Hydrological data

Hydrological Drought

Hannaford, Jamie; Muchan, Katie; Fry, Matthew; Everard, Nick; Rees, Gwyn et al

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CHAPTER

Hydrological data*

4

Jamie Hannaford[1], Katie Muchan[2], Matthew Fry[1], Nick Everard[1], Gwyn Rees[1], Terry Marsh[1], John P. Bloomfield[3], Gregor Laaha[4] and Henny A.J. Van Lanen[5]

[1]UK Centre for Ecology & Hydrology (UKCEH), Wallingford, Oxfordshire, United Kingdom; [2]Evidence & Risk, Environment Agency, Penrith, Cumbria, United Kingdom; [3]Groundwater Science, British Geological Survey, Wallingford, Oxfordshire, United Kingdom; [4]Institute of Statistics, University of Natural Resources and Life Sciences, Vienna (BOKU), Vienna, Austria; [5]Hydrology and Quantitative Water Management Group, Environmental Sciences Group (ESG), Wageningen University & Research, Wageningen, the Netherlands

Chapter outline

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4.1 Introduction

Hydrological data may include time series of hydrometeorological variables, such as river flows, groundwater levels, precipitation and temperature. Hydrological data also encompass thematic or spatial data, such as maps and datasets that describe the topography, soils, land use and other physical characteristics of relevant catchments.

Such data are the foundation of effective water management. Hydrological data may be used in the operational management of water resources, to monitor and control abstractions from and discharges to rivers, or the inflows to and outflows from reservoirs and lakes. In periods of low flow or drought, hydrological data assume even greater importance, enabling water resources managers to maintain essential water supplies, support river navigation and safeguard the ecological quality of the river. Hydrological data are also used for the forecasting of drought, providing local authorities, farmers, businesses and the general public with early warning of these extreme events and enabling the timely implementation of mitigation measures. Hydrologists, engineers and planners use hydrological data for the long-term planning of water resources or for the design of new infrastructure, to ensure resilience to periods of drought. Hydroecologists and regulators concerned with maintaining good ecological health of waterbodies use river flow data to establish the flow patterns that promote or restrict aquatic ecological diversity and drought resilience.

With global warming being a reality and the pervasive impact of human activity on the environment, hydrological data are increasingly being employed to establish whether there is evidence for long-term changes (e.g., increasing severity of drought or diminishing low flow) relevant for water resources management and to establish objective regulatory mechanisms to promote a healthy aquatic environment. Good-quality data are also vital for hydrological research, for improving our understanding of the hydrological cycle and the interactions between the many physical processes it involves, including land-atmosphere interaction, vital for improved forecasts of extremes and the further development of earth system models. This ultimately leads to the development of tools and methods to assist in the operational management of water resources, including low flow and drought.

Irrespective of purpose, a meaningful analysis of how groundwater and rivers behave in periods of low flow, or drought, requires good-quality data that adequately represent the hydrological conditions of the catchment, aquifer or region of interest. In recent decades, there has been a burgeoning of hydrological data availability, supported by huge advances in sensor technologies, both in terms of ground-based instruments and remote sensing (e.g., mounted on satellites or Unmanned Aerial Vehicles, UAVs), that has dramatically increased the volumes of data that can be captured for a given cost. Similarly, rapid increases in computing power (and the ready availability of high-performance computing) have led to huge increases in our capacity to gather, store and disseminate hydrological data. However, in step with this, the demand for hydrological data has also increased dramatically, with greater demands for ever-higher resolution data made available ever closer to real time. This presents a whole host of challenges. The modern hydrologist concerned with hydrological drought analysis or management has an unparalleled amount of data at their fingertips — but the question remains whether the vast volumes of data that can be obtained are useful or appropriate for a given purpose. While it has never been easier to obtain data, it remains the case — and is arguably more important than ever — that judicious appraisal of hydrological data (its provenance, completeness, quality and so on) is the vital first step in any low flow or drought analysis. Wilby et al. (2017) provide some cautionary tales illustrating the pitfalls of errors in hydrological data and the potential impacts on analyses. Hence, while data can be gathered and analysed at a prodigious rate, the goal is to turn raw data into useable information, which means interpreting the data, alongside its limitations and uncertainties.

The objective of this chapter is to provide an overview of the hydrological data that are typically available for the analysis of low flow and hydrological drought and the procedures that should be applied to ensure that these data are of good quality and fit for purpose for a range of applications. In Section 4.2, the key definitions and concepts related to hydrological data, including time series, spatial data and meta data, are introduced. Section 4.3 provides an introduction to the diversity of data that researchers and practitioners concerned with low flow and hydrological drought should be aware of. Firstly, key hydrological datasets are described (river flow and groundwater) and their derivation and quality control. Supporting hydrometeorological datasets are also briefly considered (precipitation, evaporation and soil moisture) and other types of information (e.g., on human interventions). In Section 4.4, important contextual spatial datasets are addressed (information on, e.g., hydro-climatological data, hydrological data, physiographic data) needed to carry out low flow and drought analysis. Section 4.5 presents the example datasets that will be used for worked examples of other chapters. They include: an International Dataset, representing a number of different hydrological regimes around the world; a Regional Dataset of Eastern Austria, representative of central European lowland plains in combination with hilly terrain; and two local datasets, containing detailed data for a single catchment in the Mediterranean (the Upper-Guadiana) and groundwater data from a typical well in a chalk aquifer (the Stonor Park well, UK). A brief summary of the chapter is given in Section 4.6.

