the artificial influence may have changed over

time. This invalidates extreme value analysis (Chapter 7), which assumes a stationary process with no trends in the data.

10.4.2 Ungauged sites

At an ungauged site, low flows can be estimated by using a continuous simulation model to determine a time series of daily or monthly flows (Chapter 9).

This series is then adjusted for artificial influences, using recorded (at a daily or monthly time step) or estimated (usually using mean monthly values) abstractions and discharges (section 10.3). Low-flow statistics can also be estimated at ungauged sites. Standard procedure is to develop a regional model (Chapter 9) to estimate natural flow statistics for each month of the year, for example, the natural flow-duration curve for each month. These are then adjusted using a monthly influence profile.

10.4.3 Construction of monthly influence profiles

It is necessary to define the cumulative impact of all upstream artificial influences before adjusting the natural low-flow statistics at an ungauged location.

The net impact of these artificial influences during each month can be represented by a monthly influence profile that allows the monthly variations in operating regimes to be taken into account. The three key steps to the construction of a monthly influence profile at a specific location are the following:

(a) The identification of all occurrences of artificial influences upstream of the ungauged site;

(b) The quantification of monthly abstraction, discharge and reservoir impacts for each identified artificial influence;

(c) The summation of monthly abstraction, discharge and reservoir impacts at the location.

Although as a general rule recorded data should be used, in practice, estimated data may have to be used following the above guidelines. This can be carried out manually, yet it is more efficient to digitally overlay catchment boundaries on spatial data files containing the location and monthly profiles of artificial influences. An operational example of this is the LowFlows 2000 software, which is used for estimating natural and artificial low-flow statistics at ungauged sites in the United Kingdom (section 12.3).

The impacts of an impounding reservoir can be taken into account using the following steps:

(a) Identify reservoirs that lie immediately upstream of the ungauged site and draw the catchment boundaries of the reservoired catchment(s);

(b) Identify all influences that lie within the impounded catchment(s) and discount them from the list of influences above the ungauged site of interest;

(c) Estimate the natural-flow statistics using a regional model only for the incremental catchment, which is the catchment lying between the site of interest and any upstream reservoirs (this is illustrated in Figure 10.3). Lastly, treat the influence profile(s) for the impounding reservoir(s) as discharges released into the ungauged, incremental catchment.
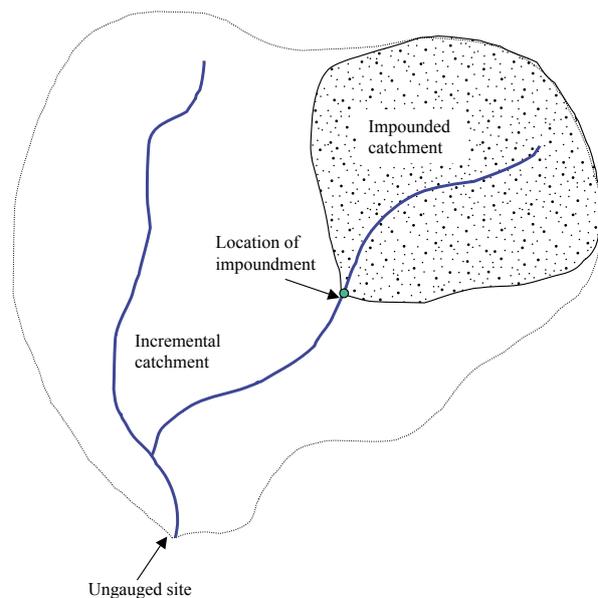
Figure 10.3 *Schematic representation of the treatment of impounding reservoirs*

10.4.4 Summation of monthly abstraction, discharge and reservoir impacts

The monthly influence profile at an ungauged (or even gauged) site is the net balance for any given month of all upstream abstractions and positive values of discharges and reservoir releases. In the case of a catchment containing only abstractions and discharges, the monthly artificial influence profile can be simplified to the following:

IP(k) = Discharges (k) – Abstractions (k), where k = months 1 to 12.
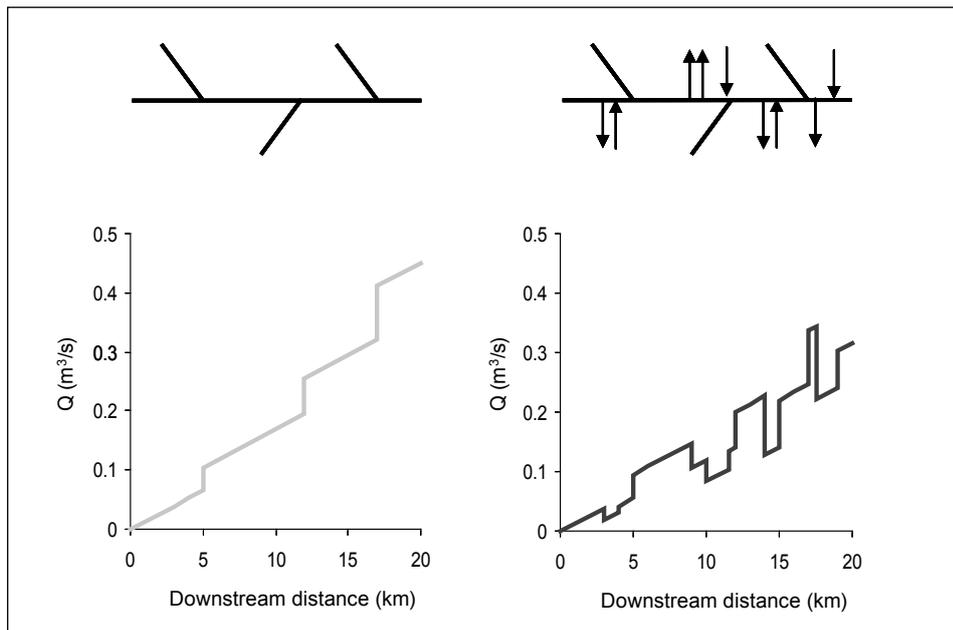
Figure 10.4
Flow accretion diagram (left); residual flow diagram (right)

The calculated monthly influence profile can be:

(a) Negative in all months in a catchment in which abstractions exceed discharges throughout the year;
(b) Positive in all months in a catchment in which discharges exceed abstractions throughout the year; or
(c) Positive and negative in different months in more complex catchments, particularly when seasonal abstractions are significant.

Once the natural low-flow statistics have been determined and the profiles for the upstream artificial influences constructed, the impacts of the influence can be incorporated into the natural monthly flow statistics. These influenced monthly flow statistics can then be recombined to give annual statistics.

10.4.5 Residual flow diagrams

Residual flow diagrams and flow accretion diagrams (Figure 10.4) provide a useful tool for displaying and interpreting the effects of artificial influences within a catchment. The diagram shows how, for a given flow statistic (mean flow in the example shown), the estimated flow increases, or decreases, along a river: first, when no artificial influences are considered (flow accretion diagram – left); and, second, when artificial impacts are considered (residual flow diagram – right). Step changes are seen where a tributary, abstraction or discharge occurs.

10.5   Flow naturalization

The process of distinguishing the natural flow component from the measured artificially influenced flow record is called naturalization. A key application is to identify whether observed changes in river flow are due to natural variability or to artificial influences changing over time.

The adjustment of gauged daily or monthly flows is normally carried out for the largest and most easily quantified artificial influences, for example, "exported" abstractions above the gauging station or "imported" effluent discharges into a river. Long series of naturalized flows can be exceptionally valuable in detecting low-flow trends. Normally, no attempt is made to account for the often subtle impacts of land-use change, and these may be important.

Essentially, naturalization involves the adjustment of the observed (artificially influenced) flow record according to the known artificial influences upstream. The procedure requires a systematic record of the influences, including the times, rates and durations of abstractions, discharges and reservoir releases. The data should be in compatible units, and an appropriate method to temporally disaggregate the data should be applied, as necessary (for example, from monthly to daily). On any day, the natural flow, Q_n, at a gauging station can be approximated by simply adjusting the observed flow, Q, according to the net upstream artificial
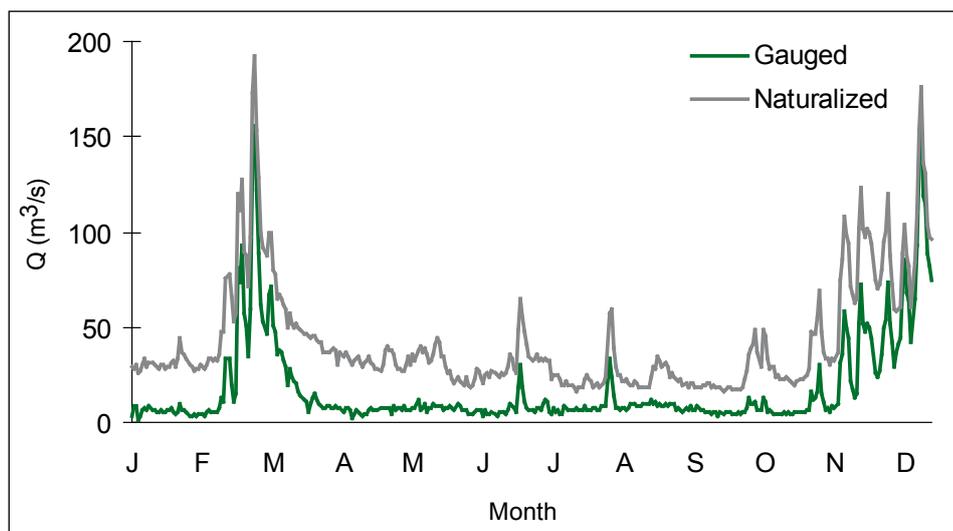
Figure 10.5
Disaggregation of river
flows into gauged and
natural components
(River Thames at Kingston,
United Kingdom, 1997)

influences. For example, if upstream of a gauging station there is a constant abstraction for water supply of 15 m³/s and an "imported" sewage effluent discharge of 5 m³/s, then the net impact is a reduction in river flow of 10 m³/s. In order to derive a naturalized flow record from a time series of gauged flows, it would be necessary to add 10 m³/s to each measured mean daily discharge. If abstractions or discharges vary on a daily basis, the net impact must be calculated daily and the time series of gauged flows adjusted accordingly. Given that there are often several artificial influences in a catchment, it is important to identify all upstream impacts in the catchment and to use abstraction and discharge data to calculate the total net impact in order to adjust a gauged time series. These may vary seasonally and over decadal time scales. If abstraction and discharge measurements are not taken, then they will have to be estimated using the best data available (section 10.3).

It should be noted that there could be a high degree of uncertainty in estimating artificial influences. While, typically, there may be an error of ±5 per cent in the observed flow, the error associated with the artificial influence can be around ±40 per cent, or higher. An example of a naturalized hydrograph for the River Thames, a heavily influenced catchment in the United Kingdom, is shown in Figure 10.5. In January 1997, the naturalized discharge was approximately 20 m³/s higher than the gauged discharge measured at Kingston. This is the result of a net reduction in river flows caused by high abstraction rates for public water supply in London.

Figure 10.6 illustrates the time series of 30-day annual minima flows derived from the 120-year gauged and

naturalized time series (Figure 10.5) for the River Thames. It shows that the gauged flow series indicates a decrease in 30-day minimum flows. However, once the record is adjusted for the artificial component (primarily, increasing abstractions for public water supply in London), recent low flows are seen to be substantially higher than those which characterized the early record.

10.6 Climate and land-use change

The impacts of both climate and land-use change on low flows are complex. Chapter 9 reviews the modelling procedures that can be used to estimate the impact of changing land use and the sensitivity of low flows to different climate change scenarios. It is often difficult to differentiate between the effects of land-use change and other human influences and climate variability. Approaches include paired catchment studies with contrasting land use and using hydrological models to simulate the impact of changing vegetation parameters on low-flow response.

In a review of land-use change impacts on low flows, Tallaksen and van Lanen (2004) identified a wide range of different responses, depending on land-use change and climate regime. With respect to climate variability, although individual catchment studies have identified positive and negative trends in long time series of low flows, studies over large regions do not indicate consistent patterns (Hisdal and others, 2001). Analysing the sensitivity of low flows to changing climate inputs provides a methodology for estimating the range of low-flow responses to climate change. However, these produce only scenarios of possible outcomes and not forecasts of future events.
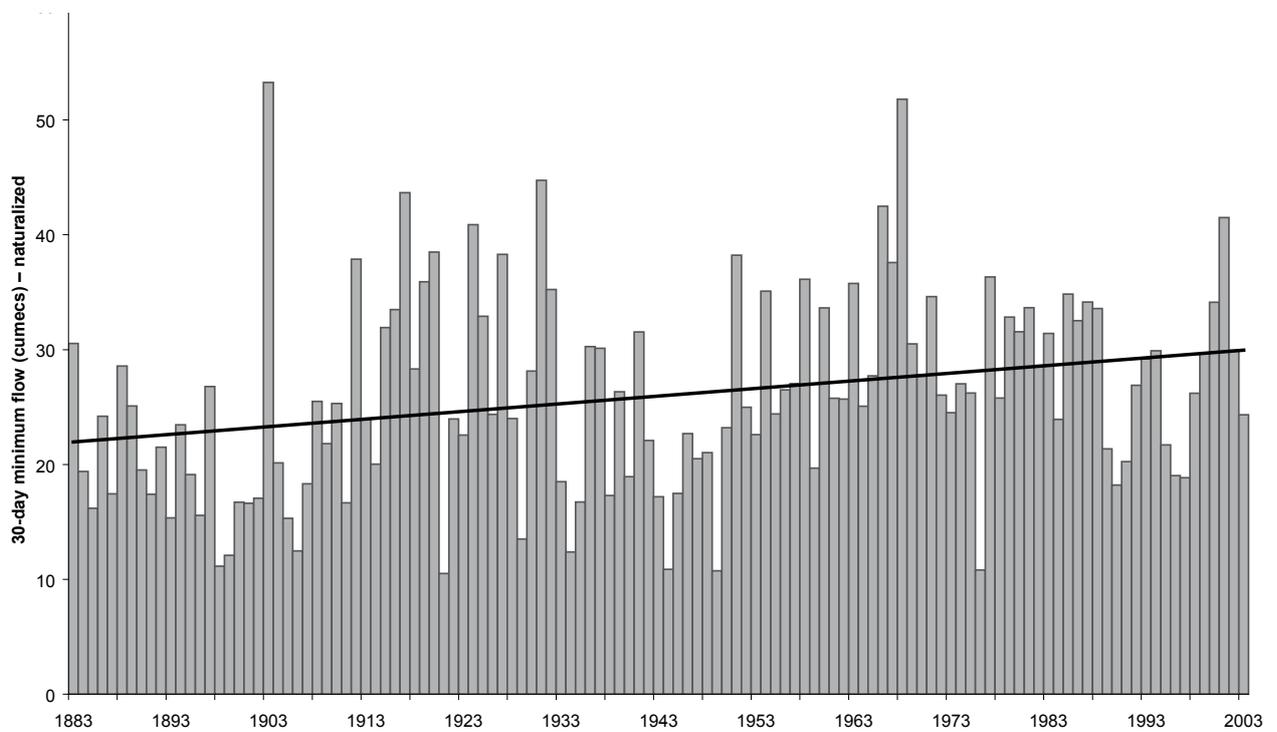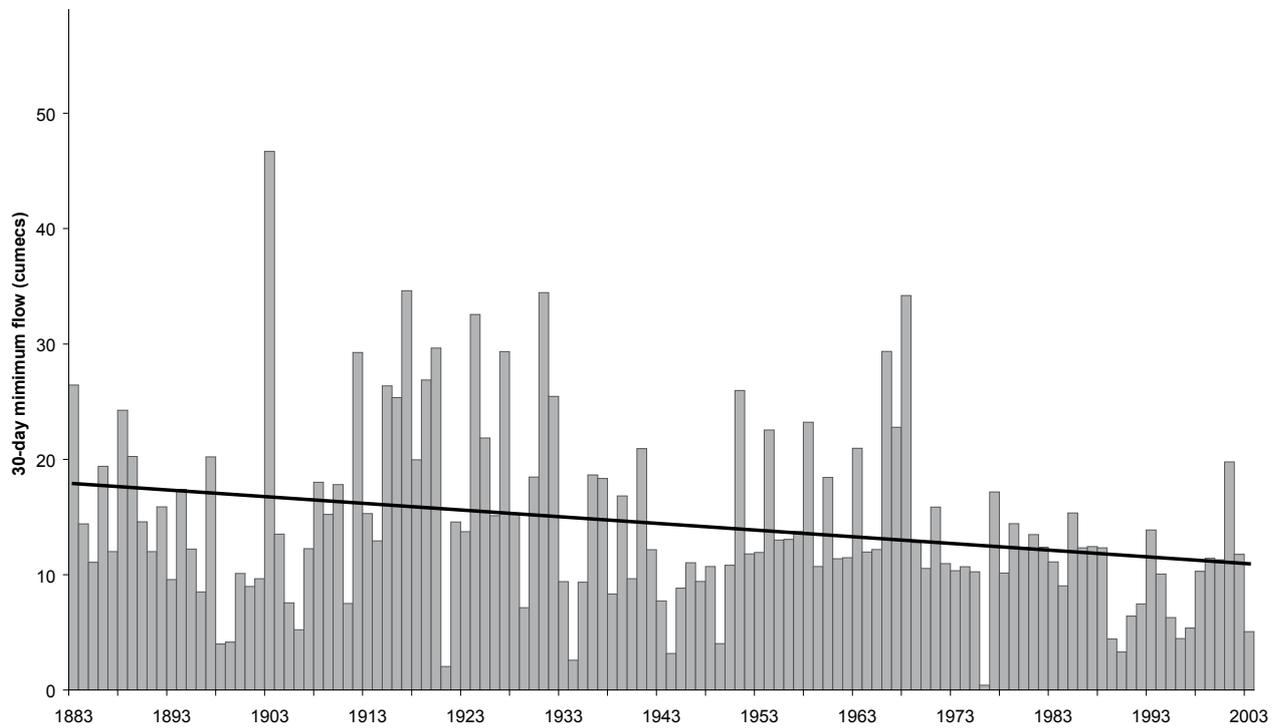
Figure 10.6 *Trend line for 30-day annual minima for gauged and natural flow series (River Thames in the United Kingdom)*
(Source: Terry Marsh, Centre for Ecology and Hydrology, Wallingford, United Kingdom)

References

Bullock A., A. Gustard, K. Irving, A. Sekulin and A. Young, 1994: *Low Flow Estimation in Artificially Influenced Catchments*. NRA R&D Note 274, Bristol, United Kingdom.

European Environment Agency (EEA), 1998: *Europe's Environment: The Second Assessment*. Copenhagen.

Gustard, A., G.A. Cole, D.W. Marshall and A. Bayliss, 1987: *A study of compensation flows in the UK*. IH Report No. 99, Wallingford, United Kingdom.

Hisdal, H., K. Stahl, L.M. Tallaksen and S. Demuth, 2001: Have streamflow droughts in Europe become more severe or frequent? *International Journal of Climatology*, 21: 317–333.

Rees, G. and G.A. Cole, 1997: *Estimation of renewable water resources in the European Union*. Eurostat, Brussels.

Tallaksen, L.M. and H.A.J. van Lanen (eds), 2004: *Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater*. Developments in Water Science, 48, Elsevier Science B.V., Amsterdam.

Theis, C.V., 1941: The effects of a well on the flow of a nearby stream. EOS Trans. AGU, Volume 22, pp. 734–738.

11. Low-flow forecasting

11.1 Introduction

This chapter examines low-flow forecasting and the types of situations in which forecasting is provided to improve decisions on water resources-related operations. In many regions of the world, climate change will have a profound impact on low flows, given that small decreases in rainfall combined with increases in evaporation and temperature will extend the period of low flows in rivers, thereby affecting their operational management. Some of these operations include the following:

(a) Water supply: The development of restriction policies for public water supplies, reservoir operations, irrigation and hydropower scheduling;

(b) Industry: The operations of many industries depend on the level and flow of a nearby river;

(c) Environment: Environmental flows for ecological purposes, compensation flows and dilution flows for improving the quality of water from treatment plants or power generating plants;

(d) Commercial navigation: On many larger rivers, raw materials and finished products are shipped on barges and other ships. Knowledge of river levels and discharge is essential for managing shipping schedules and for the optimum use of lock systems.