4.2 Definitions and concepts

In this section, we first address some key underpinning definitions and concepts relevant for hydrological data. As we have learnt for Chapters 3 and 10, the flow of water in a river and the behaviour of groundwater are essentially the result of the interaction between the natural processes and human activities in the upstream catchment, in the case or rivers or in the wider aquifer in the case of groundwater. While river flow and groundwater data are clearly fundamental for most hydrological analyses, data that describe the catchment (or aquifer) processes — and any changes in the catchment or aquifer — are also very important. An introduction to some of these different types of data is provided in Sections 4.3 and 4.4. Before delving into particular variables, their measurement and processing, it is worth first considering terminology and distinguishing between some key generic types of data (time series, spatial data, metadata). Key concepts relevant to hydrometric data are also considered — namely, spatial and temporal scales and uncertainty.

4.2.1 What is meant by ‘data’?

Firstly, it is worth some qualification of what is meant by the word ‘data’ itself. Among the various dictionary definitions of the word, the Wikipedia (URL 4.1) entry for ‘data’ states “data are characteristics or information, usually numerical, that are collected through observation”. This is a useful definition to adopt here, in that the focus is primarily on observations of hydrological variables, typically made using some sort of instrumentation or sensing equipment, or measurement of some landscape characteristic. In modern geophysical settings, however, it is worth adding some nuance to this definition.

Some data are exclusively based on direct measurement or instrumental readings, for example, a precipitation gauge measurement or a river level (or ‘stage’) measurement. However, many types of hydrological data involve some process of derivation or estimation. Examples include river flow (discharge), estimated through a stage-discharge relationship, or areal precipitation, aggregated from several point measurements. Despite being 'derived', such data still are generally accepted as observations (or observational data). However, it is increasingly common for hydrologists to consider outputs from hydrological models as 'data'. Sometimes called 'simulated observed' or 'proxy observed' data (Section 9.2.1), these often are not labelled as such and are simply referred to as 'data'. Other 'data' can be a blend of observations and model outputs, such as reanalysis data (Section 4.3.6, Box 9.1), which are essentially based on numerical simulation models, but incorporate up-to-date observational data — a process known as data assimilation — so that their initial model state more accurately represents current conditions, thus helping to improve their predictions.

4.2.2 Time series data

For any quantity that varies in time, a sequence of readings, or measurements, generate a time series of data for that quantity. For example, repeated measurements of rainfall at a single rain gauge generate a time series of rainfall data at the gauge. Similar quantities that are regularly measured at specific locations to form time series include other weather variables (e.g., air temperature, solar-radiation, wind-speed, humidity, barometric pressure), snow storage, soil moisture and groundwater levels. Repeated measurements of river level and flow also produce time series data. However, in contrast to variables whose information refers to conditions at the location of the gauge, or instrument, only, river flow data represent the conditions of the entire catchment area upstream of the gauge. This, therefore, gives rise to the further definition of a point measurement, corresponding to conditions at a specific location (point) only, and an areal measurement, which represents the conditions of a particular area or region.

Once a time series has been established and a sufficient number of readings have been taken, the data can be processed to produce further time series of aggregated data. For example, a daily time series may be calculated as the mean, or sum, of 15-min values during each day. As can be seen in Fig. 4.1, the aggregation of daily data may produce further time series data; monthly time series and 7-day, or 30-day, moving average data are often used in low flow analyses. A whole range of statistics,

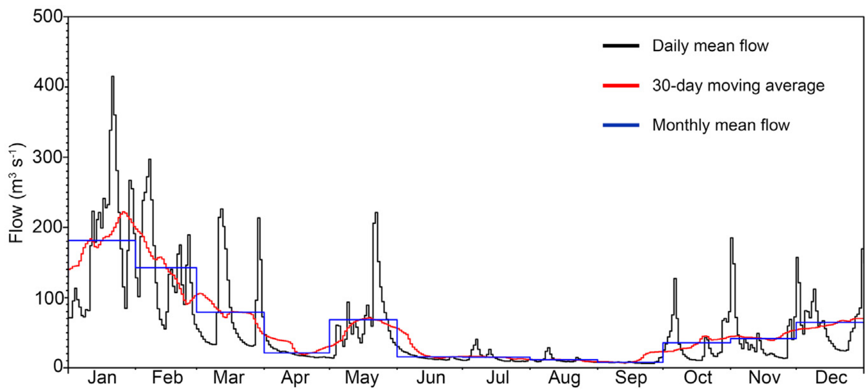

FIGURE 4.1

Aggregation of time series data, in this example from daily river flow data (*black*) into a 30-day moving average flow (red) and a monthly mean flow (*blue*).

such as means, maxima, minima, standard deviation, coefficient of variation, decile and percentile values (Sections 5.3 and 6.5.1.1) can also be derived for different periods covered by the time series to provide a useful summary of the data and form the basis of analysis.