The major objective of low-flow forecasting is to evaluate the consequences of flows in conjunction with future water-use demands, given a set of drainage basin moisture conditions and climate conditions at a given time.

The lead time for performing low-flow forecasting is generally much longer than for flood forecasting, varying from a few weeks to a few months and even years. Given that there is great uncertainty surrounding future meteorological conditions, both deterministic and probabilistic forecasts are used, depending on the time frame of forecasts. A probabilistic forecast can be made using probable estimates of rainfall that can be generated from global climate models combined with local teleconnection relationships.

Forecast periods
Although there are many ways to group forecasting methods, one useful approach is to characterize the forecast period into short-, medium-, and long-term periods. The efficacy of different methods and the relevance of different hydroclimatic variables vary with forecast period length.

The degree to which current flows and local antecedent conditions are relevant to the prediction of future flows varies somewhat with the size and nature of the drainage basin; however, in general, such information is useful for short-term forecasts of approximately seven days' duration. Although our ability to utilize synoptic, sea surface temperatures and global-scale hydrometeorological observations varies with location and time of year, generally, such information can be used to develop medium-term three- to six-month forecasts. The relevance of any antecedent information reduces with the length of the forecast period, and long-term forecasts will be predominately based on historical climatology, that is, on the basis of statistics derived from extended periods of historical observations. It is increasingly prudent to consider the possibility of climate change or local shifts in climate state for longer-term predictions. To this end, it would be normal to rely on only a censored portion of the historical record in combination with the outputs of numerical models of global weather circulation.

Different methods have been developed to take advantage of the various information sources. Methods based on the recession analysis of streamflows (that is, on the storage-depletion behaviour of the drainage basin in the absence of rain) provide a useful conservative forecast of short-term flow conditions. For medium-term forecasts, it is necessary to consider weather forecasts that, in combination with knowledge of antecedent

conditions, can be used to develop regression or simple transfer-function predictions of future flows. The nature and degree of complexity of models used for longer-term forecasts vary widely, and this reflects the varied efficacy of a wide range of different climate drivers. The notional range of application of some data sources and applicable methods is shown in Figure 11.1.

Forecast period	1– 7 days	1– 4 weeks	1– 3 months	6– 18 months
	Short			
		Medium		
				Long
Predictive variates	Current streamflow			
	Antecedent hydroclimatic conditions			
	Weather forecasts			
	Synoptic scale indicators			
			Intercontinental scale indicators	
				Long-term climatology
Typical modelling approaches	Recession analysis			
	Regression analysis			
		Non-parametric data analyses		
		Long-term climatalogy		
			Global climate modelling	
				Paleohydrological techniques
Nature of uncertainty	Analytical and quantifiable			
			Speculative and scenario-based	

Figure 11.1 Notional range of application of different aspects of forecast methodology

The interaction of the critical nature of drought and low-flow probability varies with the climate regime (Chapter 4) of the drainage basin. Forecasting in a drought situation also encompasses the forecasting of water demand, the availability of stored water and low flows. Other factors that affect the choice of forecasting method are drainage basin size, climate regime, geology and topography, all of which will be discussed below.

Flows for a particular drainage basin will correspond to the climate of the region, depending on seasonal attributes. This will also depend on the size of the drainage basin, geology and topography. McMahon and Finlayson (2003) stated that, generally, individual streams will have an expected pattern of low flows, which depends on their seasonal hydrological regime type. These climate/regime zones tend to dictate the necessity of forecasting and the type of forecasting required. Haines and others (1988) classified 15 types of regimes globally based on the nature of low-flow periods. Their studies have shown that, in unregulated rivers, shallow groundwater storage regimes supply the water for low flows. Ten flow regimes were identi-

fied in Australia, and the low-flow sequences tended to follow the following patterns: perennial streams with low annual flow variability which have seasonal low flows but do not cease to flow; perennial streams with high annual variability which cease to flow in extreme years; ephemeral streams that regularly cease to flow in the dry season; and arid zone streams with long and erratic periods of no flow.

On the other hand, the effects of river regulation on low flows can vary. In general, regulation mitigates the severity of low flows. Forecasting low flows in regulated rivers depends entirely on the operational strategies of river regulations. The simple routeing of releases, taking into account transmission losses and abstractions from the river, can result in accurate forecasting.

In tropical zones with defined wet and dry seasons, the recession limb of the wet season to the lowest flow in the dry season is important for forecasting flows for run-of-river schemes. This is also the case in some high mountain regions where snowmelt and ice melt in the dry season enable simple recession-based forecasting procedures to be used.

In temperate zones, although the recession limb of individual hydrographs will be important for determining base flows, those in the summer season will be more important. Forecasting flows after major anthropogenic events, such as bush fires, agricultural activities and the building of cities, which affect base flows is particularly problematical.

River and level forecasts for specific river systems, such as navigation on the Rhine, are available to all operators through the Web and now bring the hydrological forecasting of low flows to all river users. There is no single best practice methodology to forecast low flows. The efficacy of different methods and the relevance of different hydroclimatic variables vary with the length of the forecast period.

11.2   Short-term forecasting

11.2.1 Purpose
Short-term forecasts (one to seven days ahead) are seemingly more important for flood warning and the optimization of reservoir storages for flood control than the release of water for irrigation and the environment. A common requirement for short-term forecasting is the management of dilution flows, for instance, from a

sewage treatment plant where treated effluent can be disposed only when flows exceed some specific threshold or a power station where the temperature of cooling water is of interest. Short-term forecasting is also commonly required for water-supply systems that abstract water directly from rivers, or for the optimization of pumping schedules for conjunctive use schemes that have multiple supply sources. The typical requirement for such short-term forecasts is from one to seven days.

Three commonly used approaches for developing short-term forecast models are based on the use of recession analysis, low-flow frequency analysis and autoregressive regression models. Each of these three approaches are described in turn below.

11.2.2 Recession analysis
Recession analysis, which is described in section 5.3, provides estimates of streamflows in the absence of rainfall. Although the length of the achievable forecast period depends on the size of the drainage basin and its degree of storage, in general it is possible to derive forecasts between 1 and 20 days. The maximum length of the forecast period is evident from the slope of the derived recession curve and the degree of pessimism concerning the likely length of time before rain is expected.

The simple nature of a recession-based forecast is illustrated in Figure 11.2. This figure shows a master recession curve for a drainage basin with a sustained reduction in flow over a 20-day period starting from around 90 ML/d. Let us assume that the current flow in the river is 74 ML/d and that an estimate is needed of how long it might take before streamflows are reduced to a threshold of 30 ML/d. The forecast might be undertaken graphically as shown in Figure 11.2, where the number of days before streamflows are re-
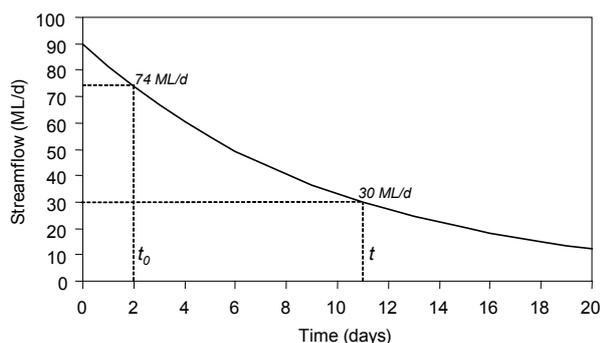

Figure 11.2 *Forecast based on a master recession curve*

duced to the threshold of interest can be estimated directly as the difference between t and t_0, which in this case is $11 - 2 = 9$ days. Of course, if the master recession curve was fitted to a mathematical function, then the forecast could be carried out analytically. The forecast is conservatively low, in that it is based on the assumption that no rain occurs over the intervening period.

11.2.3 Regression analysis
Regression analysis is a more flexible tool that can be used for forecasting. The development of models for short-term forecasts will generally include streamflow and/or rainfall terms from prior time periods, for example:

$$Q_{t+2} = a + b.Q_t + c.R + d.S_t + ... \qquad (11.1)$$

where Q_{t+2} represents streamflows to be forecast over the next two-day period; Q_t denotes current streamflows; R represents rainfall that has occurred over the previous day; S_t is a seasonal term; and a, b, c and d are fitted coefficients. For most short-term forecasts, the inclusion of a term representing current streamflows (Q_t) is important because of the high serial dependence in flow conditions, and the inclusion of the previous period's rainfall (R) is a useful means of allowing for a subsequent increase in flows. It is sometimes useful to include the seasonal term, S_t, which may be defined by a function such as $\sin(1+2\pi n/N)/2$, where n represents the sequential day number of the year and N represents the total number of days in the year. Alternatively, to achieve a slight phase shift in seasonal response, the cosine function can be used instead of the sine function. In most cases, fitting a regression model to successive observations will infringe the independence requirement (an assumption required for fitting by least squares) because of the high serial dependence in the data. The simplest way of avoiding this problem is to fit the regression model to a censored dataset where intervening days of dependent data are excluded. Alternatively, a more sophisticated approach can be taken where an autoregressive model can be fitted to the residuals.

The main advantage of a regression approach is that additional terms can be included to improve the fit of the model. Ideally, some form of climate forecast could be included, yet, in practice, archives of short-term (less than seven days) climate forecasts have not been traditionally collected, or are non-stationary as a result of the improvements in forecasting methods.

Synoptic and global climate indices are useful for the prediction of medium-term (one to six months) forecasts, and a variety of information on sea surface temperatures and measurements related to global circulation patterns are commonly used (for example, the Southern Oscillation Index (SOI), the North Atlantic Oscillation Index, the Indian Ocean Dipole and the Troup Index). The use of regression models also allows confidence intervals to be provided. Thus, rather than providing merely a single "best estimate", confidence intervals can be provided.

The development of regression equations for streamflow forecasts presents particular challenges, particularly for shorter-term periods where streamflows may be zero. The presence of zero flows creates an asymmetrical boundary in the datasets which, without care, can undermine the validity of a least-squares regression model. The simplest practical approach to mitigating this problem is to trial a range of transformations applied to both the independent (that is the predictor) and the dependent (streamflow) variates. Logarithmic and simple power transformations of the data are often useful, whereby the flow and rainfall variates are first transformed into the logarithmic domain, or raised to a power (in a range of 0.2 to 1.0). An alternative approach is to develop regression models that are conditional upon the time of year, or on a range of flow conditions of interest. Thus, it may be effective to develop separate regression models for summer and winter seasons, or for certain sets of flow conditions, where periods of antecedent rainfall is above or below average conditions.

11.2.4 Other models
Radar rainfall can be used to improve very short term rainfall forecasts. The most accurate method to forecast rainfall for very short lead times (1 to 2 h) is to use weather radar to estimate the spatial distribution of rainfall and then to advect the rainfall field forwards in time.

At some point in the forecast period, the errors associated with this approach exceed those from numerical weather prediction (NWP) models, and the regional rainfall forecast using this approach is projected to match the NWP model forecast.

Generally, if a large rainfall event is projected over a drainage basin, the low-flow situation is ameliorated, but the reservoir storage problem might not be resolved (Seed, 2003).

11.3   Medium-term forecasting

11.3.1 Purpose
Medium-term forecasts of river flows are required for a number of purposes, including for knowledge on inflows to water storages for hydropower generation and water-supply purposes for town water supplies, irrigation and cooling water. Other applications include the forecasting of flows from springs.

11.3.2 Low-flow frequency analysis
Low-flow frequency analysis provides an alternative means of determining simple probabilistic streamflow forecasts when climate forecasts are either not available or not accurate. The means of undertaking a low-flow frequency analysis is described in Chapter 7. Figure 11.3 illustrates a three-monthly analysis.
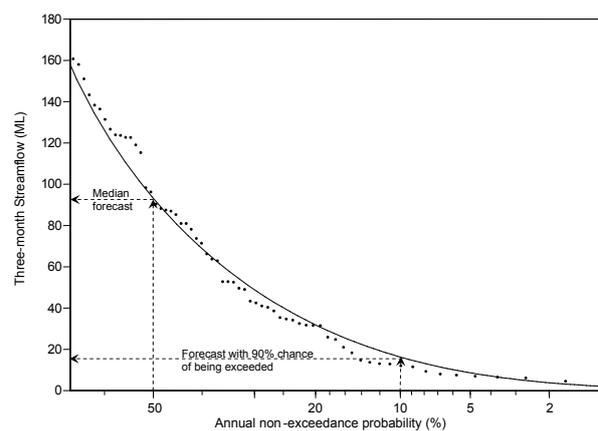
Figure 11.3 Probabilistic forecast based on low-flow frequency analysis

The median (or "typical") forecast is that which is exceeded 50 per cent of the time. In this illustration, the median forecast is 93 ML. For more risk-averse forecasts, rarer non-exceedance quantiles can be used. For example, the figure shows that there is only a 10 per cent chance that streamflows over the next three months will be less than 16 ML. In essence, such forecasts are merely a statement of likelihood based on historical precedent; however, the annual minima used to fit the distribution can be selected from a censored period that reflects the antecedent conditions of interest. For example, if the preceding three-month period was drier than average, then the annual minima could be extracted from a censored data series comprised of only those years where the relevant three-month flows were less than the median recorded flow for that period.

11.3.3 Using weather predictions to forecast flows

In a drought situation where extreme low flows already exist, it is possible to use a number of techniques, including long-term weather predictions to forecast flow and forecasts using ensemble analysis of likely future, or past, events. Forecasts of climate variables, of which rainfall is the most important in water resources applications, can be obtained from NWP models, which are routinely run by weather agencies in many countries. Although NWP models can provide reasonable large-scale forecast out to one week or longer, because of their coarse spatial resolution they have limited skill in forecasting point or drainage basin-scale rainfall. Rainfall forecasts for a local region can be improved by downscaling NWP model forecasts to drainage basin-scale forecasts, using dynamic downscaling methods (using a higher resolution NWP model constrained by results from the low-resolution NWP model) or statistical downscaling methods (relating large-scale atmospheric predictors estimated by a NWP model to drainage basin-scale rainfall).

Estimates of future rainfall for various periods can be obtained from meteorological institutions, either in the form shown in Figure 11.4, in depths of rainfall or as total rainfall.
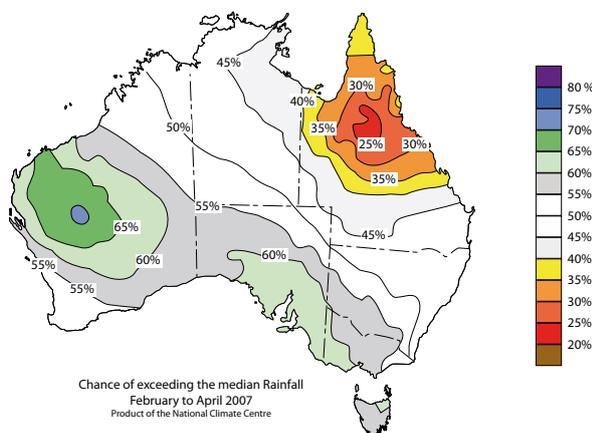

Figure 11.4 *Future rainfall for the next three months (http://www.bom.gov.au/climate/ahead/maps/rain.national.lr.gif?20070123) (accessed 7 November 2008)*

These types of models are used for agricultural purposes and invariably are not converted into flows. Increasing importance will be placed on these models in the future to develop procedures for forecasting environmental flow releases, while at the same time attempting to maintain the reliability of water for other uses.

11.4   Purpose of long-term forecasting

Long-term forecasts (several months to several seasons ahead) of hydroclimate variables can be used to help manage water resources systems, particularly systems with high interannual variability. Seasonal forecasts of water availability allow water managers to make more realistic decisions on water restrictions in cities and towns and water allocation for competing users and to make probabilistic forecasts of water allocation, streamflow volumes and the number of pumping days available to help farmers make informed risk-based decisions for farm and crop management (Chiew and others, 2003).

The hydroclimate variables can be forecast several seasons ahead by exploiting the lag relationship between the hydroclimate variable and the El Niño/Southern Oscillation (ENSO).

For example, Figure 11.5 shows that the spring (Sep–Oct–Nov) inflow into a reservoir in south-east Australia is generally higher when the winter (Jun–Jul–Aug) SOI is positive. The SOI is based on the Tahiti minus Darwin sea-level pressure and, together with sea surface temperature anomalies (particularly across the equatorial Pacific Ocean, for example, NINO3) and upper atmospheric pressure, is commonly used as an indicator of ENSO.

The relationship between ENSO and climate is the scientific basis for seasonal climate forecasts provided by research institutions and meteorological agencies throughout the world.
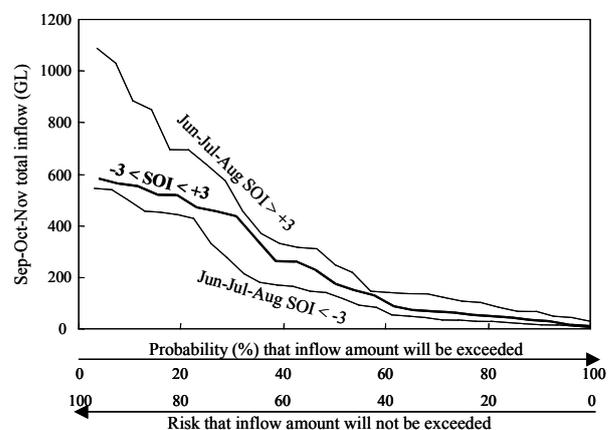

Figure 11.5 *Distribution of spring inflow into Wyangala Dam (in south-east Australia) for three categories of winter SOI values*
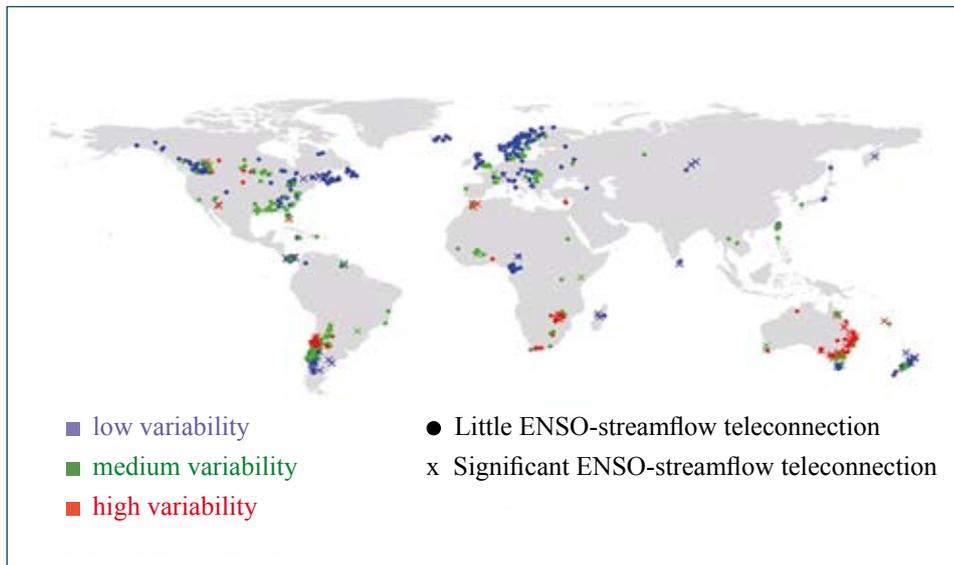
Figure 11.6

Global ENSO–streamflow teleconnection and streamflow interannual variability (581 drainage basins)

The ENSO-streamflow teleconnection is particularly strong in Australia (low streamflow is associated with El Niño), South America (high streamflow is associated with El Niño on the Pacific coast, and low streamflow with El Niño in the north-east) and Central America (low streamflow is associated with El Niño), with medium strength ENSO-streamflow teleconnection in parts of Africa and Northern America as shown in Figure 11.6 (Chiew and McMahon, 2002).

The one- to two-month lag serial correlation in streamflow is often higher than the streamflow-ENSO correlation and should therefore be used together with ENSO to forecast streamflow. However, the strength in the ENSO–streamflow relationship is maintained over a longer lead time compared with the streamflow serial correlation.

The hydroclimate forecast is usually determined using statistical methods that relate the hydroclimate variable to ENSO indicators. For example, the exceedance probability forecast could be established simply by using the streamflow distributions resulting from discrete categories of antecedent ENSO conditions (like the discrete SOI categories in Figure 11.5). The probabilistic forecasts are particularly important for water resources applications where water resources systems are typically managed with very low risks (right-hand side of Figure 11.5). Sharma (2000) and Piechota and others (2001) describe more complex and reliable non-parametric methods for deriving probabilistic streamflow forecasts that take into account the continuous relationship between streamflow and the explanatory variables.

The statistical seasonal forecasting methods are useful in a data-rich environment. However, statistical methods assume that climate processes are stationary and linear, which is contrary to our knowledge of the way in which the climate system behaves. For example, statistical methods cannot easily take into account the different ENSO-streamflow relationship in different inter-decadal periods or in an enhanced greenhouse climate. For this reason, climate models are increasingly used to determine seasonal climate forecasts, particularly as climate models continue to improve. It is likely that future seasonal forecasting methods will utilize the advantageous features of statistical methods and climate models. For example, statistical methods can be used to downscale the large-scale forecast of climate models to drainage basin-scale rainfall in order to drive hydrological models to provide probabilistic streamflow forecasts. The rainfall and climate forecasts can be used as inputs into hydrological and river operation models to forecast hydrological fluxes and states and river flows. In data-rich areas and in regions where reliable estimates of soil moisture and evapotranspiration can be obtained from remote-sensing, data assimilation methods can also be used to constrain the model simulations and correct the model errors, so that more reliable predictions can be obtained.

Seasonal models, such as the Non-parametric Seasonal Forecast Model (NSFM), can forecast continuous exceedance probabilities of streamflow (or any other hydroclimate variable). The NSFM forecasts the exceedance probabilities of streamflow several months ahead by exploiting the lag relationship between streamflow and ENSO and the serial correlation in streamflow.

11.5   Basic modelling techniques for forecasting

11.5.1 Purpose

The aim of this section is to provide the reader with some modelling tools for making forecasts based upon the time series of river flows only, that is, without rainfall or climate inputs. Three model types are presented, each with varying degrees of difficulty in terms of concept and implementation. The first method is the autoregressive moving-average (ARMA) modelling technique, which is suitable for forecasting at timescales greater than one week. The second and third methods described are a two-state Hidden Markov Model (HMM) and a shifting-level model cast in a HMM framework, respectively. These techniques are more involved stochastic models. More information regarding these practices can be found in the appropriate references given in the relevant paragraphs. Models that provide good approximations of low-flow forecasting include the intervention model of Kuo and Sun (1993) and the conditional forecasting approach of Coley and Waylen (2006). Both of these models are variations of the techniques presented in this section.

11.5.2 Autoregressive moving-average models

The ARMA models have successfully modelled natural phenomena, and, indeed, it has been suggested that they be used as a basis from which most natural processes can be modelled adequately (Montanari and others, 1997). ARMA models make use of persistence characteristics in observed data by combining autoregressive and moving-average parameters, thereby relating the new, or forecast, value to a specified number of previous values and the deviation of those values from the long-term observed process. For a good introduction to ARMA and general time series modelling, see Chatfield (2004). The generic equation for an ARMA model is given in equation 11.2. When used for flow forecasting X_{t+1} represents the forecast flow; μ is the mean flow; Z is the measure of deviation of the given value from the estimate of the long-term process at the given time, with the best estimate of Z_{t+1} equal to 0, assuming normally distributed errors; α and β refer to the autoregressive and moving-average coefficients, respectively, with p equal to the order of autoregression and q equal to the order of the moving-average component of the ARMA model.

$$X_{t+1} = \sum_{i=1}^{p} \alpha_i \left(X_{t+1-i} - \mu \right) + \sum_{j=1}^{q} \beta_k Z_{t+1-k} + Z_{t+1} + \mu \qquad (11.2)$$

The ARMA(1,1) Model was used in streamflow analysis by Stedinger and others (1985). The (1,1) indicates that it is a first-order autoregressive and moving-average model, meaning that both p and q in equation 11.2 are equal to 1, returning only one value of α and β. Equation 11.2 therefore becomes:

$$X_{t+1} = \alpha_1 \left(X_t - \mu \right) + \beta_1 Z_t + \mu \qquad (11.3)$$

As explained above, the best estimate of Z_{t+1} is 0 and has therefore been omitted.

Methods for estimating the number and value of autoregressive and moving-average coefficients have been suggested in the relevant literature. Chatfield (2004) implements a first-principles approach in his technique. This method involves examining the tendency of the data to autocorrelate (be related to previous values) and determining an appropriate number of coefficients before using a least-squares solving technique for coefficient values. This method offers a good introduction to some of the statistics behind time-series modelling; but, it can also be replicated using a statistical software suite. One such suite, widely used and recommended by the authors of this chapter is R, which can be downloaded free of charge at the following Website: www.r-project.org.

Typically, low-order ARMA models are preferable to higher order variations (Hosking, 1984). Models such as ARMA(1,1) (for example, see Stedinger and others, 1985, and Venema and others, 1997) and ARMA(1,0)
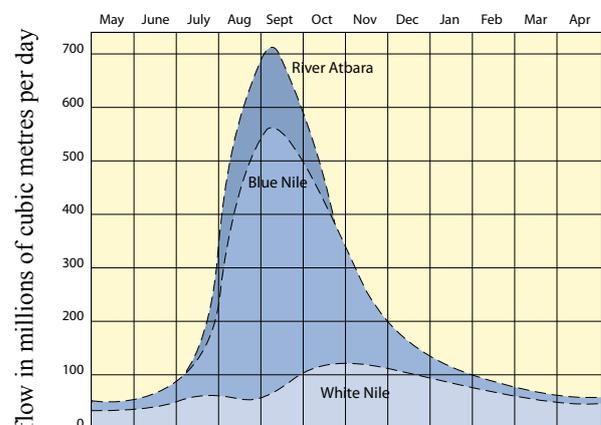

Figure 11.7 *Nile River inflows with two seasons and respective means demarcated (adapted from the Nile River Fact File: http://www.mbarron.net/ Nile/fctfl_nf.html (accessed 7 November 2008))*

(for example, see Kendall and Dracup, 1991) have been used successfully in annual and monthly stream-flow modelling. The ordinary ARMA process can be extended through techniques such as differencing the data and adding a seasonal component to the model. These methods rely on the modeller having a more thorough understanding of the flow data. One simple alternative technique is to stratify the time series.

Using the Hurst (1951) case study of the Nile Delta, it can be seen in Figure 11.7 that the inflows follow very different patterns based on the time of year, with mean flow different for each season. One way to include this variability, other than using a seasonal model, is to divide the year into two parts: January to June and July to December. Each of these segments will have a different mean, and it is this mean that is used in equation 11.2, with the model switching parameter values at the change of the selected seasons.

11.5.3 Two-state Hidden Markov Model

A two-state HMM, illustrated in Figure 11.8, assumes that the climate is in one of two states (wet or dry), with each state having an independent flow distribution. A range of distributions can be compared, and these depend entirely on the observed data. However, a good start would be to use a Gaussian distribution. The fitting and optimization of probability distributions will not be discussed in this chapter; but, McMahon and Mein (1986) offer good explanations and infor-mation regarding several probability distributions in a streamflow context. The persistence in each demarcated state varies according to state transition probabilities, calculated in the calibration of the model. These tran-sition probabilities dictate the probability of transition from one state to the other and hence the probability of remaining in the current state. A schematic diagram of this process is given in Figure 11.8. By providing an explicit mechanism to replicate the variable length wet and dry cycles present in climatic data, Thyer and Kuczera (2000) indicate that a two-state HMM goes some way to explaining the complex non-linear climate dynamics responsible for these patterns in hydrological time series, including streamflow. This capacity for the inclusion of non-linearity makes HMMs generally preferable to linear time-series techniques such as ARMA modelling.

The "hidden" state in the HMM refers to the fact that, rather than being specified by the user, the wet and dry climatic phases of the HMM are included in the set of parameters to be optimized in the calibration stage.
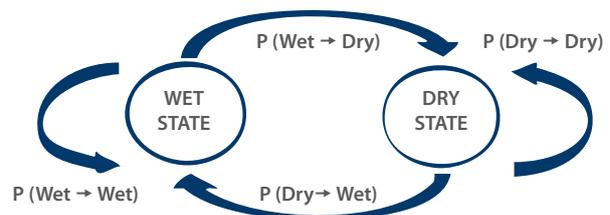

Figure 11.8 *Model framework of a two-state HMM (after Thyer and Kuczera, 2000) where the transition probabilities P(.) going from state to state are labelled*

Therefore, prior information regarding certain climatic shifts does not need to be known or inferred. The set of parameters to be optimized includes the state transition probabilities, the parameters governing the respective wet and dry probability distributions and the hidden state time series, indicative of the states of previously observed values.

Several methods are available for calibrating the HMM. One technique used in hydrological applications, and favoured by Thyer and Kuczera (2000) and Perreault and others (2000), is that of the Gibbs sampler. This tech-nique forms part of a family of Markov Chain Monte Carlo (MCMC) simulation methods. More information regarding the Gibbs sampler, accompanied with detailed and extensive examples, can be found in Gilks and others (1995).

A fully calibrated HMM allows the user to recognize the state of the current streamflow total and to determine the likelihood of a transition from that state in the next time step. The forecast will then be the mean of the distribution of the most likely state at the next time step. Reference can be made to the confidence surrounding the prediction by framing the forecast in terms of the variability of the selected distribution. Lu and Berliner (1999) used HMMs to successfully model daily stream-flow totals in a rainfall-runoff scenario. A starting point for interested readers would be Charles and others (1999) and Zucchini and Guttorp (1991).

11.5.4 Shifting-level model

The third technique is the shifting-level model, cast in a Bayesian HMM framework. Conceptually, it is straight-forward and combines aspects of ARMA and HMM modelling. The shifting-level model has been used suc-cessfully (for example, Salas, 2000) and was recently extended by Fortin and others (2004) to have the capa-city to forecast monthly and annual streamflow totals.

The shifting-level model of Salas and Boes (1980) consists of four parameters used to describe a process that is modelled as the sum of two independent stochastic processes, that is, $x_t = m_t + \varepsilon_t$, where m_t and ε_t are independent and ε_t is a normally distributed random variable. While ε_t is a white noise, m_t is slightly more complicated, referring to the unobserved mean level, m_t, corresponding to each observation, x_t, that is, $m_t = E[x_t \mid m_t]$. This mean level is also normally distributed, but remains constant for epochs whose duration follows a geometric distribution, given a parameter η. Sudden changes in the mean of the time series are taken into consideration by the shifting-level model, including an element of randomness necessary to describe a natural process. This effect can be seen in Figure 11.9. The time series seems almost random before the 60th observation; however, 12 shifts in mean level are observable in that period. There is a shift of considerable amplitude at the 60th observation, followed by four more shifts in the following 40 observations. The shifting-level model identifies these shifts and is applicable to hydrologic data that exhibit such shifts, such as streamflow data.

With the new shifting-level model, an MCMC routine (see Gilks and others (1995)) can be applied to calibrate the model. Fortin and others (2004) used the Gibbs sampler, as outlined above. The forecasting method is slightly more difficult than that of a two-state HMM, with a predictive sample generated from the probabilistic relationships obtained using the Gibbs sampler. As with the two-state HMM, the forecast value will be a predictive distribution, giving some boundaries to the forecast. However, unlike the two-state HMM, the forecast value using a HMM-framed shifting-level model contains information on the local state of the data and not just the long-term means of the states, thereby increasing the usefulness of the forecasting model.

Fortin and others (2004) applied their forecasting model to the Senegal River (West Africa) and forecast the 1987 total annual streamflow value, the last value with which the model was not calibrated. The forecast, with the long-term mean, is displayed in Figure 11.10.
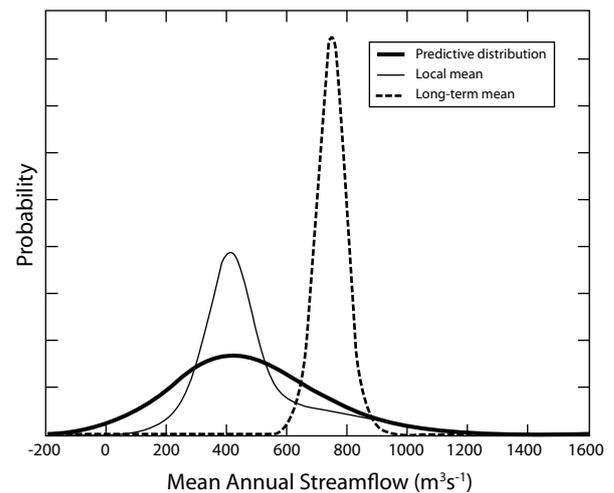
Figure 11.10 *Probabilistic forecast of 1987 annual streamflow total for the Senegal River (West Africa) (after Fortin and others, 2004)*

The actual value was approximately 200 m^3/s, which was the lowest observed flow ever recorded. It can be argued that, with the long-term mean being in excess of 700 m^3/s with small variance, the model performed extremely well. Fortin and others (2004) also explain how the shifting-level model can be used to forecast multiple time steps ahead and demonstrate the potential of the shifting-level model compared with conventional hydrologic models, such as the ARMA(1,0) and ARMA(1,1) models.

11.5.5 Concluding remarks
The shifting-level technique is the most flexible of the three models. ARMA models offer a good entry point into streamflow modelling and forecasting, and the variations on the general model provide insight into the characteristics of the flow data, without the compromise of the time requirements, difficulty and computational expense of the other techniques. The HMMs used to define persistent climatic states are useful when applied to low-flow analysis given that an understanding of the distribution and likely magnitude of low flows is gained. However, the models presented in this chapter should provide an adequate means of low-flow forecasting on multiple time scales.

Figure 11.9 *Example of a shifting-level model over 100 observations (after Fortin and others, 2004)*

11.6 Conclusions

There is no best practice for forecasting low flows. The efficacy of various methods and the relevance of different hydroclimatic variables vary with the length of the forecast period. However, the models presented should provide an adequate means of low-flow forecasting on multiple time scales. The nature and degree of complexity of the models used for longer-term forecasts vary widely, and this reflects the varied efficacy of a wide range of different climate drivers. The majority of models used for forecasting low flows follow the short-term methods of recession curves and regression. As forecasting breaks into longer periods of time, a variety of climate-driving signals are used for predicting the persistence of low flows.

References

Charles, S.P., B.C. Bates, P.H. Whetton and J.P. Hughes, 1999: Validation of downscaling models for changed climate conditions: case study of southwestern Australia, Climate Research, 27(8): 1–14.

Chatfield, C., 2004: The Analysis of Time Series: An Introduction. Chapman and Hall/CRC.

Chiew, F.H.S. and T.A. McMahon, 2002: Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. Hydrological Sciences Journal, 47: 505–522.

Chiew, F.H.S., S.L. Zhou and T.A. McMahon, 2003: Use of seasonal streamflow forecasts in water resources management. Journal of Hydrology, 270: 135–144.

Coley, D.M. and P.R. Waylen, 2006: Forecasting dry season streamflow on the Peace River at Arcadia, Florida, USA. Journal of the American Water Resources Association, 42(4): 851–862.

Fortin, V., L. Perreault and J.D. Salas, 2004: Retrospective analysis and forecasting of streamflows using a shifting level model. Journal of Hydrology, 296: 135–163.

Gilks, W.R., S. Richardson and D.J. Spiegelhalter (eds), 1995: Markov Chain Monte Carlo in Practice (Interdisciplinary Statistics). Chapman and Hall/CRC.

Haines A.T., B.L. Finlayson and T.A. McMahon, 1988: A global classification of river regimes. Applied Geography, 8: 255–272.

Hosking, J.R.M., 1984: Modelling persistence in hydrological time series using fractional differencing. Water Resources Research, 20(12): 1898–1908.

Hurst, H.E., 1951: Long-term storage capacity of reservoirs. Transactions of the American Society of Civil Engineers, 116: 770–799.

Kendall D.R. and J.A. Dracup, 1991: A comparison of index-sequential and AR(1) generated hydrological sequences. Journal of Hydrology, 122(1–4): 335–352.

Kuo, J.T. and Y.H. Sun, 1993: An intervention model for average 10-day streamflow forecast and synthesis. Journal of Hydrology, 151(1): 35–56.

Lu Z.-Q. and L.M. Berliner, 1999: Markov switching time series models with application to a daily runoff series. Water Resources Research, 35(2): 523–534.

McMahon T.A. and B.L. Finlayson, 2003: Droughts and anti-droughts: the low flow hydrology of Australian rivers. Freshwater Biology, 48(7): 1147–1160.

McMahon, T.A. and R.G. Mein, 1986: River and Reservoir Yield. Water Resources Publications, Littleton, United States.

Montanari, A., R. Rosso and M.S. Taqqu, 1997: Fractionally differenced ARIMA models applied to hydrologic time series: identification, estimation and simulation. Water Resources Research, 33: 1035–1044.

Perreault, L., J. Bernier, B. Bobee and E. Parent, 2000: Bayesian change-point analysis in hydrometeorological time series. Part 1: The normal model revisited. Journal of Hydrology, 235(3–4): 221–241.

Piechota, T.C., F.H.S. Chiew, J.A. Dracup and T.A. McMahon, 2001: Development of an exceedance probability streamflow forecast. ASCE Journal of Hydrologic Engineering, 6: 20–28.

Salas, J.D., 2000: Stochastic analysis and modelling for simulation and forecasting, Consulting report for Hydro-Quebec, Colorado State University.

Salas, J.D. and D.C. Boes, 1980: Shifting level modelling of hydrologic series. Advances in Water Resources, 3: 59–63.

Seed, A.W., 2003: A dynamic and spatial scale approach to advection forecasting. Journal of Applied Meteorology, 42: 381–388.

Sharma, A., 2000: Seasonal to interannual rainfall probabilistic forecast for improved water supply management: Part 3 – A nonparametric probabilistic forecast model. Journal of Hydrology, 239: 249–259.

Stedinger, J.R., D.P. Lettenmaier and R. Vogel, 1985: Multisite ARMA(1,1) and disaggregation models for annual streamflow generation. Water Resources Research, 21(4): 497–509.

Thyer, M. and G. Kuczera, 2000: Modelling long-term persistence in hydroclimatic time series using a hidden state Markov model. Water Resources Research, 36(11): 3301–3310.

Venema, H.D., E.J. Schiller, K. Adamowski and J.M. Thizy, 1997: A water resources planning response to climate change in the Senegal River basin. Journal of Environmental Management, 49(1): 125–155.

Zucchini, W. and P. Guttorp, 1991: A hidden Markov model for space-time precipitation. Water Resources Research, 27(8): 1917–1923.

12. Case studies

12.1   Summary of the case studies

Transboundary rivers

This case study considers the issues faced by the regulators of transboundary rivers and how low-flow information is used for their management. The Columbia River basin in North America and the Mekong River in South-East Asia are used to illustrate some of the most important issues related to water management and planning.

Catchment-based water resources decision-support tool within the United Kingdom

This case study summarizes the current policy background to low-flow estimation within the United Kingdom and proceeds to describe the development and application of the LowFlows decision-support tool to meet requirements for estimating natural flows within ungauged catchments and assessing the impacts of water use on the natural flow regime. The techniques for estimating low flows at ungauged sites are described more fully in Chapter 9, and for estimating the impact of artificial influences in Chapter 10.