4.2.3 Spatial data

The term 'geospatial data' defines data that has a geographic component to it. It usually includes this location information alongside attributes, that is, non-spatial information describing the characteristics of the object in questions (e.g., for a river, its name, various dimensions, average flow rates and catchment characteristics, to name but a few): such descriptive attributes can, in turn, also be considered metadata (Section 4.2.4). Commonly, geospatial datasets are described simply as spatial data, and, for simplicity, this term will be used throughout. Such datasets can also be defined as thematic data. Spatial data of particular use in hydrology include area, shape, orientation, slope and elevation of the catchment upstream of a gauging station. Data describing the distribution of climatic variables (e.g., precipitation, evaporation, relative humidity) and other physiographical features (e.g., topography, soil types, geology, land use, vegetation) of catchments or aquifers would also be classed as spatial data. Such datasets are of crucial importance for interpreting river flow, groundwater or other time series data measured within the catchment or more generally, across a large region including multiple catchments or aquifers.

The classification of time series and spatial data, however, is not mutually exclusive. With hydrometeorological data, for example, the areal distribution of variables can be represented in map form by the interpolation of data from a time series of point measurements. Precipitation is one variable that is commonly represented in map form, using interpolation methods such as those described in Section 4.3.8. These methods can be used to derive map representations of instantaneous (e.g., air temperature at 9 a.m. today) or aggregated values (e.g., average annual precipitation), and, clearly, a sequence of such maps can result in a time series of spatial data. Commonly, many such spatial datasets are represented by a two- or three-dimensional grid (a raster dataset) overlying the catchment, or area of interest, with a time series of observations available at each cell or grid point. This is frequently referred to as a gridded dataset, and there are specialist file formats that can be used to store such data (e.g., netCDF files, URL 4.3).

Topographical data, featured as contours on a map, or represented by a digital elevation model, are particularly useful as they can be used to delineate the boundary of a catchment. The catchment boundary (Section 3.4.2.1) is one of the most important types of spatial data in hydrology, as it not only describes the areal extent of the catchment, giving the catchment area, but it can also be used to derive other pertinent catchment characteristics or descriptors. By overlaying the boundary onto other spatial data, many catchment descriptors, such as mean and maximum elevation, mean slope, aspect and the proportion of different soils, geological formations and land cover (e.g., proportion of forest, urban, or lake), can be readily determined.

A type of digital spatial data that are increasingly being used in hydrology is the data from remote sensing (Section 4.4). Remote sensing images, obtained from Earth Observation satellites or aerial photography, provide valuable data, often at a high grid resolution, on weather, climate and a variety of terrestrial and morphological features (e.g., topography, stream density, lake levels, land cover and land use, vegetation, snow cover, soil moisture). Orbiting the earth several times a day, satellites provide instantaneous snapshots of land features and processes, a sequence of which can be collated to provide a time series of spatial data or large-gridded datasets.

4.2.4 Metadata

Metadata provides information about data. For time series data, metadata includes a definition of the variable being measured, the method of measurement, the type of instrumentation used, its age and when it was installed and calibrated. Details of the organisation responsible for measurement (measuring authority), the individual responsible for the observation, telephone numbers, site directions, grid reference and any other relevant information would make up the metadata for a single gauge or monitoring point. Similarly, information on how the time series data are processed, stored and disseminated would be considered to be metadata. For spatial data, metadata may comprise details of its derivation, such as source maps, digitising methods, data collection methods, its ownership and copyright restrictions. International standards have been defined for the design and handling of metadata (e.g., ISO 19115, URL 4.4) and those developing hydrological metadata catalogues or databases are well advised to conform to these.

4.2.5 Importance of scale: spatial and temporal

The type of data required varies according to its application. For example, the hydrological study of a single catchment may be adequately served by the time series data from a representative network of precipitation gauges or a river gauging station and information from local maps. An assessment of regional water resources would, however, require long-term data from many gauges, to represent the spatial and temporal variability of the hydrological regimes of the region. Maps that consistently describe the distribution of key physical features in the entire study area would also be necessary. Similarly, there is a growing request for large-scale hydrological studies that cover whole countries or even larger domains, including continental and even global scales. Such 'large sample hydrology' studies (e.g., Addor et al., 2019, Section 10.4.2) are very data hungry and require readily accessible, consistent time series and spatial data over these large domains and these are increasingly being made readily available — an example being the Global Streamflow Indices and Metadata archive (GSIM, Do et al., 2018). Such datasets present huge opportunities to hydrologists, but also significant challenges — and thus uncertainties — given the inherent difficulties in hydrometric measurement at even a local scale, as illustrated later (Section 4.4).

The temporal resolution of the data is an important factor too. Some hydrological measurements are taken with very high frequency — it is not uncommon for river stage (and thus flow) measurements to be captured every 15 min. For some applications, for example, flooding in small responsive catchments, this resolution is necessary — and it is often the case that such measurements are needed rapidly, which implies needing the technology to serve up data close to real time. Generally, for drought and low flow applications, such fine temporal resolution assumes less importance, and daily or even monthly resolution data can be adequate. Nevertheless, there are still clear benefits to generating data as close to real-time as possible, for drought monitoring and early warning applications (Sections 13.3 and 13.4).

One should not underestimate the value of short time series, for example, for the estimation at the ungauged site (Section 8.6). However, for many applications, long-term observations are needed. One- or two-years river flow data barely provide a snapshot of the hydrological behaviour of a catchment and, on its own, provides little indication of how the catchment has behaved, or is likely to behave, in the long-term, particularly when trends are considered (Section 7.4). Generally, the longer the time series the better, although caution should be exercised when dealing with long records, in case changes in the method of measurement, or changes in land use and water management, have affected the values obtained. Time series data should also be continuous, containing as few gaps, or missing data, as possible (Section 4.3.7) and providing data across the entire range of possible values, ideally capturing a range of extreme low flow and drought events. The observational approach (network design, nature and quality of measurements) of the hydrometeorological variables will ultimately have a bearing on the utility of the data in this respect.