Low-flow management issues in the United Kingdom

Wetlands derive their nature from a range of features associated with both surface water and groundwater sources. They are maintained by persistently high water levels at, or near, the ground surface which are caused by poor drainage or proximity to a permanent water source, for example a river and its floodplain, or by a defined geological structure forming springs or the upwelling of groundwater.

This case study explores the interrelationships between streamflow and groundwater support of wetlands and sensitivity to abstractions using examples from the United Kingdom.

Real-time management of environmental flow requirements (Thukela River, South Africa)

The revised National Water Act of South Africa makes provisions for the protection and sustainable develop-

ment of aquatic resources through the establishment of environmental water requirements. These have been established for the Thukela basin using standard approaches that result in a set of low-flow and high-flow requirements designed to reflect the variability of the natural flow regime.

This case study describes the methods being established to provide for the low-flow component of the environmental water requirements. Measured or estimated data can be used as hydrological inputs. Methods for regionalizing conceptual hydrological models in the region are described in Chapter 9.

Regionalized resources models for small-scale hydropower: India and Nepal

In contrast to the case study from the United Kingdom, this case study describes the development of a decision-support tool for the design of small-scale hydropower schemes within Nepal and northern India. These schemes are generally run-of-the-river schemes, meaning that they do not have artificial storage to provide a constant water supply. The estimation of the flow-duration curve (Chapter 6) is a critical part of the design procedure.

Residual flow estimation and hydropower: Norway

As is the case with many hydrological topics in Norway, low-flow research has been related to hydropower production. These studies mainly focus on how to set instream flow requirements (residual flows) downstream of hydropower reservoirs or abstraction diversions. As a result of the increased awareness of the negative environmental impacts of water resources development, there has been a shift in research focus towards finding methods to calculate low flows in catchments where few or no measurements are available.

This case study explores the estimation of low flows to support the development of a hydropower scheme in Norway and draws comparisons between the results obtained using a regionalized model and local data from the region.

12.2 Transboundary rivers

12.2.1 Towards international water management

Transboundary rivers cross one or more national borders or flow along borders between sovereign nation states. There are more than 260 transboundary rivers worldwide, the basins of which are shared by between 2 and 17 different countries (Wolf and others, 1999). In many of these international river basins, there has been dispute and conflict over the water resources provided by the river. Wolf and others (2003) conclude from their study of global international river basins that changes to a transboundary river, and its flow, and the absence of the institutional capacity of the riparian countries to deal with these changes are the most likely combination of factors contributing to violent conflict. Unilateral development, such as the building of a dam by an upstream country and subsequent changes in the hydrological regime and possible reduction in flow to the downstream country, is a typical example. Conversely, upstream countries may be unable to develop water resources if undue economic or political pressure results in adverse restrictions on legitimate developments. Basins subject to high interannual climatic variability and extreme hydrological situations are particularly prone to disputes over their resources (Stahl, 2005). This reflects the fact that, in geographical regions with highly variable water availability, rivers are often critical to political and economic success.

However, there is also a great deal of cooperation in international river basins around the world. In this context, it is important to remember that transboundary rivers are subject to international law. The fundamental principles of international law are the principle of "equitable" use of the resource and the "obligation not to cause significant harm". These principles are enshrined in the United Nations Convention on the Law of the Non-navigational Uses of International Watercourses (United Nations, 1997). In essence, customary international law requires any riparian country to be reasonable in the use of the resource. Additional legal frameworks that go far beyond these general principles may apply. For example, the European Union Water Framework Directive, which requires that joint management plans be established by the riparian countries of transboundary rivers, along with specific agreements or treaties between two or more riparian countries.

The planning process for any development in a transboundary river basin therefore requires a thorough assessment of the hydrology and hydrological variability of streamflow. Water quantity, minimum flows, flood protection and hydropower are some of the most contentious issues in transboundary rivers. An assessment of hydrological extremes in the entire basin, not only in one of the countries, is therefore an essential step towards the negotiation of treaties and joint management that will comply with the principle of equitable use. This case study draws from hydro-logical studies in two transboundary rivers that present contrasting cases in terms of their development and the development of their riparian countries. The Columbia River basin, shared by Canada and the United States, is one of the most developed rivers in the world. As the largest energy-producing river in North America, it has a series of large and small dams. Flow management in the mainstream is regulated by one of the oldest international treaties, the Columbia River Basin Treaty, established 1961 (for a review, see, for example, Muckleston, 2003). The mainstream Mekong River, which flows through China, Myanmar, Thailand, Cambodia, the Lao People's Democratic Republic and Viet Nam is still relatively undeveloped. Through the Mekong River Commission (MRC), the riparian countries of the Lower Mekong are currently working towards a basin-wide flow management strategy. Despite the different levels of development, the pressure on this resource in both basins is currently high, particularly during the dry season. The countries in both basins are reviewing additional opportunities for development and water withdrawals. The following sections briefly describe the basins and low flow-related issues studied as part of these reviews. Rather than discussing the technical details of the analyses carried out, this chapter focuses on discussions concerning the particular circumstances and constraints common to transboundary rivers.

12.2.2 The Columbia River: Balancing flows for fish, agriculture and hydropower

The Columbia River basin drains 670 800 km² of western North America and flows for over 2 000 km from British Columbia (Canada) into and through the State of Washington (United States) before discharging an average of 7 400 m³/s into the Pacific Ocean along the border to the State of Oregon. Although the Canadian portion of the basin is only 15 per cent of the total basin area, it receives much higher amounts of annual precipitation (Figure 12.1) and hence accounts for about 30 per cent of the annual flow to the Pacific. This proportion is even higher in the Middle Columbia in Washington State, where most of the United States hydropower plants are located. However, most of the precipitation falls in winter and is stored as snow, which results in a
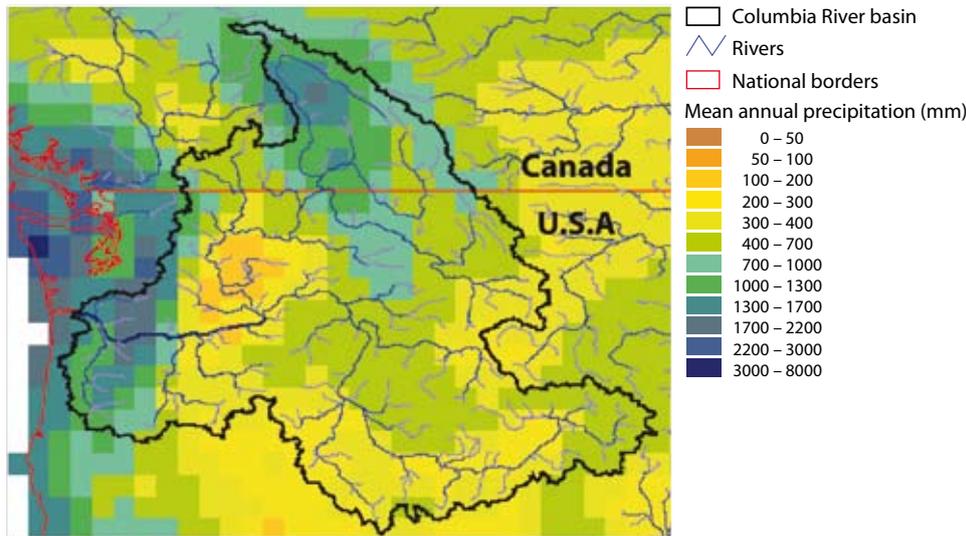
snowmelt-driven hydrological regime with the highest flows during spring to summer (May to July) and low flows during the winter (October to March). This annual cycle is the opposite of energy demand, which is at its highest in winter.

At the beginning of the twentieth century, the Columbia River was known for its abundance of many species of salmon, which had been the main food source for native peoples for centuries before. In need of cheap energy, and under the pressure of the increasing development of the North American West, Canada and the United States signed the Columbia River Basin Treaty in 1961. Under the Treaty, several dams were built in Canada. They now store water from the spring snowmelt, which is then released gradually throughout the winter low-flow season allowing hydropower generation from the United States dams. In return for storage on its territory, Canada currently receives 50 per cent of the "downstream benefits" of the power production in the United States.

The building of dams and the storage of water across seasons drastically changed the hydrological regime of the Middle and Lower Columbia (Figure 12.2).

In both countries, it has been recognized that the fish habitat was severely affected by this altered regime as well as by wide diurnal variations below the dams. Although passageways for salmon have been built at the dams, and in the 1970s operational management schemes were revised to include flow targets below the dams, salmon populations have declined significantly since the construction of the dams.

In Washington State, where annual rainfall is low and summers are hot and dry, the Columbia River is also a major source of water for irrigation purposes. A study by the National Research Council Committee on Water Resources Management, Instream Flows, and Salmon Survival (NRC, 2004) reviewed and commented on the implications for salmon survival of additional water withdrawals from the mainstream Columbia River in Washington State. The study was requested by the Washington State Department of Ecology, which issues water-use permits for this stretch of the Columbia River. At the time of the study, the Department had several applications pending for permits and was seeking an improved scientific basis for decision-making.

The change from the natural hydrological regime of high summer flows to the current regulated regime with lower summer flows and late summer low flows has had wide implications for salmon. The main concerns during low-flow conditions in the mainstream Columbia
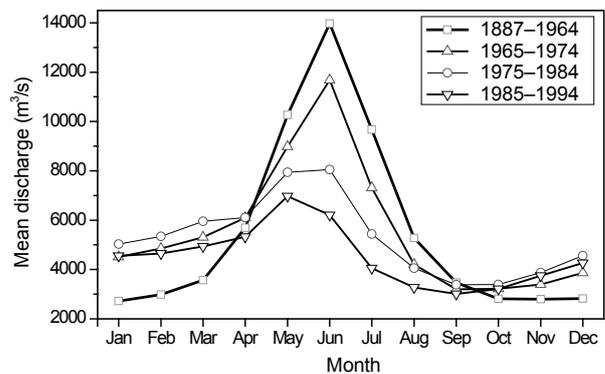

Figure 12.2 Mean monthly discharge in the Columbia River for different time periods

are a decrease in flow velocity and increase in water temperatures. Low-flow velocities make it more difficult for juvenile salmon to swim out to sea, and high water temperatures cause stress for adult salmon returning to spawn in late summer. Most of the basin has a long, hot and dry summer season during which fish consequently compete with irrigation abstraction for agricultural purposes.

The study reviewed management schemes, historical flows and withdrawals. It was discovered that prospective additional withdrawals have the largest relative impact during the summer dry-weather season. The upper end of the prospective withdrawals would increase withdrawals from the current 16.6 per cent to about 21 per cent of the minimum July flow. With the water temperature at this time of year already being a concern at the current rate of withdrawal and the low dilution capacity of the river for polluted return flows from agriculture, salmon species migrating through the river during the low-flow season would be exposed to greater risk.

Despite strict regulation, flow in the Columbia River still fluctuates from year to year. These fluctuations, as well as future changes through further developments upstream in Canada and through climate and environmental change, also need to be considered for decisions on future water-use permits in Washington State. In low-flow years, the fish flow targets below the dams have already been difficult or impossible to meet. With populations in upstream British Columbia and Washington State growing steadily, consumptive water use and the need for hydropower will remain unchanged or may even increase. Fundamental changes to the flows established in the Treaty which guarantee year-round hydropower production are therefore unlikely. Additionally, a climatic trend of decreasing snowpacks and increasing summer temperatures is predicted to continue under most greenhouse gas-driven scenarios of climate change. This suggests a risk of further reductions in natural summer flows.

The study had no mandate to make policy suggestions. However, it concluded that there is limited opportunity for additional withdrawals during the summer and therefore recommended that, if additional permits are issued, they should include conditions that allow withdrawals to be discontinued during critical low-flow periods (NRC, 2004). In the light of the threat to salmon survival during low-flow years even under current conditions, the study also suggests that adjustments and more efficient use of the existing water resources be considered.

12.2.3 The Mekong River: Low-flow origin along the river

The Mekong River drains 795 000 km² of land across six South-East Asian countries (Figure 12.3). Its headwaters lie at over 4 500 m.a.s.l. on the Tibetan Plateau. Dropping around 4 000 m in elevation, the river flows through the Yunnan Province of China and into the Lao People's Democratic Republic, which lies almost entirely within the Mekong Basin. Here, the "Lower Mekong" is also the Lao People's Democratic Republic's eastern border with Myanmar and Thailand. Eventually, the river flows through Cambodia and then discharges a mean of 475 km³ of water annually into the South China Sea through its delta in Viet Nam.

The countries of the Lower Mekong all heavily depend on the river for food, water, transport, and so on. The annual cycle of the Mekong's highly seasonal monsoon-shaped hydrological regime (Figure 12.4) is essential for the production of rice and vegetables. However, since many dams have been built recently and more are under construction, concerns have been raised over fishery sustainability and the effect of a "flattened" regime on an ecosystem and farming practices that rely on the annual cycle of floods and low flows.

The Mekong River Commission, successor to the Mekong Committee (which was founded by the United Nations), was established in 1995 by an agreement between the Governments of Cambodia, the Lao People's Democratic Republic, Thailand and Viet Nam, with China and Myanmar being dialogue partners. The mandate of the organization is "to cooperate in all fields of sustainable development, utilisation, management and conservation of the water and related resources of the Mekong River Basin" (MRC, 2005a). The activities conducted by the Commission since the 1995 agreement have included the facilitation between member countries for several strategies and plans concerning hydropower, flood protection, irrigation and other issues. Furthermore, the member countries have signed sub-agreements, including one on data and information sharing and exchange, an important step for any hydrological assessment and planning process. The Commission's major tasks include the development of integrated river basin management (IRBM) activities. The long-term objective of IRBM is to gather information on which member states can base their decisions on basin developments. Specifically, the MRC aims to
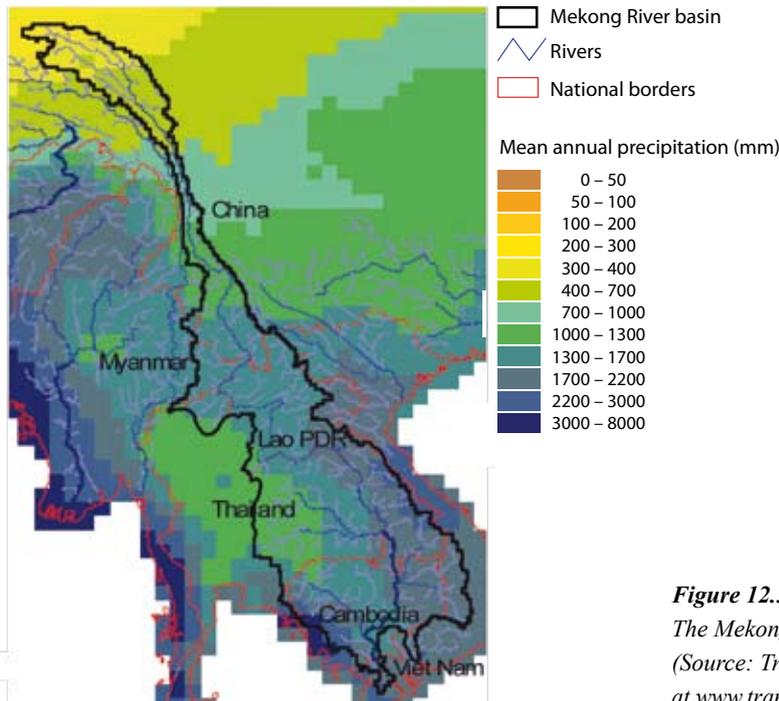
Figure 12.3
The Mekong River basin
(Source: Transboundary Freshwater Dispute database GIS
at www.transboundarywaters.orst.edu and CRU precipitation)

provide basic technical assistance for discussions on compromises between development and the social and environmental impacts, as well as discussions between member states to ensure the "reasonable and equitable share" in beneficial uses of water (MRC, 2005a). The first component in this procedure was an extensive study of the hydrology of this large basin (MRC, 2005b). As part of the MRC Water Utilisation Programme, the study was financed by the Global Environment Fund through the World Bank (MRC, 2005b) and revealed some interesting aspects on low flows and droughts in the basin, as summarized below.

The largest proportion of streamflow in the Lower Mekong mainstream originates from the major left-bank tributaries in the Lao People's Democratic Republic, where rainfall amounts are highest within the basin (Figure 12.3). About 16 per cent of total annual flow
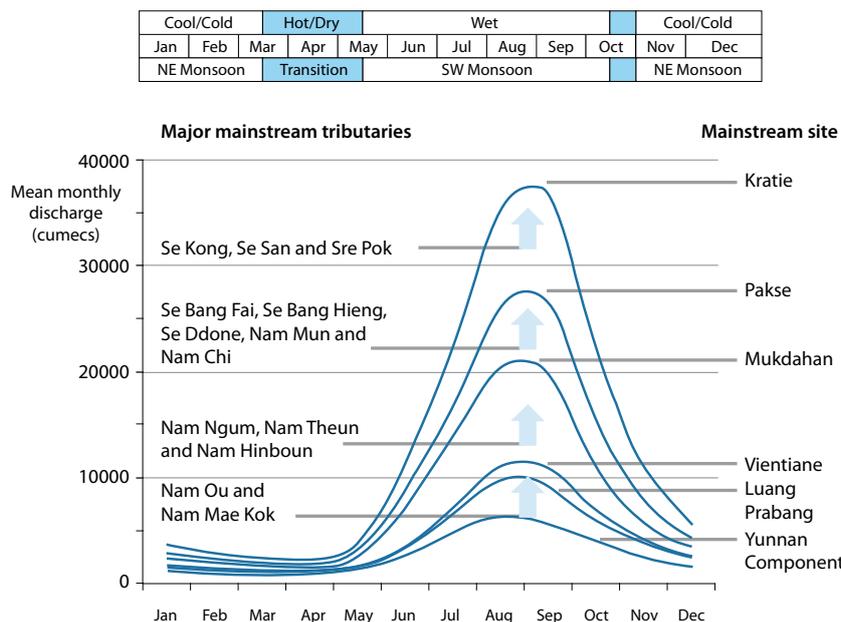
Figure 12.4
Seasonal climate and river flow in the Mekong River basin (from MRC, 2005b)

comes from the headwaters in China. However, during the dry season, which is also the low-flow season, the relative contributions from the Upper Mekong, particularly from China, are much higher because of delayed snowmelt runoff from the mountains. During the low-flow season, the contribution of this so-called "Yunnan component" to main river flow reaches up to 80 per cent at Vientiane (Lao People's Democratic Republic) and 40 per cent at Kratie (Cambodia). The specific details of current dam developments in the Yunnan Province of China are not widely available. However, it is reasonable to assume that this development may have a considerable impact on all downstream countries during the low-flow season.

There is also considerable variability in the mainstream flows from year to year. The MRC study analysed low-flow parameters along different reaches of the Mekong. The minimum 90-day mean discharge from 1960 to 2004 showed no trend. However, the low-flow history along the more than 4000 km long river varies longitudinally and severe low flows along the entire river occur only rarely.

In the dry season, water is needed for many purposes, such as irrigation, domestic use, industrial applications and navigation, and for environmental reasons. Cambodia and Viet Nam have two extraordinary ecosystems that are very sensitive to the annual cycle of flood and low flow. A flow reversal during the flood season pushes water up the Tonle Sap River into the Great Lake in Cambodia. During the dry season, water is gradually released from that storage. Augmenting low flows, this system minimizes the risk of saltwater intrusion in the similarly vulnerable Mekong Delta.

The study of the basic low-flow hydrology of the Mekong reveals a complex dependence of the low-flow period on the flood period. Low flows in the Lower Mekong are sustained mainly by the Yunnan component, that is, water stored as snow in the Upper Mekong, and the outflow of water stored in the Great Lake in Cambodia. Therefore, changes to the flood hydrology, such as the irregular failing of the monsoon in the northern mountain regions or flood retention in reservoirs built in the main flood-producing left-bank tributaries in the Lao People's Democratic Republic, may ultimately have a major influence on low flows further downstream.

12.2.4 Conclusions

In transboundary rivers, low-flow studies often become necessary within the context of international water management and planning. The issues may concern, among others, new developments that will effect downstream countries or require specific flow management from an upstream country, the determination of shared benefits or the mitigation of existing low flow-related problems. In both examples, the possibilities for improving flow management are being reviewed, taking into account the adverse effects of further developments and withdrawals on fish habitat during the low-flow season. Owing to the high degree of regulation in the mainstream of the Columbia River, any alterations to current flow regimes are primarily a question of outflow regulation from the major dams. These, however, are bound by the Treaty and the energy market and therefore provide very little flexibility.

In the Mekong River, the flow is still more or less natural and the impacts of changes on the environment and society are being discussed now, before major developments are initiated. However, several dams are under construction and a total of 14 cascaded hydropower stations and associated dams were planned for the Upper Mekong in China (Ministry of Water Resources, 1993) without extensive analysis of downstream impacts or discussions with the downstream countries that would be affected.

A recurrent problem in other transboundary rivers is that of extreme and unexpected low flows. Few countries have fully considered the interannual variability of climate, and fewer still have considered future climate change in international water management plans and treaties. In the light of the difficulties in predicting future conditions, it is advisable to make all agreements and allocations flexible and to account for exceptional situations by requiring the revision and renegotiation of flow allocations and minimum flow guarantees in the event of extreme drought and climate change.

The two examples illustrate how the matter of low flows in transboundary rivers is one of many issues to be considered; but, it is the issue that is most strongly bound by existing allocations and national interests. Ideally, an international commission, such as the International River Commission in the case of the Columbia River and the MRC, should facilitate the development of an international management plan to guarantee equitable use of the resource. Regular discussions, joint monitoring, data management and research are crucial to understand hydrological facts, cultural and economic interests and the issues within an international basin.
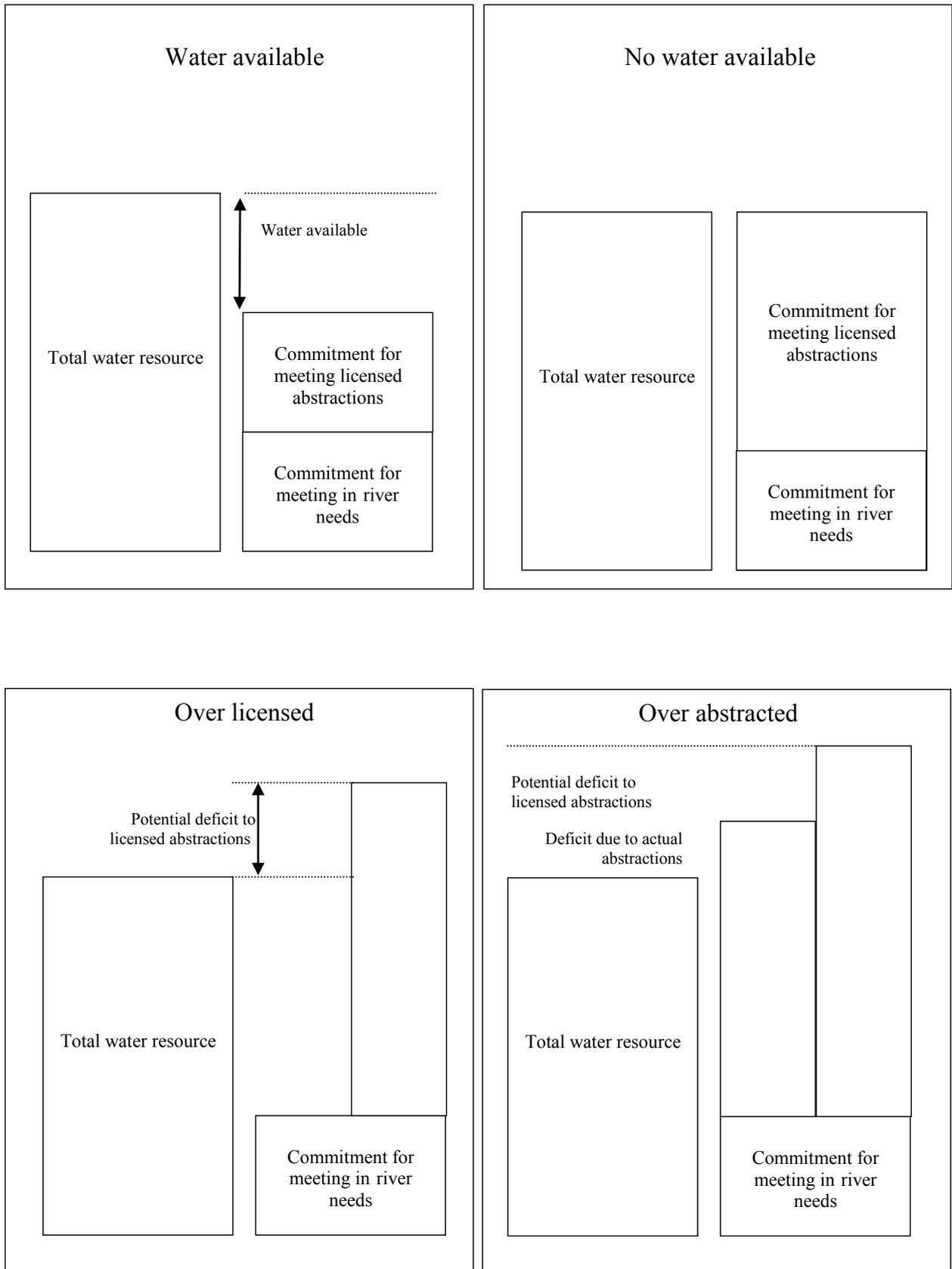
Figure 12.5 *Concept of resources availability status at low flows (Environment Agency, 2002)*

12.3 Catchment-based water resources decision-support tool in the United Kingdom

12.3.1 Introduction

The current policy on low-flow estimation in England and Wales has the objective of making information on water resources availability and abstraction licensing more accessible to the public and of providing a transparent, consistent and structured approach to this aspect of water resources management. This is being achieved through a regulatory process called the Catchment Abstraction Management Strategy (www.environment-agency.gov.uk), which is an implementation component of the European Union Water Framework Directive (WFD) within England and Wales. In Scotland, the WFD is being implemented by the Scottish Environment Protection Agency through the Controlled Activities Regulations (www.sepa.org.uk). Within both regulatory jurisdictions, a basic hydrological management tool is the flow-duration curve (FDC). The evaluation of modifications to the FDC arising from water use and the consequences of such modifications for aquatic ecosystems are key management issues within both jurisdictions.

12.3.2 European Union Water Framework Directive

Low-flow information is used to implement national and international law and policy directives. In Europe, the most important of these is the WFD, which was adopted by the European Parliament and the Council of the European Union in September 2000. This has established a strategic framework for the sustainable management of both surface water and groundwater resources. Each country must set up a competent authority to implement the Directive and log every significant body of water, above ground and below it, inland and on the coast. Most of the provisions of existing water-related European Directives, covering issues such as water abstraction, fisheries, shellfish waters and groundwater, will be combined, with past legislation being repealed or modified as the new regulations incorporate them.

The WFD requires that water management be based on river basins, rather than on administrative issues, political boundaries or water sectors. River basin management plans are being developed for each river basin district. The objectives are to provide protection for the basin in terms of aquatic ecology, unique and valuable habitats, drinking water resources and bathing waters. To achieve these ambitions, all those who have an impact on a river must be identified and involved in planning how to meet the Directive's requirements. In England and Wales, the Environment Agency has developed a number of initiatives to implement the Directive which include the Catchment Abstraction Management Strategy (CAMS). This strategy is a sustainable, catchment-specific approach to water resources management which aims to balance human and environmental water requirements both in the present and in the future.

12.3.3 Managing catchment abstractions in England and Wales

The key objective of CAMS implementation in England and Wales is to provide a consistent and structured approach to local water resources management, recognizing both the reasonable water requirements of abstractors and environmental needs. It has made information on water resources publicly available and provides an opportunity for greater public involvement in the process of managing abstraction at the catchment level. A key element of CAMS is to assess the low-flow resources available. This provides information on whether there is a surplus of water available to meet current licensed abstractions, or a deficit. It also enables time-limited (normally 12-year) abstraction licences to be issued, in contrast to the historical practice of issuing perpetual licences. The CAMS approach is to produce FDCs for a range of situations, including the natural, current and future demand scenarios. This makes it possible to identify river reaches that have the potential for further development, that are overabstracted or overlicensed or that have insufficient water for further development. FDCs are being derived from over 800 continuously recording flow gauges in England and Wales. However, despite this gauging network, which is dense by international standards, over 95 per cent of reaches in England and Wales are located far from a flow-measuring station. These sites use the LowFlows methods and structure, which are implemented by the regulatory agencies in the United Kingdom. The balance between the available resources and the environmental needs of the river, current abstractions and licensed abstractions determines the status of a specific location (Figure 12.5). By developing water resources in a sustainable manner, the CAMS strategy will reduce conflict at the basin level between competing water users.

The need to develop a rapid, nationally consistent approach to estimating natural and artificially influenced FDCs within ungauged catchments led to the development of the LowFlows software system (Young and others, 2003). The system is underpinned by regionalized hydrological models that enable the natural,
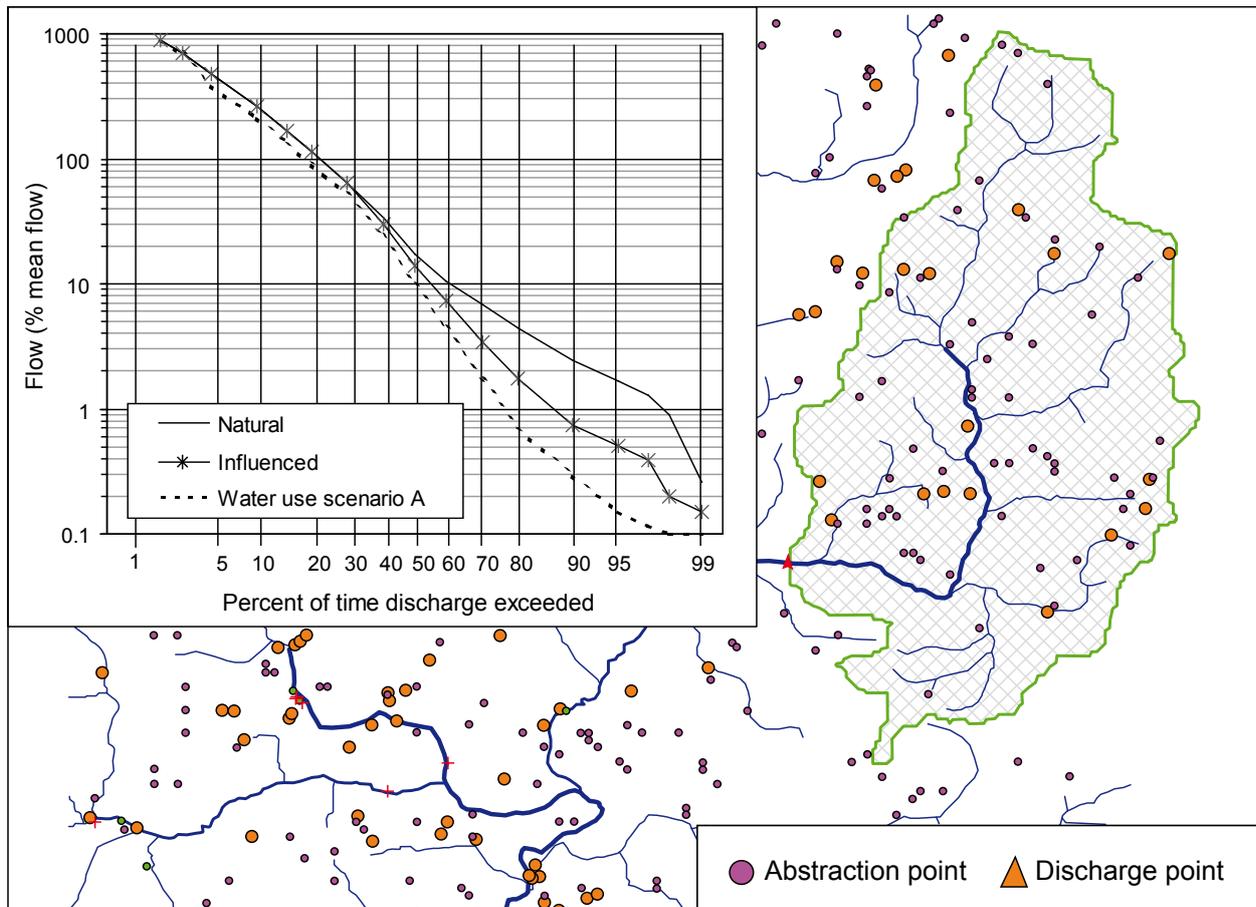
Figure 12.6 *FDCs for natural and influenced flow regimes obtained from the LowFlows 2000 software*

long-term FDCs to be estimated for any river reach in the United Kingdom, mapped at a 1:50 000 scale. Both long-term "annual" statistics (considering variability within a year) and "monthly" statistics (considering variability within a calendar month) are provided. The impact of artificial influences is simulated using a geographically referenced database that quantifies seasonal water use associated with individual features.

12.3.4 Region-of-influence model

The regionalized models employed within LowFlows are based on a region-of-influence approach, which removes the need for a priori identification of regions and instead develops a "region" of catchments similar to the ungauged catchment (section 9.5). The approach is founded on the dynamic construction of a region, based upon the similarity of the characteristics of the gauged catchments to those of the ungauged catchment. The application of this approach for estimating "annual" and "monthly" flow-duration statistics is described fully by Holmes and Young (2002) and Holmes and others (2002a, 2002b). In summary, the similarity bet-

ween the ungauged catchment and other catchments is assessed based on the distribution of soils and parent geology classes using an Euclidean distance metric. A region of the 10 most similar catchments is then identified from a good quality dataset of catchments with natural flow regimes. Estimates of the flow statistics for the ungauged catchment are then calculated as a weighted combination of the observed (standardized) flow-duration statistics for the 10 catchments in the region.

The standardized annual FDC is re-scaled by multiplying by an estimate of annual mean flow from a national runoff grid derived from a daily soil moisture accounting model (Holmes and others, 2002b). A similar approach is used to determine the FDC for any month based on a distribution of annual runoff within the year (Holmes and Young, 2002).

12.3.5 The LowFlows software system

LowFlows (Young and others, 2003) incorporates the regionalized hydrological models within a PC-based software framework using contemporary programming

tools. A geographic information system-based graphical interface provides access to the spatial datasets of catchment characteristics and the climatic variables required for the application of the regionalized models. These are defined for the entire United Kingdom at a 1 km × 1 km resolution. A 1:50 000 scale vectored digital river network and a set of digitized catchment bound-aries are used in conjunction with a digital terrain model to define catchment boundaries.

In practice, natural flow duration statistics are obtained by first selecting a point on the digital river network which defines the catchment outlet. A boundary is automatically generated by a digital terrain model. This boundary is overlaid onto the spatial datasets to obtain the catchment characteristics, such as the distributions of soil classes within the catchment, and the other variables required by the underlying hydrological models described above. The required natural flow duration statistics are returned at a "monthly" and "annual" resolution and are displayed in tabular and graphical form. Examples of output from the software are shown in Figure 12.6.

Water use within the catchment is simulated by utilizing data stored in a flexible database system. Seasonal water-use patterns associated with point influences, including abstractions, discharges and impounding reservoirs, are geographically referenced to enable catchment-based data retrievals. The net influences acting within a catchment are calculated by summing the individual influences, where discharges and releases from reservoirs are positive and abstractions are negative. The "influenced" flow-duration statistics are presented, together with the natural statistics, at a "monthly" and "annual" resolution. Hence, practitioners can make a comparison between the natural regime and associated river-flow objectives, and the regime as modified by current water use within the catchment. Furthermore, the software can be used for scenario analysis, for example, to investigate the effect of increasing the abstraction rates across a particular catchment for simulating a future water-use strategy.

The Environment Agency in England and Wales and the Scottish Environment Protection Agency have both adopted the LowFlows system as the standard decision-support tool for low-flow estimation in ungauged catchments. More than 170 trained staff use the system on a weekly basis at over 95 installations across the United Kingdom. The system is routinely used as an operational tool in the process associated with granting new abstraction licences and discharge consents, as well as for reviewing licence renewal applications. Furthermore, the results obtained using LowFlows are being used extensively in the implementation of the WFD.

12.4 Low-flow management issues in the United Kingdom

12.4.1 Introduction
Wetlands derive their nature from a range of features associated with both surface water and groundwater sources. They are maintained by persistently high water levels at, or near, the ground surface which are caused by poor drainage or proximity to a permanent water source, for example a river and its floodplain, or by a defined geological structure forming springs or the upwelling of groundwater. Under seasonal and climatic fluctuations alone, wetlands would always be subject to some variability of wetness, even to the extent of peripheral drying out. However, under the effects of human intervention in river basin management, such as land drainage and river and groundwater abstraction, wetlands may become more susceptible to drought. Even if this impact does not result in the wetlands drying out completely, the artificial extension of low water conditions, and interference with the timing and extremes of the seasonal water balance, will have an adverse effect on their ecology.

Wetlands are usually characterized by a high level of biodiversity, with the exception of some high-altitude peat bogs. In addition to the diversity of wetlands, a number of species are restricted to their habitats. Human development over the centuries has progressively reduced the extent of wetlands and, in particular, produced fragmentation, for example, along river valley bottoms. This inhibits or completely prevents the movement of species between wetland sites. If a site becomes extensively degraded by drought, species cannot migrate, and recovery or recolonization once drought conditions have ceased is severely impeded.

Drought management is particularly important for determining how low flows and depressed groundwater levels affect the condition of wetlands and the conservation of river flora and fauna. Since both aspects can be covered by legislation, the duty to protect falls upon the agency responsible for managing water resources. Management responsibility also extends to water-supply agencies and agricultural users, and remedial action and control activities can be implemented through licensing arrangements and drought management provisions.

Instream conservation is usually managed by defining the minimum flow (volume) requirements and quality conditions to support aquatic life and habitats. In recent years, the overall classification of river conditions has been undertaken on a national or supranational basis, for example, the European Union Water Framework Directive (section 12.3.2). This is intended not only as a baseline for current conditions, but as a means of establishing future quality targets to improve degraded watercourses. Quality conditions are increasingly defined with hydroecological indicators as measures, rather than the simpler chemical/biological criteria.

In low-flow conditions, the impact of an effluent reaching watercourses becomes significant. Effluent concentrations are usually controlled, as well as the capacity of the receiving water to provide dilution to absorb and reduce concentrations to below suitable limits. During low-flow periods, dilution capacity decreases, and the concentration of pollutants in the receiving waters increases. To prevent a critical build-up, it is desirable to reduce or curtail effluent discharge. In practice, this is difficult to implement in the case of continuous effluent delivery from, for example, sewage treatment works or industrial processes. Where these types of problems are recurrent, some additional treatment or the temporary storage of effluent should be established. Aeration is often an appropriate measure, ei-

ther for the effluent or the receiving waters, where the critical immediate impact is through increased BOD (biochemical oxygen demand) or COD (chemical oxygen demand) loadings.

The depth of flow is of primary importance to migratory species; but, on a more limited scale, it may have important impacts on the breeding and population diversity of aquatic species. The exposure of riverbed forms such as bars or rapids in low-flow conditions can introduce barriers to movement and reduce suitable habitats or affect breeding conditions.