4.2.6 Uncertainty

The topic of uncertainty in observations is a vast one, central to any scientific discipline. Unlike some disciplines that offer more scope for repeatable experimentation under controlled laboratory conditions, environmental sciences, such as hydrology involve measurements of complex earth system processes that are often not measurable directly, requiring much estimation and inference. Naturally, any scientific observation comes with an inherent uncertainty, even for simple measurements such as reading a river level on a staff gauge, simply due to the precision with which it is possible to take a measurement. For hydrometric measurements, such as river flow or areal precipitation, which are typically complex and require various steps in their derivation (each involving some degree of translation or estimation), the potential for errors is significant. There are many ways of categorising uncertainty, and MacMillan et al. (2018) draw a distinction between: measurement uncertainty, derived data uncertainty, interpolation uncertainty, scaling uncertainty and data management uncertainty.

In this chapter, uncertainty estimation approaches are not covered in detail. The reader is referred to standard textbooks focused on hydrometry, notably Herschy (2009), and publications that discuss observational uncertainties more generally (e.g., MacMillan et al., 2012, 2018). However, uncertainty is considered as part of the description of the various approaches to observation that are set out below. Suffice it to say that those planning to analyse any low flow or drought observational data should consider the attendant uncertainties that go with the datasets, and the implications it may have for analysis. As noted in Box 9.4, uncertainties in hydrological data inputs will propagate through into any hydrological model predictions, with the potential for significant impacts on decisions made using the data.

4.3 Data for hydrological drought

4.3.1 River level data

Measurement of water level or 'stage' is a fundamental observation in hydrology. While levels are useful in and of themselves (most notably in flood applications), the majority of hydrologists concerned with low flow and drought wish to derive long, continuous records of river flow or discharge (Section 4.3.3). River levels provide the foundation for this, typically through the establishment of stage-discharge relationships (Section 4.3.2).

The most basic method of measuring stage (in rivers or large surface water bodies, e.g., lakes) is by means of a staff gauge — this is usually a graduated measuring plate installed at the side of the river, ideally in an area where water flows are relatively slow and gradually varying (i.e., close to uniform). The stage of the river is simply read off the staff gauge and recorded to the nearest millimetre, where possible.

At many gauging stations, a stilling well provides a controlled environment for the measurement of stage. Commonly, a float and counterweight are attached to a stretch-resistant steel cable that passes over a pulley connected to a suitable recording device, known as a shaft encoder. The water level in the stilling well may also be measured by use of a radar or acoustic water level gauge or a pressure transducer, either of which are generally more sensitive to variations in water levels than measurements from a staff gauge.

River level can also be measured with no requirement for a stilling well, either with in-channel acoustic sensors or, increasingly, non-contact radar sensors mounted above the water surface (e.g., on a bridge). The elimination of a stilling well can reduce other potential inaccuracies that are particularly problematic at low flow (e.g., a lag in responding to small changes in flow, the silting up of intake pipes).

Stage readings are generally recorded at millimetre resolution on digital data loggers and telemetry outstations, which store readings at 5 or 15-min intervals (or more frequently if required). These loggers and outstations have to a large extent replaced manual-stage observations and autographic recorders tracing onto a paper chart. Once logged, the stage data can be manually downloaded during a visit to the gauging station or transmitted via telemetry (i.e., telephone, radio or satellite communications) in real time, at prescribed times each day, upon manual interrogation or when a key trigger level is hit. Readings of a shaft encoder, pressure transducer, acoustic or radar sensors should be compared with a manual observation at least once a month.

4.3.2 Rating curves and spot gaugings

In order to convert the recorded river level into river flow, a stage-discharge relationship needs to be determined. This is a unique relationship between the measured level (stage) and the resultant discharge, or flow, in the river. The ‘control’ section of a river (point or reach) is characterised by such a unique relationship and is unaffected by conditions upstream or downstream. Natural controls are commonly a section of the river where there is an abrupt change in channel conditions, whereas weirs and flumes are structural controls (Section 4.3.3). Once such a relationship is established (i.e., a rating curve) that pairs corresponding measurements of stage and discharge (i.e., spot gaugings), measurements of stage are all that is required to produce estimates of river flow. There are various ways of achieving this, and they vary between different types of gauging stations (Section 4.3.3).

4.3.2.1 Spot gaugings

Spot gauging is an ‘instantaneous’ measurement of discharge (river flow), that is, the volume of water flowing past a specific point at a given time. A common and well-established approach to spot gauging involves the use of mechanical propeller- or cup-type current meters to measure the stream velocity at defined depths and distances across the river. These velocity readings are combined with the cross-sectional area (derived from precise measurements of cross-river width and depth) to yield an estimate of the volume of water flowing past the point.