12.4.2 Public water abstractions

These abstractions account for some of the most significant demands on water sources and are often closely linked to wetland management problems. Historically, these sources have been exploited where conditions are most suitable, either by controlling river sources in their headwaters through reservoir impoundments, or by extracting water from near-surface groundwater sources. These abstraction points were first developed on public health grounds, moving sources for potable water abstraction away from areas at risk from contamination from industrial waste or sewage disposal. However, controlling headwaters has an effect on the flow regime downstream; this can become particularly detrimental during extended droughts, where reservoir

Table 12.1 Stages of drought management (United Kingdom)				
Drought stage	**River-flow status**	**Groundwater level status**	**Water quality/Fisheries**	**Abstraction**
Non-drought	Within normal ranges for time of year – no restrictions			
Potential drought	At or below "trigger" value for time of year	At or below "trigger" value for time of year	Signs of local deterioration	Some prescribed flow conditions already active
Established drought	Many below Q_{95}	Close to, or at, historical minima	Reported low DO in places	Remaining prescribed flow conditions active. Reducing spring flows
Severe drought	At or below historical minima	At or below historical minima	Increased incidence of WQ, DO and fisheries problems	Significant reductions in spring flows. S57 restrictions in place. Possible drought orders/permits
Post-drought "wind-down"	Clear evidence of recovery to normal	Clear evidence of significant upturn in levels	General improvement in WQ/DO	Restrictions lifted

Notes: DO = Dissolved oxygen; WQ = Water quality; S57 = Refers to section 57 of the Water Resources Act, 1991; Prescribed flow is a condition attached to an abstraction licence which may limit abstraction when the discharge is at, or below, a specific flow rate.

replenishment delays the flow recovery in the downstream reaches. This effectively extends the duration of low-flow hydroecological conditions and increase adverse impacts as the river regime may be out of sequence with other seasonal cycles. For example, the replenishment of reservoir drawdown in summer depends on rainfall excess in winter. Reduced winter rains will result not only in a lack of reservoir recovery, but, during that period, discharges downstream will have to be reduced to maximize storage recovery in order to deal with demand the following summer. Thus, the river environment loses its synchronization with seasonality and associated life cycles.

With regard to groundwater sources, the recommended good practice for the water industry in the United Kingdom since the 1920s has been to focus abstraction above spring lines. This is typical of many countries where wetlands are identified as a convenient and low-cost water source. Such an approach was considered to provide reliability of supply while allowing more direct control, for example, in respect of residual flows. The geological structure of the chalk in lowland England, with hard bands (Melbourne rock, chalk rock) providing widely recognized spring horizons in the aquifer, lent itself very well to this approach, and, since they occur generally on higher ground, they were automatically at some distance from centres of population. The occurrence of spring sources is also affected by local fissure patterns, which produce specific locations for springs at the headwaters of rivers (for example, the River Cam, River Hiz, River Darent), rather than gen-eral seepage from the full length of the river along the strike of outcrop of hard bands. In some parts of the chalk regions in south-east England, main spring sources also support wetland areas, as well as ecologically significant chalk stream habitats. During times of drought, combined with continued abstraction, the depletion of spring flow can lead to the drying-out of chalk streams at considerable distances below what is considered their upper limit of perennial flow.

After severe droughts in southern England in the 1990s, the level of cooperation and management between the catchment management authority (the Environment Agency) and public water suppliers became very high. The development of a drought situation has clearly defined stages that can be managed through legislation, depending on the range of hydrological (rainfall, river flow or groundwater level) or related triggers. Table 12.1 below summarizes the stages for increasing restrictions.

12.4.3 Low-flow support

Low-flow support relates to the need to maintain residual flows downstream of an abstraction or impoundment at, or above, a minimum level, and is sometimes referred to as a prescribed flow. Flows are designated as quantities and are determined in relation to environmental requirements and may be subject to specific conditions once a drought is officially designated. In the United Kingdom, a drought order, which is aimed at managing both the river conditions and water sources requirements, is issued. In some cases, reservoir releases or support pumping may be required to keep downstream conditions within the specified limits: there is usually a point below which river flows are not allowed to fall, sometimes known as the "hands-off" flow.

Remedial discharges can be provided from external sources, and, on a large scale, these may be obtained from inter-basin transfers. This term usually applies to surface water transfers; but, in catchments where both surface water and groundwater sources are available, remedial groundwater support into a piped network can be used. Since waters derived from other sources and catchments may have a different basic chemical composition to the receiving waters, for example hardness, inter-basin transfers for environmental support must be carefully considered. Within catchments where both surface water and groundwater sources are available, this allows conjunctive use schemes, where abstraction switches between surface water and groundwater, depending on conditions. Thus, it may be operationally beneficial to continue groundwater abstractions in the normal recharge season, while leaving reservoir sources untouched to allow the maximum effect of replenishment.

Pumped abstraction from groundwater is sometimes used as a means of low-flow support to provide water to maintain base flows above minimum levels, or to maintain water in headwater reaches that are likely to dry out below the normal perennial flow point, as surface water and shallow groundwater sources dry out. This may be carried out for environmental or aesthetic purposes. In parts of south-east England where the major chalk aquifer is the main source of water supply, integrated schemes exist to maintain flow in main rivers, for example the River Kennet, a major headwater of the River Thames, the River Darent (Kent) for ecological and scenic purposes, and the River Hiz to maintain flows through the town of Hitchin (HR Wallingford, 2001). The sources for remedial flows are separate from supply
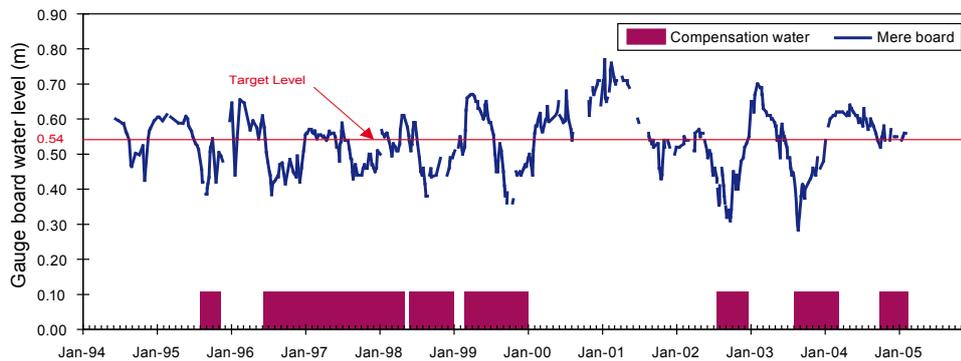
Figure 12.7

Application of the compensation water method to maintain optimum water levels at Fowlmere Reserve

abstractions to avoid interference, and also from deeper parts of the aquifer so as not to affect existing spring sources by setting up localized circulations.

Drought support can also be applied on a site-specific basis, and this is particularly relevant as a remedial measure where a licensed abstraction has a detrimental impact on a nearby wetland. The provision of remedial water support can be included in the terms of the abstraction licence. Figure 12.7 illustrates the provision of pumped compensation water to Fowlmere Reserve, a protected wetland mere in eastern England (Dent, 2005). The compensation method is applied during a winter period when the normal rainfall excess for replenishment failed. The target is a specific level on a lake (mere) gauge, which is related to the water control on the rest of the site.

12.4.4 Wetland hydrology monitoring

Wetland water conditions are an intricate balance between surface water and groundwater sources and losses caused by outflow and evaporation. Slight variations in topography and elevation have significant bearing on plant communities and the behaviour of water. Water levels at the site may also be controlled by, or linked to, external water features, such as a river or groundwater source, and may also be affected by abstraction operations. The subtleties of these relationships make the application of theoretically based models problematical in terms of scale and suitable data for detailed calibration.

Detailed monitoring is therefore the most appropriate option to observe the changes in conditions and to provide information on operations for controlling water level or for initiating remedial support measures. An example of wetland monitoring is presented in Dent (2005) for the Fowlmere Reserve. To develop a monitoring network, the relationship of the site to the sur-

rounding hydrological environment, including the abstraction sources, must be ascertained. In the case study, instrumentation is operated by the catchment management authority (observation boreholes, river-flow stations) and by the Reserve's oper-ators (gauge boards, piezometers): these records can be compared with the operations of the water-supply abstraction boreholes.

The site has a number of control and distribution features, and their interrelationship is illustrated in the network schematic Figure 12.8. This figure shows the interrelationship between external sources and controls, for example streams and springs, and the necessary monitoring components used to identify the overall water balance and internal water management.

12.5 Real-time management of environmental flow requirements for the Thukela River in South Africa

12.5.1 Description of the study area

The Thukela River basin (29 046 km²) is located on the western seaboard of South Africa (Figure 12.9) and has its headwaters in the Drakensberg mountains. Mean annual rainfall varies from over 1 500 mm in the mountain areas to about 700 mm in the drier central parts of the catchment and is highly seasonal, with a wet season between November and March and a dry season between May and August. Mean annual potential evaporation varies between 1 200 and 1 500 mm. There are over 40 streamflow gauging stations within the basin; however, they have variable length and quality records, and most of them are influenced by upstream developments. In the past, there was a reasonably dense raingauge network (over 50 daily reporting gauges distributed throughout the basin); however, this network has deteriorated substantially since the late 1990s, such that data are now routinely available only from some 15 gauges. Water resources developments within
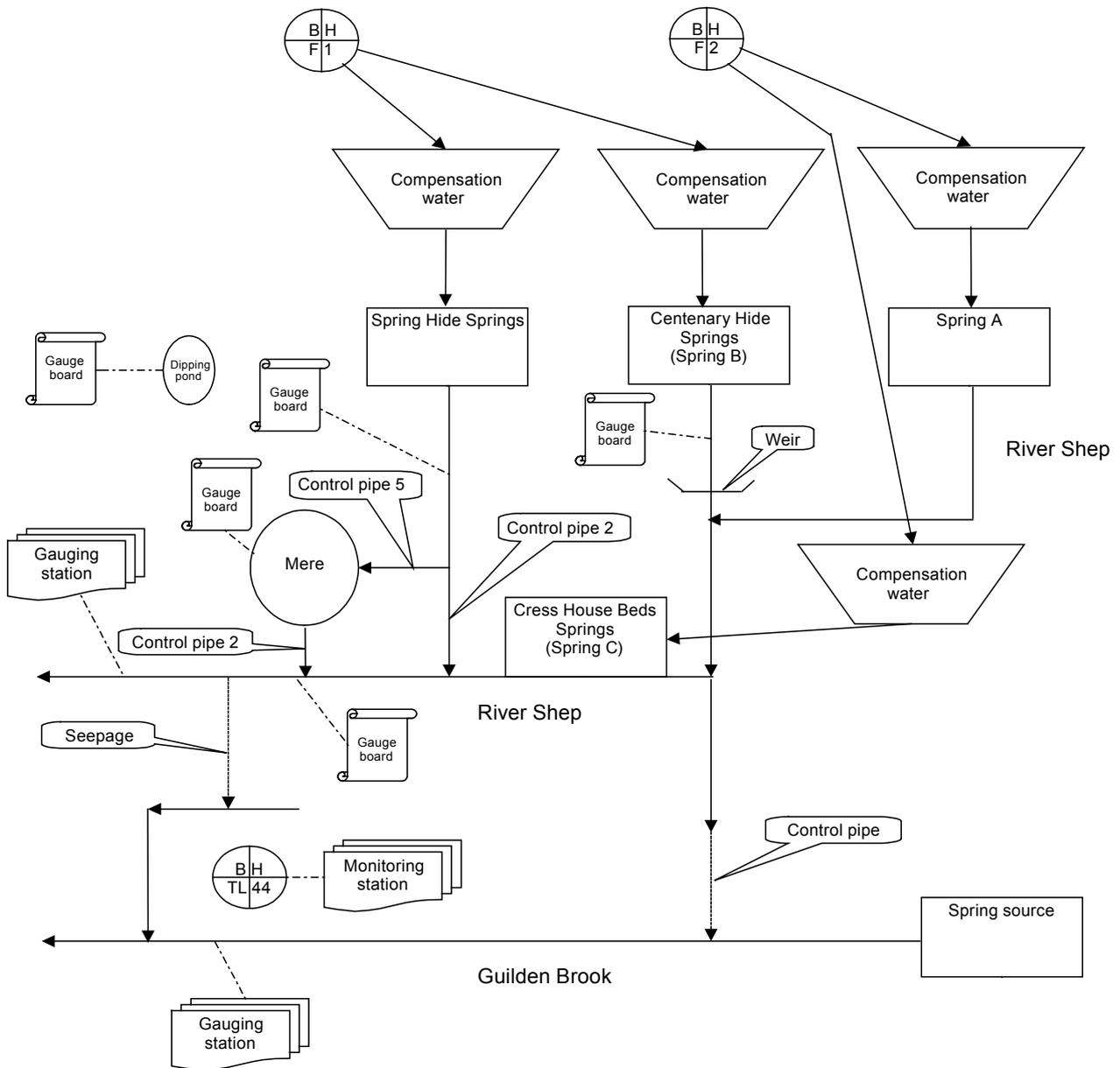
Figure 12.8 *Schematic diagram for wetland support and monitoring system*

the basin consist of several major reservoirs for local supply as well as for inter-basin transfers, plus many distributed run-of-river abstraction schemes for domestic, industrial and irrigation purposes.

12.5.2 Background to the study

The revised National Water Act of South Africa (DWAF, 1997) makes provisions for the protection and sustainable development of aquatic resources through the establishment of environmental water requirements (EWR). A major project, completed in 2004, established the EWR for 16 sites within the Thukela basin using
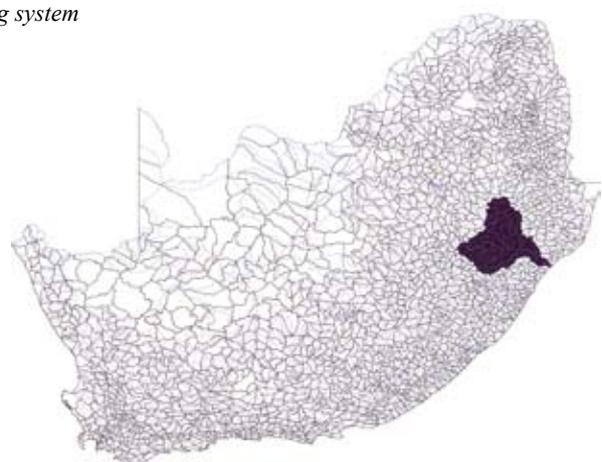
Figure 12.9 *Location of the Thukela basin in South Africa*

standard South African approaches that result in a set of low-flow and high-flow requirements designed to reflect the variability of the natural flow regime (King and Louw, 1998; Hughes and Hannart, 2003). The next step in the process was to design the approach to implement the EWR as part of the standard operating procedures used by the regional office of the Department of Water Affairs and Forestry. The operating procedures include releases from reservoirs (sustained low flows, as well as intermittent, short-term high flows) and restrictions on the abstractions allowed by various user sectors. It was previously agreed that the principles used in determining the EWR should be reflected in the way in which they would be implemented in practice. This example concentrates on the methods being established for the low-flow component of the EWR.

12.5.3 Analysis methods

The prerequisite that the EWR should reflect variations in natural flow, coupled with the fact that most of the streamflow gauging stations do not measure natural flow, suggested that an alternative approach was needed to generate the required signals for EWR releases. A monthly rainfall-runoff model (the Pitman model; Hughes, 2004) was established for 87 sub-basins within the Thukela based on historical rainfall data available from the 15 gauges that were still active and able to supply near-real-time data (10-day cycles).

The calibration was based on comparisons with existing flow simulations using an earlier version of the model and more rainfall data, which were used in setting the EWR as well as in previous water resources yield assessment studies.

Two new "models" have been added to the SPATSIM database and modelling framework (Hughes and Forsyth, 2006), the first of which is used for manually capturing the near-real-time daily rainfall data (sent to the project team on a 10-day cycle by the South African Weather Service), performing some checks and building the gauge and sub-basin rainfall data time series (Figure 12.10). The second model is used for updating the rainfall-runoff simulations, viewing and editing the operating rules (including the EWR and user curtailment rules) and displaying the operating rules decision-support information (Figure 12.11).

The input information for this second model includes reservoir releases and user curtailment rules that have been generated using a system yield model (Mallory, 2005) and were found to be sustainable on the basis of simulations using more than 50 years of historical data. The decision-support information is based on the quantification of a drought severity index using the percentage points of calendar month flow-duration curves. All operating rules are related either to the drought severity value or the manually input reservoir levels.

12.5.4 Current progress

The modelling system and all the operating rules have been established (in cooperation with the regional water resources managers) for a number of decision points within the basin, and trial operations began during the latter part of 2006.

The intention is to operate the Thukela system according to the information generated by the implementat-
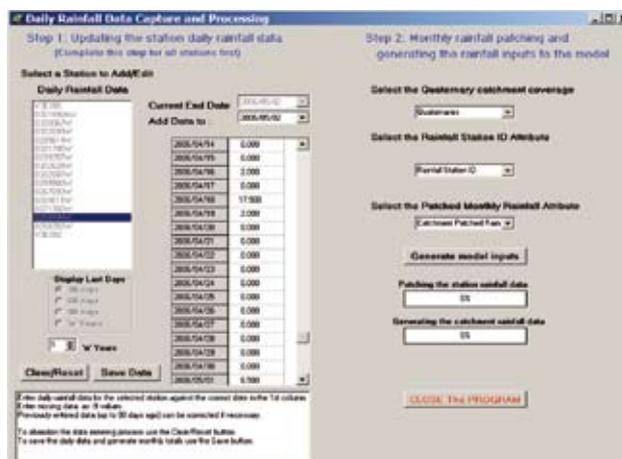

Figure 12.10 *Real-time rainfall data capture screen*
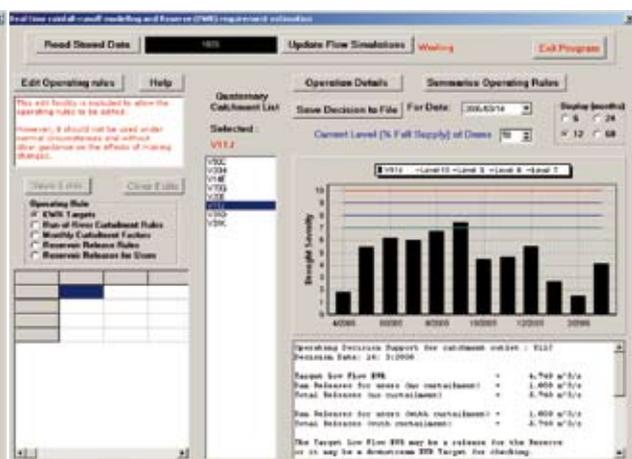

Figure 12.11 *Water management decision-support program screen*

ion software and assess whether the EWR flow objectives are being met at a downstream gauging station near the basin outlet.

12.5.5 Conclusions and recommendations
It is too soon to report on the successes or failures of the system; however, a number of issues have already been identified. There have been some difficulties in obtaining reliable near-real-time rainfall data, which illustrates the importance of data collection and emphasizes the weakness of current data networks. There are initiatives to develop improved real-time rainfall data generation (based on various sources, including ground, radar and satellite observations). However, problems may still exist in terms of linking the historical rainfall information used to calibrate the model with future sources of rainfall data (Hughes, 2006).

Although the implementation model relies upon restrictions placed on users under drought conditions, there are no management structures currently in place to ensure compliance. The South African water management infrastructure is currently in a state of flux, and it has been assumed that future procedures will ensure compliance with water abstraction licences that provide for curtailment during water shortages.

12.6 Regionalized resources models for small-scale hydropower: India and Nepal

12.6.1 Introduction
In contrast to major hydropower schemes with significant reservoir storage, small-scale hydropower schemes frequently have no artificial storage to provide a constant supply of water for power generation (Figure 12.12). These schemes therefore rely entirely on the natural river flow to generate electricity. There are many hydropower scheme components for the prospective developer to consider. For example, the proximity of the scheme to the consumer and implications for transmission, site accessibility, the extent of civil engineering works, the practicalities of acquiring and maintaining the electromechanical equipment, the mitigation of environmental impacts, the likely profitability of the scheme, and so on. However, there is one vital ingredient, without which none of the above can be contemplated seriously: a sufficient and reliable water supply. In small-scale hydropower design, as with many other water resources projects, such as water supply, irrigation and water quality management, the conventional method for describing the availability of water in a river is to use the flow-duration curve (FDC). Many prospective

sites for small-scale hydropower are also located in remote areas where the river has never been gauged.