Mechanical current meters, whilst having the benefits of relatively low cost and light weight, have the disadvantage of needing to be positioned at a range of locations across the river, which can be difficult to achieve in low water levels, and also tend to be insensitive at the lowest flows, as stream velocities approach zero. In these conditions, the use of more modern technology, such as acoustic Doppler velocimeters (ADVs), able to accurately measure even the slowest of water speeds (velocities), is recommended. However, for all, but the smallest of streams, acoustic Doppler current profiler (ADCP) instruments are now very widely used for spot flow measurements. These instruments use pulses of sound to measure the speed and direction of water flow. In contrast to a mechanical current meter, which provides a limited number of measurements of water speed for discrete points in the river cross-section, an ADCP reports water speeds for a large number of points in the vertical profile (>100), and does so up to several times a second, whilst being moved across the surface of the river, typically using a remote-controlled boat, with measurements delivered in real-time to a laptop via a radio link (Fig. 4.2). However, the top and bottom sections of the velocity profile are not measured (due to proximity to the sensor and river bed, respectively, Fig. 4.2), which becomes a particular issue at low flow, as these unmeasured areas can represent a large proportion of the cross-sectional area when water levels are low.

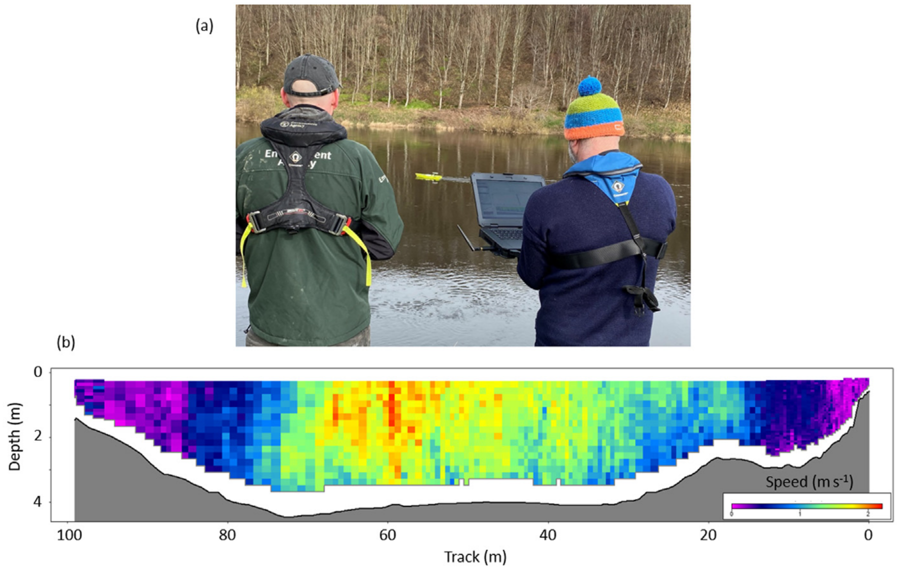

FIGURE 4.2

Use of an Acoustic Doppler Current Profiler (ADCP) on the River Tweed at Norham, UK: (a) mounted on a remote-control boat, with measurements delivered in real-time to a laptop via radio link, and (b) horizontal transect of the river cross-section, showing velocity readings across the profile according to colour scheme ranging from zero velocity (*purple*) to 2 m s^{-1} (red). Note: areas close to the water surface and bed (*grey*) are blank (*white*) as readings are not possible.

Photo and profile image from Nick Everard (UKCEH, Wallingford, UK).

Another method of instantaneously measuring discharge is dilution gauging, which is particularly well suited to shallow and turbulent streams, such as headwater streams where water levels are low and water only flows between rocks on a river bed. By adding a suitable tracer (chemical) to the river, and quantifying the dilution of that tracer some distance downstream, accurate measurements of discharge can be achieved in watercourses that may be difficult to measure with the methods previously mentioned. Automated dilution gauging systems are available that offer the potential to carry out a discharge measurement automatically, either periodically, or when certain trigger conditions are met, with no manual intervention required.

4.3.2.2 Rating curves

Fundamentally, stage-discharge relationships encapsulate a unique relationship between measured discharge values plotted against the corresponding stage (water level), with a smooth curve drawn between the points, as seen in Fig. 4.3. The curve, which defines the stage-discharge relationship, is known as the rating curve. A single relationship does not necessarily apply to all conditions, and the rating curve can therefore comprise several segments with each segment being valid for a particular range of water levels and flows. Note that a looped rating curve results (i.e., for a given discharge Q, the stage for falling discharge will be higher than for rising discharge) if the flow depends on other factors than depth only.

Once the rating curve has been obtained, continuous monitoring of stage at the gauging station provides a continuous record of discharge data. The rating curve can be represented with a relationship of the form:

$$Q = const(H + H_o)^b \tag{4.1}$$

where H_0 (L) is the water level at zero flow.

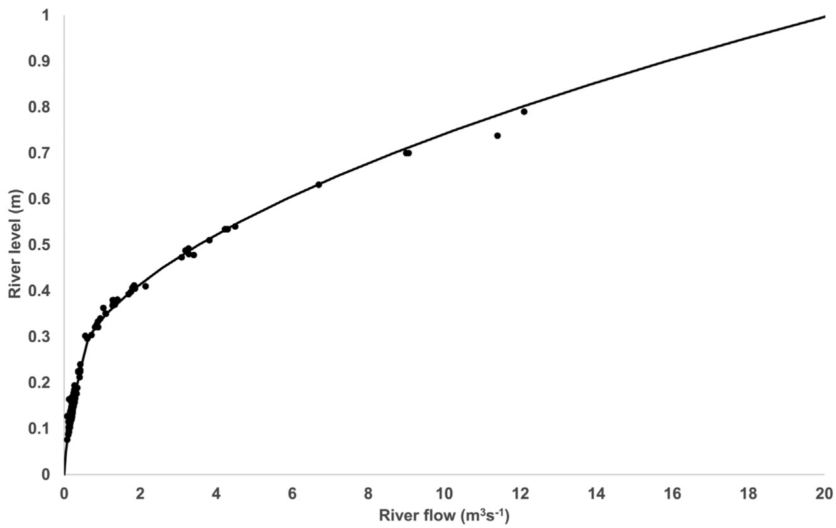

FIGURE 4.3

A rating curve fitted to instantaneous measurements of stage (water level) and river flow (spot gaugings).

This provides an estimate of the discharge, Q ($L^3\ T^{-1}$), for a simultaneous value of stage, H (L). The constant (*const*), the exponent, b, and the intercept, H_0, are all determined from measurements by curve fitting.

Whatever type of gauging station is used to produce the river flow time series (Section 4.3.3), the unique relationship between stage and discharge needs to be established specifically for each station. For ‘velocity-area’ stations, a series of flow measurements (instantaneous spot gaugings) are taken alongside corresponding stage measurements, and the rating curve can be plotted. For gauging structures such as weirs or flumes, stage-discharge relationships are effectively ‘built in’ by the use of a measuring structure such as a weir calibrated theoretically or under laboratory conditions. Whatever the type of station, the stage-discharge relationship should be regularly checked. Whilst spot gaugings are most easily obtained for flows around the average discharge, particular effort should be made to obtain gaugings also in the extreme range to ensure the accuracy and reliability of the flow record for both the high and the low flow regime.

4.3.2.3 Factors affecting the stage-discharge relation

In all types of environments, a number of factors can affect the stage-discharge relation. For example, the erosion, or deposition, of sediment can alter the cross-section area of the river and, hence, the relationship between stage and discharge. The build-up of aquatic vegetation (weed growth) reduces the cross-sectional area of the river, raises the water level (backwater effect) and increases the flow resistance, causing an overestimation of discharge. At gauging stations with structures for flow measurement, the build-up of vegetation in the downstream section can be sufficient to raise the downstream water level enough to create non-modular or drowned conditions. This means there is no longer a sufficient drop in water level at the weir, that is, critical flow is no longer present at the weir; or, in other words, the weir is no longer acting as a weir and the weir equation (stage-discharge relantionship) is no longer valid for flow calculation.

Vegetation growth is a particular problem for low flow as, in many parts of the world, the season of lowest flow (summer) coincides with the period of greatest weed growth. If removal of the vegetation is not possible, a different stage-discharge relation may be required for the different phases of growth, and reliability of the data can only be improved by increasing the frequency of spot gaugings.

The formation of ice has a similar effect to vegetation because it raises the water level as the water freezes and reduces the cross-section area at the gauging site. This makes the interpretation of winter records difficult and is an important consideration when analysing the low flow of catchments that experience winter minima (e.g., mountainous or high-latitude catchments). Several methods have been developed to correct the observed flow record under such conditions, including spot gaugings during winter and comparison with nearby catchments not affected by ice. Backwater effects, that is, an upstream increase in water level due to reduced flow capacity downstream, influence the relationship between stage and discharge. A frequent cause is vegetation or ice in the river channel, tidal effects from the sea or backwater from downstream tributaries.

4.3.3 Continuous river flow measurements

Arguably, the most useful data in hydrological analysis are those which describe the flows in a river. River flow “is the only phase of the hydrological cycle in which the water is confined in well-defined channels which permit accurate measurement to be made of the quantities involved” (Herschy, 2009).

FIGURE 4.4

Examples of different types of gauging stations: (a) velocity-area station, (b) crump weir, (c) flume, and (d) ultrasonic. The insert to Fig. 4.4d shows a close up of the racks containing ultrasonic transducers.

Photos from UK stations (URL 4.2).

Ensuring that the observed time series of flow data is an acceptably accurate and reliable representation of the actual river flow is essential for hydrological analysis. While Section 4.3.2 introduced spot-gaugings, as one-off, periodical measurements of river flow, ideally hydrologists need continuous and long-term measurements. The rating curve plays here a vital role, allowing measurements of stage to be easily transformed to river discharge. The point on a river where stage (or flow directly) is regularly measured — and where there is a unique relationship between stage and discharge (control section) — is called a gauging station. There are many types of gauging stations, as described in this section, and some examples are shown in Fig. 4.4. Herschy (2009) provides a fuller account of the many types of gauging stations and their operation.

4.3.3.1 Velocity-area gauging stations

Velocity-area gauging stations are, globally, by far the most common, as they are typically established at a natural section of the river and do not require extensive construction works. River level is measured using methods such as those described in Section 4.3.1, and discharges (flow) are calculated using a rating curve (Section 4.3.2). To ensure the discharge measured at the gauging station is not affected by backwater effects and thus to create a unique relationship between stage and discharge, a control section is usually present at, or some short distance downstream of, the gauging station. Controls (Section 4.3.2) can be natural or artificial; waterfalls, rapids and a widening of a river are types of natural control, while a low dam is an example of an artificial control (WMO, 2020).