12.6.2 The FDC in hydropower design
Figure 12.13 illustrates that not all of the water flowing in a river will be available for hydropower generation. A certain amount of residual flow ($Q_{residual}$) should be left in the river to meet the needs of water users immediately downstream of the scheme and to preserve the ecology of the river. Neither is it possible to harness all of the flow: turbines that would operate at high flows could not function at the lowest flows. The highest design flow, or rated flow (Q_{rated}), therefore determines the range of flows for generation and also the minimum flow of a turbine (Q_{min}). The residual flow, rated flow and minimum flow, together with the FDC for the site, thus determine the volume of water the scheme will use.

12.6.3 Estimating the FDC at an ungauged site
The Himalayas, which are characterized by high mountains, rapid changes in elevation and a monsoon-influenced climate, have a relatively sparse network of hydrometric and meteorological stations and this compounds the difficulty of hydrological modelling. This case study describes the development of a regional model for predicting the FDC within Nepal and the state of Himachal Pradesh in northern India. The methodology for Himachal Pradesh presented here was confined to a relatively hydrologically homogeneous rain-
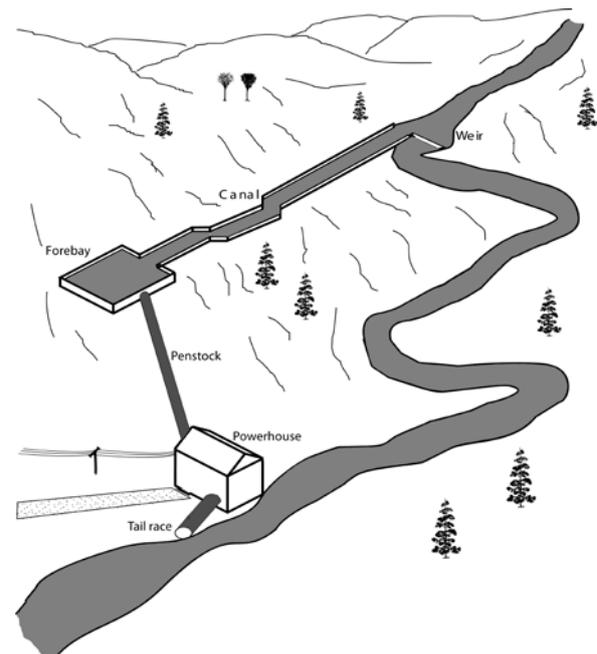

***Figure 12.12*** *Typical layout of a small-scale hydropower scheme*
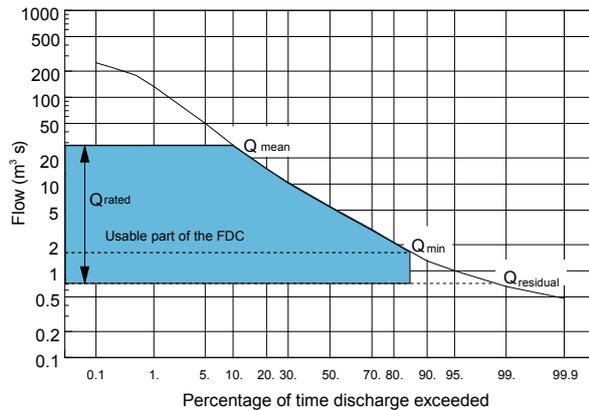
Figure 12.13 The FDC in hydropower design

and snow-fed region at an elevation between 2 000 m and 5 000 m. Having favourable topography, relatively easy access and a reliable supply of water throughout the year, this part of the state is the most suitable for small-scale hydropower development. At lower altitudes (below 2 000 m), there is little variation in topography and, with runoff derived solely from rainfall, rivers tend to be ephemeral. At higher altitudes (above 5 000 m), the remoteness and harsh conditions rule out extensive small-scale hydropower development. Although objective methods, such as cluster analysis and principal component analysis, could have been used, the homogeneous region was delineated according to the advice of local hydrologists with reference to topographical maps and snowline remote-sensing data from the Himachal Pradesh.

The development of a regionalized model requires good-quality hydrometric datasets from catchments that are representative of the study area, together with meteorological and other spatial data that adequately describe the region's climate and hypsographical features. The first step was to identify gauged catchments with a long time series of flows with limited artificial (human) influences that were sufficiently widespread to be representative of the flow regimes in the study area. Data from 60 gauging stations in the rain- and snow-fed region were obtained from the state authorities. Subsequent quality control checks to identify catchments suitable for the low-flow analysis reduced the final sample dataset to 41. The catchment boundary for every catchment was drawn from 1:50 000 topographic map sheets, digitized and stored as polygons in the ArcInfo geographic information system. A variety of spatial datasets, describing the climate and physiographical nature of the study area, were also identified.

The regional model for Himachal Pradesh (Rees and others, 2002) seeks to capture the observed relationships between the shape of the hydrograph and the nature of the catchment hydrogeology through the development of a multivariate linear regression model relating the Q_{95} flow (expressed as mean flow percentage) to the proportional extent of different soil (or geology) classes, including a class for snow and ice, within a catchment. The relationship yields an estimate of standardized Q_{95} for each soil (or geology type) encountered. A map of standardized Q_{95}, based on the distribution of soils (or geology), can thus be derived for the region. Overlaying the boundary of an ungauged catchment onto the map enables the Q_{95} of that catchment to be determined. The approach of Gustard and others (1992) was adopted to extend the estimation from Q_{95} to a full FDC. A family of flow-duration-"type" curves was determined for the region by averaging curves derived from observed flow data with similar Q_{95} values. The shape of the estimated FDC at the ungauged site is then determined using the predicted Q_{95} value. An estimate of the catchment mean flow is necessary to rescale the FDC in absolute units. A detailed analysis of precipitation, flow and altitude revealed that the distribution of runoff in the rain- and snow-fed region of Himachal Pradesh was best described by means of a simple linear relationship between annual runoff depth and altitude.

12.6.4 HydrA-HP

HydrA-HP is a software package that has been developed incorporating the Q_{95} model and the mean flow model as separate grids at a spatial resolution of 1 km. It provides an easy-to-use, menu-driven interface that allows even those with a minimal understanding of hydrology to rapidly estimate the FDC and, hence, the
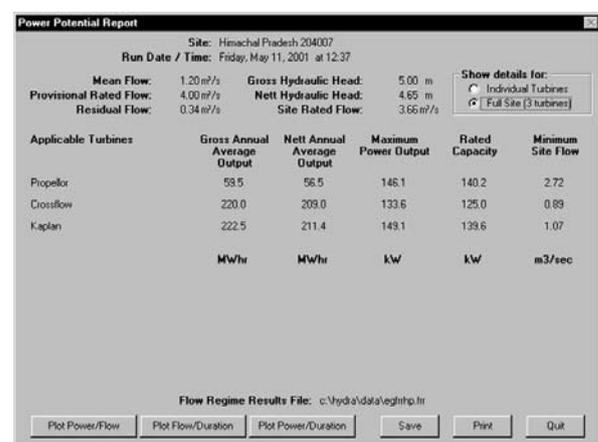

Figure 12.14 Power potential report

hydropower potential at any prospective site. The software user is simply required to enter the geographical coordinates delineating the catchment boundary upstream of the site of interest. The software identifies the constituent grid cells and derives a FDC specifically for the site. Referring to the FDC, the user is then required to enter the rated (or design) flow, the residual (or ecological) flow and head conditions at the site.

The hydropower potential (annual energy output, maximum power and rated capacity) can be calculated for up to eight types of turbine. Once the user has entered the values of hydraulic head and rated flow, the software refers to the operational envelopes of eight standard turbine types to identify which will operate under the stated conditions. For each selected turbine type, the software determines the usable part of the FDC (determined by the rated capacity of the turbine and the residual flow that is to be left in the river). Subsequently, by referring to the relevant flow-efficiency curves, it calculates the average annual energy potential (MWh) and the power-generation capability (kW) of the site. The single page report that results from this procedure is shown in Figure 12.14.

12.7 Residual flow estimation and hydropower: Norway

12.7.1 Introduction
As with many hydrological issues in Norway, research on low flows has been related to hydropower production. These studies mainly focused on how to set instream flow requirements (residual flow) downstream of hydropower reservoirs or abstraction diversions. Owing to an increased awareness of the negative environmental impacts of water resources development, a number of water utility companies, hydropower companies, consultants and municipalities now have a professional interest in low flows. Current topical

water resources issues include the consequences of pollution, reservoir design and management, and the withdrawal of water from rivers for irrigation, small hydropower plants and drinking water supply. This has shifted research focus towards finding methods to calculate low flows in catchments with few or no measurements.

The Norwegian Water Resources and Energy Directorate (NVE), an agency of the Ministry of Petroleum and Energy, is responsible for administrating the nation's water and energy resources and is also one of the administrators of the Norwegian Water Resources Act. A hydropower company applied to the NVE for a licence to regulate the Stølsvatn Lake and build the Dirdal hydropower plant in the small river, the Stølsvatnsbekken (Figure 12.15) in south-west Norway. When the application was made, there were no other types of flow regulation or water use within the catchment.

The riparian ecosystems of the Stølsvatnsbekken River included species of rare mosses and lichens which were dependent on spray from the river during the summer. Consequently, the NVE sought to specify a minimum residual flow in the summer months (May to August) in order to maintain this habitat. When determining these flow requirements, it was necessary to calculate low-flow indices for the Stølsvatnsbekken River.

12.7.2 Estimation of low-flow indices for the Stølsvatnsbekken River
There were no observations of river flow for Stølsvatnsbekken; but, two nearby stations, Sætervatn and Saglandsvatn, had daily records for the periods 1973 to 2000 and 1973 to 1993, respectively. Basin characteristics, for example the area, the lake percentage and the range of elevations present, were also available for the three basins (Table 12.2).

Table 12.2 Basin characteristics for Stølsvatnsbekken, Sætervatn and Saglandsvatn			
	Stølsvatnsbekken	Sætervatn	Saglandsvatn
Area (km²)	4.30	15.80	1.80
Mean annual runoff (l/s/km²)	86.90	85.30	44.90
Effective lake percentage	5.04	5.36	21.87
Lake percentage	6.80	14.70	22.30
Elevation (m.a.s.l)	420–760	295–720	120–280
Basin length (m)	3 026	5 382	1 754
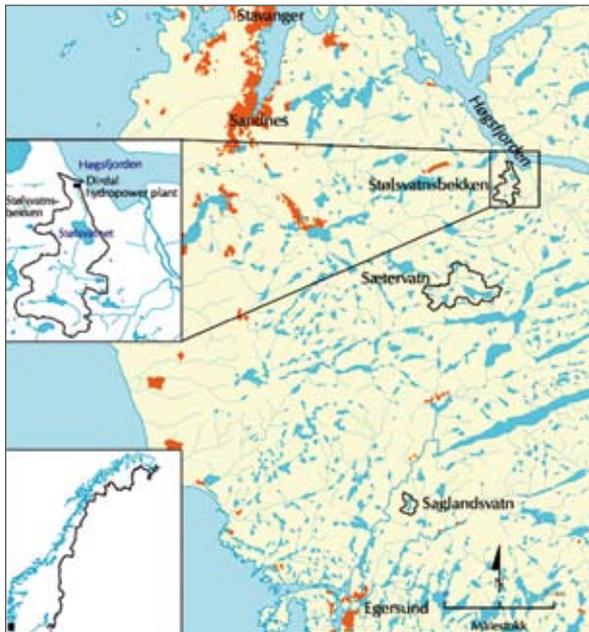
Figure 12.15 *The Stølsvatnsbekken catchment in south-west Norway*

In Norway, there are no requirements or standard methods for estimating low-flow indices at ungauged sites, and subjective methods are frequently applied. For Stølsvatnsbekken, estimates of the mean annual minimum 7-day flow (MAM(7)) were derived using a combination of the following two methods:

1. Regional regression equations to calculate MAM(7), with mean annual flow and basin characteristics as independent variables.

2. Estimates based on the streamflow observations from two similar nearby catchments at Sætervatn and Saglandsvatn.

The regional regression equations (section 9.3) were determined using data from 172 stations in a frequency and regression analysis (Krokli, 1988). The country is divided into regions according to the different hydrological regimes. Regression equations are defined for MAM(D) values (D = 7, 30 and 60 days) and the 10-year return frequency of MAM(D) for both a summer and winter season, for each region. This is essential in Norway because, in winter, low flows are caused by precipitation being stored as snow and ice, whereas summer low flows are caused by lack of precipitation and high evaporation losses. The regression equations relate MAM(7) to basin characteristics, while other duration minima MAM(D) are expressed as functions of MAM(7).

The region of Stølsvatnsbekken is dominated by autumn floods and summer low flows. The regression equation for MAM(7) for the summer period is defined by:

$$MAM(7) = Q_n (0.0322(Efflake + 0.1)^{0.314})(H_{max}^{0.131}) \quad (12.1)$$

where Qn is the mean annual runoff (l/s/km²); Hmax is the maximum difference in altitude in the basin (m); and Efflake is the effective lake percentage.

$$Efflake = \frac{100\sum_{i=1}^{n} A_i a_i}{A^2} \quad (12.2)$$

where n is the number of lakes in the basin; Ai is the drainage area of lake I; ai is the area of lake I; and A is the total basin area.

For Stølsvatnsbekken, these equations yield an estimate of MAM(7) of 10.0 l/s/km². The estimated MAM(7) values for Sætervatn and Saglandsvatn are 10.3 and 7.2 l/s/km², respectively. These three values were used as a starting point to set the minimum residual flow requirements.

12.7.3 Conclusions

A study of the hydrological operation of the scheme and its impact on the ecology concluded that the moisture supply resulting from spray from the river, supporting the riparian ecosystem, would be heavily reduced if minimum residual flow requirements were not set. The environmental consequences of this could include a local reduction in biodiversity. Guaranteeing the supply of sufficient moisture during the growth season in the summer was seen as the most important factor to preserve the rare mosses and lichens. Outside the growth season (September to May), it was assumed that precipitation and floods would give sufficient moisture support to the ecosystem; therefore, there was not considered to be a need for a minimum residual flow requirement in this period. Following an economic analysis of the impact of possible levels of minimum residual flows, the NVE recommended that an abstraction licence be granted with a seasonal restriction on abstraction between June and August, when abstraction may take place only when river flows exceed 35 l/s/km². This is about three times the estimated MAM(7) value and is almost equal to the mean flow. When inflows to the Stølsvatn reservoir are less than this required residual flow, hydropower cannot be produced.

References

Dent, J., 2005: English Nature: Determination of the Water Resources Requirements of Fowlmere Watercress Beds SSSI Under Varying Management Regimes. James Dent, in association with Simpson and Partners.

Department of Water Affairs and Forestry (DWAF), 1997: White Paper on a National Water Policy for South Africa. Department of Water Affairs and Forestry, Pretoria, South Africa.

Environment Agency, 2002: Managing Water Abstraction: The Catchment Abstraction Management Strategy Process. Environment Agency, Bristol, United Kingdom.

Gustard, A., A. Bullock and J.M. Dixon, 1992: Low Flow estimation in the United Kingdom. Institute of Hydrology Report No. 108, Wallingford, United Kingdom.

Holmes, M.G.R. and A.R. Young, 2002: Estimating seasonal low flow statistics in ungauged catchments. Proceedings of the British Hydrological Society Eighth National Symposium (Birmingham, 2002).

Holmes, M.G.R., A.R. Young, A. Gustard and R. Grew, 2002a: A new approach to estimating mean flow in the United Kingdom. Hydrology and Earth System Sciences, 6(4): 709–720.

— , 2002b: A region of influence approach to predicting flow duration curves within ungauged catchments. Hydrology and Earth System Sciences, 6(4): 721–731.

HR Wallingford, 2001: Hydrological and Hydrogeo logical Review: Development West of Stevenage – Phase 2. HR Wallingford Ltd., Report EX 4139.

Hughes, D.A., 2004: Incorporating ground water recharge and discharge functions into an existing monthly rainfall-runoff model. Hydrological Sciences Journal, 49(2): 297–311.

Hughes, D.A., 2006: Comparison of satellite rainfall data with observations from gauging station networks. Journal of Hydrology, 327(3–4): 399–410.

Hughes, D.A. and D.A. Forsyth, 2006: A generic database and spatial interface for the application of hydrological and water resource models. Computers and Geosciences, 32: 1389–1402.

Hughes, D.A. and P. Hannart, 2003: A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. Journal of Hydrology, 270(3–4): 167–181.

King, J. and D. Louw, 1998: Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. Aquatic Ecosystem Health and Management, 1: 109–124.

Krokli, B., 1988: Analyse av lavvannføringer [Analysis of Low Flow]. NVE Publikasjon Nr V14, Oslo, Norway (in Norwegian – extended abstract in English).

Mallory, S.J.L., 2005: The modelling of water restrictions applied in complex bulk water supply systems and the application of these techniques to operationalising the ecological reserve. Paper presented at the Twelfth South African National Hydrology Symposium (Pretoria, September 2005).

Ministry of Water Resources, 1993: A Brief Description of the Cascaded Hydropower Projects on the Middle and Lower Reaches of the Lancang River in Yunnan Province. Kunming Hydroelectric Investigation, Design and Research Institute, Ministry of Power Industry and Ministry of Water Resources, Kunming, China.

Mekong River Commission (MRC), 2005a: Webpage: About the Mekong River Commission. http://www.mrcmekong.org/about_mrc.htm (accessed 11 November 2008).

— , 2005b. Overview of the Hydrology of the Mekong Basin. Vientiane, Lao People's Democratic Republic, available at: http://www.mrcmekong.org/free_download/research.htm (accessed 11 November 2008).

Muckleston, K., 2003: International Management in the Columbia River System. UNESCO, IHP, WWAP, Technical Documents in Hydrology. PC→CP series, No. 12, available at: http://unesdoc.unesco.org/images/0013/001332/133292e.pdf (accessed 11 November 2008).

National Research Council (NRC), 2004: Managing the Columbia River: Instream Flows, Water Withdrawals, and Salmon Survival. National Academies Press.

Rees, H.G., K.M. Croker, M.K. Singhal, A.K. Saraf, A. Kumar, M.D. Zaidman and A. Gustard, 2002: Flow regime estimation for small-scale hydropower development in Himachal Pradesh. Journal of Applied Hydrology, XV(2/3): 77–90.

Stahl, K., 2005: Influence of hydroclimatology and socio-economic conditions on water-related international relations. Water International, 30(3): 270–282.

United Nations, 1997: Convention on the Law of the Non-navigational Uses of International Watercourses. International Legal Material, Volume 36.

Wolf, A.T., J. Natharius, J. Danielson, B. Ward and J. Pender, 1999: International river basins of the world. International Journal of Water Resources Development, 15(4): 387–427.

Wolf, A., S.B. Yoffe and M. Giordano, 2003: International waters: Identifying basins at risk. Water Policy, 5: 29–60.

Young, A.R., R. Grew and M.G.R. Holmes, 2003: LowFlows 2000: A national water resources assessment and decision support tool. Water Science and Technology, 48(10): 119–126.

13. Recommendations and conclusions

13.1 Introduction

In both developed and developing countries, there is increasing pressure to improve the reliability of water resources schemes and enhance ecosystems degraded by overabstraction and pollution. Both surface water and groundwater resources are under greatest pressure during low-flow periods, and with population growth and climate and land-use change these pressures will increase. It is thus essential that water resources schemes be designed and operated so that people's livelihoods and the ecosystems on which they depend are enhanced. This can be achieved only by developing and disseminating operational techniques based on a thorough understanding of drought processes, good-quality hydrological data and analytical techniques appropriate to a wide range of environments. This chapter makes a number of recommendations for improving abilities and reducing the uncertainty in predicting and forecasting low flows in three areas: data collection, operational applications and capacity-building.

13.2 Data

Estimates of the frequency of low flows require long, preferably unbroken, time series, while the need to make estimates at sites without data is reduced if there is good spatial coverage. Chapter 3 describes a number of techniques for processing, controlling the quality of, and disseminating hydrological data. In some countries these methods are well established; but, in many parts of the world the resources allocated to environmental monitoring are inadequate and both the volume and quality of data are in decline. The highest priority is therefore to ensure that there is a long-term commitment over several decades to increasing the resources allocated to data collection and disseminating good practices, particularly, but not only, in developing countries. Networks need to be expanded, data processing and quality control improved, and different environmental datasets must be integrated into geographic information systems and freely disseminated.

It is anticipated that there will be continued improvements in sensors, data loggers and processing software. Advances in remote-sensing and low-cost sensors for measuring water levels should improve the availability of data from large rivers and lakes, particularly in remote locations. The spatial resolution, global coverage, measurement frequency and record length will continue to improve along with the remote-sensed measurements of land use and snow and ice. This will have direct benefits in estimating the impacts of land-use change in large basins and that of deglaciation on dry-season flows.

In many catchments, the dominant impacts on hydrology are the artificial influences caused by the construction of reservoirs, direct river abstractions, groundwater pumping, power generation and urbanization. There is a need to improve the availability of information on the location, volume and timing of these influences using direct measurements for the dominant impacts and estimation procedures for the large number of minor influences. For the improved operation of water resources, it is essential to have access to data in real time to make decisions on, for example, the operation of a hydropower scheme or the control of abstractions. The next decade will see continued advances in the real-time dissemination of precipitation, stream flow, groundwater level and reservoir data, as well as the synthesis of this data through regular reports on the current status of the low flows and flow forecasts. The increased use of the Web as a platform for data dissemination will improve access to information and its exchange between environmental protection agencies and power and water utility companies; the general public will also benefit.

13.3 Operational applications

Where there is adequate data for understanding low-flow processes or for hydrological design, this should always be used in preference to a predictive model. However, on many occasions data are absent or inadequate. In these situations, it may be necessary to

develop a hydrological model, for example, to estimate low flows at an ungauged site or to predict the impact of land-use change.

Chapter 9 describes different regional hydrological models ranging from simple empirical relationships to more complex multivariate models. The key application of these models is to estimate the frequency of low flows at sites for which flow data is not available. The main limitation on their further development is the requirement of good-quality hydrological data for model development and calibration and the absence of the most appropriate catchment descriptors. All basin properties must be in digital form and, where necessary, new descriptors need to be developed. Although it is recognized that hydrogeology is a key variable in controlling low-flow response, it is rarely incorporated explicitly in regional low-flow models. It is also necessary to improve estimates of model uncertainty by testing the model on a subset of catchments not used in calibration.

Although the science of stream ecology is outside the scope of the Manual, the estimation of low flows is often a key issue in river-flow management. One of the most important reasons for improving our understanding of river ecosystems is to develop instream flow models for improved river management, particularly for minimizing the impact of river abstractions on the abundance and diversity of stream biota. Very rapid assessment techniques where the ratio of an abstraction to the natural low flow is very low are still in demand. Although simple low-flow statistics have traditionally been used, the availability of national field programmes and associated databases describing channel geometry and substrate combined with flow information should lead to significant advances in rapid assessment techniques.

There is considerable opportunity for improving the transfer of existing knowledge from the research to the operational community. For gauged locations, it is essential that software be available to analyse the range of low-flow indices described in this Manual, with tabular and graphical outputs in an appropriate form for the decision-making and reporting of the operational agencies. To estimate flows at ungauged sites, existing regional models must be integrated with digital databases of catchment descriptors.

This may require major national digitizing programmes to convert existing maps into digital form or the

bringing together of disparate databases of meteorology, hydrogeology, soil surveys, river networks, land use and topography.

There have been considerable advances in hydrological modelling over the last two decades using different types of hydrological models operating at a range of spatial scales. Most of this research has focused on reducing the uncertainty of model prediction based on the calibration of single catchments or small subsets of catchments. One of the most important priorities is to build on this expertise to regionalize monthly and daily continuous simulation models. Using inputs of daily precipitation and evaporation, it will then be feasible to generate long periods of daily flows at ungauged sites, extend short records and predict the impact of land-use change or the sensitivity of low flows to climate variability. The regionalization of these models will enable operational hydrologists to carry out these tasks for all river reaches within a region.

Hydrological design is rarely required in sparsely populated pristine catchments. Conversely, most hydrological problems arise in densely populated catchments and in areas with the greatest pressures from competing water users. These catchments, which have very complex patterns of water use, are rarely studied by the research community. There is an urgent need for the improved monitoring and modelling of these artificial influences. Although some impacts are relatively simple, for instance, the effect of a sewage discharge on low flows, others are more complex, such as the impact of groundwater pumping or urbanization. A holistic approach to integrated catchment management must be adopted in contrast to the historical approach of considering issues separately for each water industry sector.

At the global level, there is a need to advance operational design and forecasting in developing countries. In mountain environments, there is a need to predict the long-term impact of deglaciation on dry-season flows. This is of particular importance in the Himalayas and the Andes, where low flows derive primarily from glacial meltwater and are critical in the dry season for agricultural and drinking water.

Advances in operational hydrology will be accelerated if long-term partnerships can be established between the user and research communities. This enables the operational requirements to be clearly specified before a research programme is initiated. It is important that

the final product be compatible with the available data, the skills of the organization and its policy objectives. Normally, research will be transferred through software, which must be supported over several years so that decision-support systems can be refined according to advances in the underpinning research.

13.4 Capacity-building

The management of low flows in extreme droughts puts considerable strain on individuals and organizations if they are not well prepared. In the past, the primary concern was to develop a strong physical infrastructure, which was deemed necessary to cope with the competing demands of different stakeholders. Although infrastructures may have been appropriate to make optimal use of the available and even decreasing water resources, infrastructure management was often inadequate, such that systems were far from sustainable and the services provided deteriorated unacceptably. Thus, institutional capacity and detailed planning are crucial for good low-flow management. A key component of this is to ensure that, before an extreme event, organizations have the necessary tools and experience to analyse and interpret low flows. There is a need for a strong underlying knowledge base (as reported in the previous chapters) and the corresponding capacity of managers to act. In particular, managers have the responsibility to plan,

manage and use the available infrastructure and to ensure proper governance of the water sector. This, however, requires appropriate knowledge resources and the involvement and attention of all stakeholders, from the government level right down to individual water consumers.

Capacity development is the process by which individuals, organizations, institutions and societies develop abilities (individually and collectively) to perform functions, solve problems, and set and achieve objectives (UNDP, 1997; Lopes and Theisohn, 2003). This involves management in the areas of resolving conflicts, dealing responsibly with change, coping effectively with institutional pluralism, encouraging communication, ensuring that data and information are collected, analysed and shared, and creating the necessary conditions for knowledge generation, sharing and transfer. Three levels of capacity development can be identified (Figure 13.1), namely, the individual and institutional levels embedded in the appropriate enabling environment (van Hofwegen, 2004).

Without capable individuals who are both competent to think through the issues associated with low flows and have the authority and ability to act responsibly in a collaborative manner, little can be achieved in managing the critical situations that may arise. This is a hu-
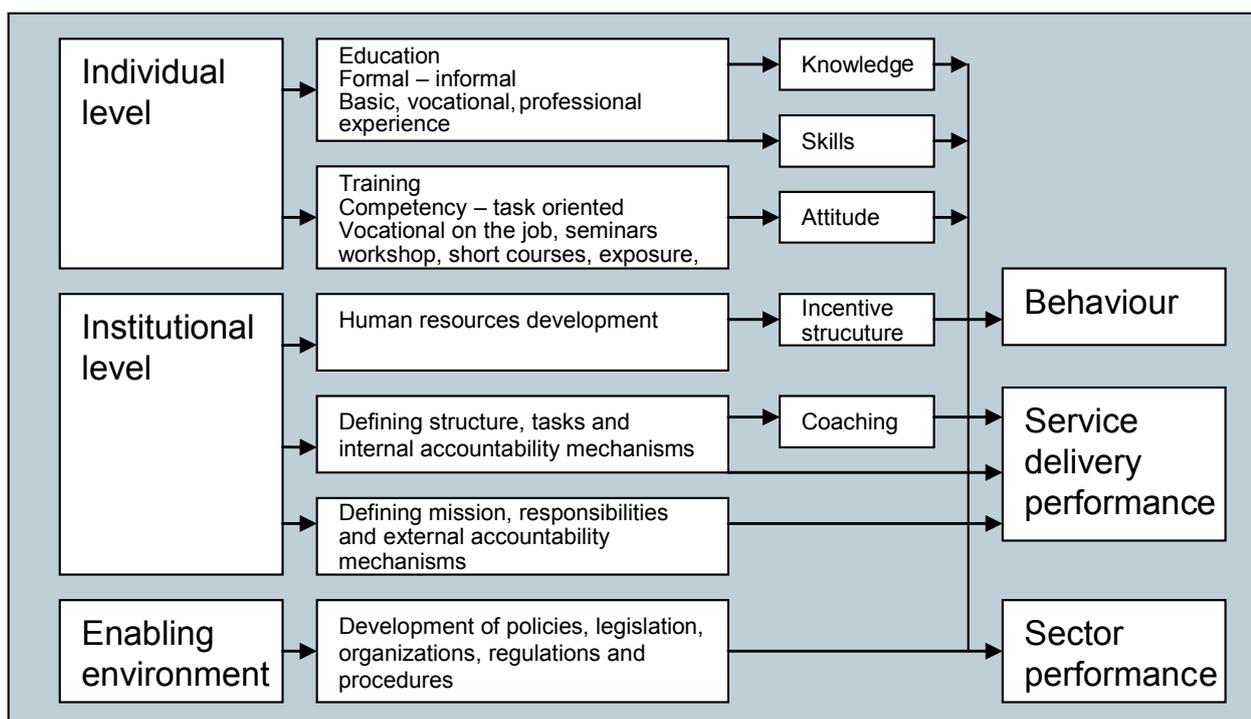

Figure 13.1 The three levels of capacity development (World Water Assessment Programme, 2006; adapted from van Hofwegen, 2004)

man resources development issue that must be thought of as a continuous process aimed at embedding knowledge in the minds of the individuals, developing their skills and changing attitudes and behaviour. This is best done on the job to maximize the benefits of knowledge-sharing and collaborative processes. However, the ability of professionals in particular to acquire new knowledge and skills on a continuing basis also depends on their formal education and professional training. Professionals, in particular, must increasingly regard life-long learning as a necessity and indeed an obligation so that they can take advantage of the growing knowledge base on every aspect of water resources management. This is particularly the case for low-flow management, which is often carried out by (mid- and high-level) professionals who work in water and environment agencies.

At the same time, academic institutions (universities, higher education institutes, post-graduate training centres) should be more concerned with improving the content and methods of the education they offer, in line with the expressed requirements of professionals and other stakeholders. This will involve taking advantage of new forms of blended learning that encourage more active and participatory learning. Low-flow knowledge that can be characterized as an advanced topic for students and practitioners with a fundamental knowledge of hydrology and hydrogeology seems an appropriate topic for blended learning methods.

Institutional capacity is concerned with the capability of an organization to look ahead and adapt to change. This is crucial for low-flow management, as low flows and droughts are subject to change because of global changes (for example, climate change, land-use change). In this sense, institutional capacity is a measure of the institution's overall performance in managing the totality of its resources, whether personnel, facilities, technology, knowledge base or funding. Inevitably, effective and efficient management involves carefully considered procedures that are consistently implemented and adapted to changing situations, when necessary. The procedures provide the context for various processes that have an impact on the institution's resources, programmes and external relationships, in other words, its capacity to manage. However, the institution's capacity is measured not only by its internal functioning and consistency, but also in its relationships with external partners, in particular the range of stakeholders, when managing scarce water resources. This can be encouraged by establishing a platform where stakeholders can express their interests and concerns and have some say

in the decision-making processes associated with the appropriate water services. As highlighted in the second World Water Development Report (WWAP, 2006), capacity development at the institutional level requires the following:

(a) A clear mandate for the managing agencies, water providers and policy-making bodies that promote and enhance the institutionalization of good water management and water use throughout all levels of society;

(b) An organizational system conducive to effective and efficient management decisions;

(c) Improved decision-support mechanisms through research on lessons learned and indigenous knowledge.

Lastly, the enabling environment sets the boundary conditions for the functioning of the agencies and institutions entrusted with the development and management of water resources and services. Such boundary conditions include the broader political, policy, legal, regulatory and administrative frameworks that promote sustainable development and are based on the view that water is a social and economic good. Sector agencies will be continually encouraged to improve their performance through the generation and acquisition of appropriate knowledge and through reform, when needed. Well-informed stakeholder groups in civil society can raise public awareness and provide information that promotes social learning.

The individual professional experience of managing low flows varies widely depending on the local infrastructure, the climatic and hydrological regime, physiographic characteristics (for example, geology, soils, land use and topography), the incidence of recent extreme events, the skills and experience of professional hydrologists and the input from a wide range of stakeholders. The apparent consequences of climate change and other global changes add urgency to the need for professionals and other stakeholders to increase their capacity to manage change in their water resources, especially where water resources are decreasing in the face of growing demand from consumers. With the burgeoning growth of the Internet and the rapid transfer of new technologies to developing countries, which have the potential to leapfrog their developed counterparts, there is every reason to anticipate that the international knowledge base on low flows can but grow, to the advantage of all who have Internet access.

References

Lopes C. and T. Theisohn 2003: *Ownership, leadership and transformation: Can we do better for capacity development?* London, UNDP and Earthscan Publishing.

United Nations Development Programme (UNDP), 1997: *Capacity Development*. Technical Advisory Paper 2. UNDP, New York, United States.

van Hofwegen P.J.M., 2004: Capacity-building for water and irrigation sector management with application in Indonesia. In: *Capacity Building in Irrigation and Drainage Issues and the Way Ahead*. FAO Water Reports, 26, Rome, Italy.

World Water Assessment Programme, 2006: *Water, a shared responsibility*. The United Nations World Water Development Report 2, UNESCO, Paris, and Berghahn Books, New York, United States.

Abbreviations

ADAM	Australian Data Archive for Meteorology
AM	Annual Minimum
AMS	Annual Minimum/Maximum Series
ARMA	Autoregressive Moving-average
BFI	Base-flow Index
CAMS	Catchment Abstraction Management Strategy (Environment Agency)
cdf	Cumulative Distribution Function
CHy	Commission for Hydrology
DWA	German Association for Water, Wastewater and Waste
ENSO	El Niño/Southern Oscillation
ERFO	Ecological River Flow Objective
EWR	Environmental Water Requirements
FAO	Food and Agriculture Organization of the United Nations
FDC	Flow-duration Curve
GEV	Generalized Extreme Value
GIS	Geographic Information Systems
GP	Generalized Pareto (distribution)
HMM	Hidden Markov Model
HNRC	HOMS National Reference Centre
HOMS	Hydrological Operational Multipurpose System
HTML	HyperText Markup Language
HYDATA	Hydrological Database and Analysis software (United Kingdom)
IC	Inter-event time and volume criterion
ICSU	International Council for Science
IRBM	Integrated River Basin Management
IRS	Individual Recession Segments
ISO	International Organization for Standardization
IT	Inter-event time criterion
MA	Moving average
MAM(7)	Mean of the 7-day annual minima series
m.a.s.l.	Metres above sea level

MCMC	Markov Chain Monte Carlo
MRC	Master Recession Curve
MRC	Mekong River Commission
NAOI	North Atlantic Oscillation Index
NINO3	Index of SSTs in the region (5S–5N; 150W–90W) of the tropical Pacific Ocean with the largest variability in SST on El Niño time scales
NSFM	Non-parametric Seasonal Forecast Model
NVE	Norwegian Water Resources and Energy Directorate
NWP	Numerical Weather Prediction
OPACHE	Open Panel of CHy Experts
pdf	Probability Density Function
PWM	Probability Weighted Moments
P3	Pearson Type 3
SHE	Système Hydrologique Européen
SOI	Southern Oscillation Index
SST	Sea Surface Temperature
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
WATSTORE	Water Data Storage and Retrieval System (USGS)
WDC	World Data Centre
WFD	Water Framework Directive (European Union)
WMO	World Meteorological Organization
XML	Extensible Markup Language

Operational Hydrology Reports

WMO No.	Report No.
332	No. 1 - Manual for estimation of probable maximum precipitation (Second edition)
337	No. 2 - Automatic collection and transmission of hydrological observations*
341	No. 3 - Benefit and cost analysis of hydrological forecasts. A state-of-the-art report
356	No. 4 - Applications of hydrology to water resources management*
419	No. 5 - Meteorological and hydrological data required in planning the development of water resources*
425	No. 6 - Hydrological forecasting practices*
429	No. 7 - Intercomparison of conceptual models used in operational hydrological forecasting
433	No. 8 - Hydrological network design and information transfer
461	No. 9 - Casebook of examples of organization and operation of Hydrological Services
464	No. 10 - Statistical information on activities in operational hydrology*
476	No. 11 - Hydrological application of atmospheric vapour-flux analyses*
513	No. 12 - Applications of remote sensing to hydrology
519	No. 13 - Manual on stream gauging - Volume 1: Field work - Volume 2: Computation of discharge
559	No. 14 - Hydrological data transmission
560	No. 15 - Selection of distribution types for extremes of precipitation
561	No. 16 - Measurement of river sediments
576	No. 17 - Case studies of national hydrological data banks (planning, development and organization)
577	No. 18 - Flash flood forecasting
580	No. 19 - Concepts and techniques in hydrological network design
587	No. 20 - Long-range water-supply forecasting
589	No. 21 - Methods of correction for systematic error in point precipitation measurement for operational use
635	No. 22 - Casebook on operational assessment of areal evaporation
646	No. 23 - Intercomparison of models of snowmelt runoff
650	No. 24 - Level and discharge measurements under difficult conditions
655	No. 25 - Tropical hydrology
658	No. 26 - Methods of measurement and estimation of discharges at hydraulic structures
680	No. 27 -Manual on water-quality monitoring
683	No. 28 - Hydrological information referral service - INFOHYDRO Manual
686	No. 29 - Manual on operational methods for the measurement of sediment transport
704	No. 30 - Hydrological aspects of combined effects of storm surges and heavy rainfall on river flow
705	No. 31 - Management of groundwater observation programmes
717	No. 32 - Cost-benefit assessment techniques and user requirements for hydrological data
718	No. 33 - Statistical distributions for flood frequency analysis
740	No. 34 - Hydrological models for water-resources system design and operation
749	No. 35 - Snow cover measurements and areal assessment of precipitation and soil moisture
773	No. 36 - Remote sensing for hydrology - Progress and prospects
754	No. 37 - Hydrological aspects of accidental pollution of water bodies
779	No. 38 - Simulated real-time intercomparison of hydrological models
804	No. 39 - Applications of remote sensing bv satellite, radar and other methods to hydrology
803	No. 40 - Land surface processes in large-scale hydrology
806	No. 41 - An overview of selected techniques for analysing surface-water data networks
813	No. 42 - Meteorological systems for hydrological purposes
884	No. 43 - Current operational applications of remote sensing in hydrology
885	No. 44 - Areal modelling in hydrology using remote sensing data and geographical information system
886	No. 45 - Contaminants in rivers and streams - Prediction of travel time and longitudinal dispersion
887	No. 46 - Precipitation Estimation and Forecasting
948	No. 47 - Manual on Sediment Management and Measurement
964	No. 48 - Hydrological Data Management: Present state and trends
1003	No. 49 - Guidelines on the Role, Operation and Management of National Hydrological Services

*Out of print