4.3.3.2 Weirs and flumes

Weirs and flumes provide a reliable stage-discharge relation, which can be determined theoretically by generating a critical flow control within their structure. This conversion from sub-critical to critical flow is imperative for the validity of the rating curve as when the flow is critical, it depends only on depth (i.e., there is a unique relationship between stage and discharge). There are several different types of weirs and flumes; weirs are structures that water passes over and change the upstream water level, whereas flumes are channel structures that water passes through. Thin-plate weirs are mostly installed in smaller streams and usually have a v- or rectangular notch shape to enable better low flow measurement. On larger streams and rivers, broad-crested weirs and flumes may be seen. The three most common types of broad-crested weirs are the triangular-profile (or Crump) weir, the flat-v weir and the rectangular-profile weir. Of these, flat-v weirs are particularly well-suited to low flow measurements, as the weir crest has a v-shape profile, to allow greater sensitivity to the very lowest flows. Flumes typically comprise an approach channel, a constriction (throat) and exit channel having a rectangular, trapezoidal or u-shaped profile. Flumes are generally less sensitive to low flow, but have high capacities for measuring floods. Despite the theoretical hydraulic behaviour of these structures, the accuracy of the rating curves should always be verified by spot gaugings and the curve corrected as necessary.

4.3.3.3 Acoustic gauging stations

At gauging stations that employ acoustic technologies, river flow (velocity) is measured directly by the instrumentation, rather than calculated from water depth (stage) using a rating curve (as with velocity area or structure gauging stations).

Transit-time ultrasonic river gauges employ arrays of transducers mounted on either side of the river (Fig. 4.4d), either at a single depth or at a range of depths. Transducers at a range of depth are preferable for the measurement of low flow as it prevents the transducer emerging above the water surface and recording zero flow when there is in fact water flowing in the river. Pulses of sound are transmitted from transducers on one bank and received by a corresponding set mounted some distance up- or downstream on the opposite bank. Water speed (velocity) is calculated based upon the difference in time taken for the pulses of sound to cross the entire width of the river, first with and then against the direction of flow. The greater the difference in the resulting ‘travel times’, the faster the flow of the water. It is common for a pair of transducer arrays to be mounted on either side of the river, such that the resulting acoustic pathways form a ‘cross’ configuration. This ‘cross-path’ configuration effectively cancels out bias that could be associated with any cross-river component of flow and provides some degree of redundancy should a transducer array become damaged or obstructed by debris.

‘Index-velocity’ acoustic instruments fall into two general classifications: ‘side-looking’ systems, which sample water speed at a single depth, in a zone extending part way across the river (in the horizontal plane) rather than across the whole cross section; and ‘up-looking’ systems that are mounted on the river bed and sample water speed in a vertical plane above that location. In both cases, cross-section discharge is usually calculated by developing an ‘index-velocity’ relationship between the velocity sampled by the instrument and the overall mean channel velocity, which is derived from conventional spot-flow gaugings combined with information on the cross-sectional area at the position where the index velocity instrument is installed.

4.3.4 Other sensing technologies

With increased flexibility and mobility, and greatly reduced infrastructure requirements, non-contact 'surface velocity' river discharge monitoring methods are rapidly growing in popularity. While these have had the greatest impact on high flow measurement, thus far, they hold considerable potential for capturing low flow under the right circumstances. The key benefit of such technologies (as with the boat-mounted ADCPs described in Section 4.3.2) is that they can be applied rapidly, at comparatively low cost, at any accessible location, rather than relying on fixed gauging stations. Two common surface velocity methods are described below.

Surface-velocity imaging velocimetry uses digital camera technology to determine the speed of flow of the water's surface. Water speed is determined by analysing the displacement of visible features within the imagery. While cameras can be fixed to bridges and other riverside infrastructure, or even be hand-held, image scaling can be simplified significantly if the video imagery is captured with a camera having a vertical view, such as can be achieved with a UAV (drone), as shown schematically in Fig. 4.5.

Surface velocity radar systems determine the frequency change, or 'Doppler shift' in radar signals returned from ripples on the flowing water surface. Compared to image-based velocimetry, radar systems have the advantage that they report a water speed directly and are insensitive to lighting conditions. Disadvantages include a need for water surface roughness and potential for bias from static surface features such as standing waves.

All surface velocity methods require knowledge of the river's cross-sectional area and the relationship between the observed surface velocity and the mean velocity in the cross-section in order to allow the calculation of discharge. Wetted channel geometry and water velocity distributions can be derived from ADCP data, with Light Detection and Ranging (LiDAR) or photogrammetry providing information for areas outside of the normally wetted area.

FIGURE 4.5

An example of a camera-based surface velocity streamflow measurement on the River Feshie in Scotland in March 2022. A 30 frame per second 1080P video shot is taken at an altitude of approximately 15 m using a standard DJI Air 2S drone (shown overlain here) and processed using Space Time Imaging Velocimetry (STIV) software. The values shown represent the downstream component of surface velocity in m s^{-1}.

Image from Nick Everard (UKCEH, Wallingford, UK).

Satellite altimetry can be used to determine discharge in very large river systems such as the Amazon or Congo. Water surface slope is derived from surface elevation readings along the river system, derived from satellite radar signals. Poor spatial resolution and difficulty in obtaining water surface elevation with acceptable degrees of accuracy mean the technique is not suited to smaller watercourses and is unlikely to offer the low levels of uncertainty that can be achieved with other methods described here. Knowledge of river cross section is also required, and this can itself be challenging to obtain for large rivers.

4.3.5 Measurement challenges at low flow

Over the last 50 years, major developments in flow measurement, water level sensing, data recording and data communication technologies have had a beneficial impact on the way river flow data during low flow are acquired, processed and archived. The increasing use of new measurement techniques, and a fuller understanding of the hydraulic behaviour of weirs and flumes, has enabled low flow to be determined with greater precision. However, many factors can combine to reduce the accuracy of processed or archived low flow data. Generally, the factors of most significance to low flow are the uncertainties associated with the measurement of very limited water depths (which can also be an issue between recording a low water level or zero water level) and velocities, and the failure to adjust stage levels to account for problems in the stage-discharge relationship (Section 4.3.2), including vegetation growth, ice and backwater effects. In addition, disturbances to low flow regimes caused by an increasing range of human interventions may be difficult to monitor and detect.

In order to reduce the uncertainty associated with computed flow values, especially in the low flow range, gauging stations are commonly located at sites where a significant change in discharge is accompanied by a substantial change in water level. Thus, by exploiting natural channel characteristics, or by the installation of a gauging structure, attempts are made to maximise the sensitivity of the measuring station. Even so, the limited water depth that normally accompanies low flow, places a premium on reliable water level sensing and recording. The lack of accuracy in stage measurements for low water levels may result in a hydrograph declining in a staircase manner with several equal values before a lower level is reached. It is also important that a clear distinction is made in the records between zero (or no flow, Section 5.4.2) and missing values.

Where hourly or 15-min recording intervals have been adopted, random errors in computed daily mean flows tend to be very low (Herschy, 2009). By contrast, systematic bias in measured river levels caused, for example, by algal growth on weir crests or datum errors, can be substantial and difficult to eliminate. In small rivers, or those with exceptionally low dry season flows, systematic errors in stage measurement can dominate the overall uncertainty in processed low flow data. In the United Kingdom, a systematic stage error of 5 mm at the lowest five percentile flow (Q_{95}, Box 5.1) translates into a flow error of at least 10% for more than a third of the gauging station network (Marsh, 2002). Hydrometric standards need to be maintained at a high level if confidence is to be placed in computed flow values, particularly those likely to be experienced during periods of extreme low flow or drought.

While the developments in flow measurement technologies described in this chapter have dramatically improved our capability to monitor low flow in a wide range of environments, they also introduce new challenges. One particular issue is the degree to which the overall homogeneity of a lengthy river flow series may be impacted by a change in the measurement technique. Systematic changes are almost inevitable with the transition from traditional technologies to more modern acoustic techniques, and these biases are most likely in the extreme flow ranges, which are of the greatest import for any long-term analysis of changing low flow regimes. It is vital, therefore, that full documentation of the technological upgrades is provided, and, ideally, parallel operation of the old and new monitoring methodologies is sufficient to identify the degree of systematic difference — particularly for low flow periods. Similarly, this places a premium on the application of quality control techniques (Section 4.3.7) in order to identify potential breaks in homogeneity in long-term low flow records.

4.3.6 Groundwater level data

The behaviour of groundwater is often of critical importance for investigating the status of the subsurface in a catchment and for determining the low flow response of a river (Section 3.4). Data that describe variations in groundwater level and groundwater recharge and discharge are, therefore, valuable for drought analysis. While groundwater levels and localised groundwater discharge (springs) can be readily measured, it is practically impossible to directly gauge groundwater recharge and diffuse groundwater discharge (e.g., seepage areas along the river channel).

Data on groundwater hydraulic head are obtained using piezometers (Section 3.4.1). An observation well is a special piezometer that measures the position of the phreatic water table with the pipe having a longer screen (e.g., 2 or 3 m). The bottom of the screen should be below the lowest level of the water table, and the top should be above the highest level to allow free inflow of groundwater over the whole range of the water table fluctuation (Fig. 3.12). Both automated-recording and manual-operated instruments are available to measure the groundwater hydraulic head in piezometers and the water table in observations wells.

Nested piezometers provide reliable measurements of the groundwater hydraulic head distribution, especially in anisotropic aquifer systems (where the hydraulic conductivity and storage characteristics are not uniform in all directions) or in areas where significant vertical groundwater flow occurs. Rapid and accurate water table measurements are best made in small diameter observation wells, although depending on the purpose of the study. If the diameter is too large, the volume of water contained in the well may cause a time lag in water table changes, although this is not so critical during drought because of the slow decline of the groundwater level. Large-diameter wells show a delayed response of the water table to groundwater recharge and, consequently, tend to attenuate the drought response, resulting in longer and fewer events.

4.3.6.1 Automatic recording of groundwater levels

Automatic recording of groundwater levels using a pressure transducer is common, where the water pressure is converted to an electrical signal. Although pressure transducers are able to take high-frequency measurements, one measurement per day is generally sufficient for drought studies due to the overall slow change in water levels as compared to river flow fluctuations. Pressure transducers are typically accurate to 1 cm, or less, and have the capability to store data for several months. In some regions, a float-tape gauge is used as an alternative to the pressure transducer. It is important to regularly check the friction of the pulley to prevent a staircase appearance to the resulting data. Furthermore, the length of the cable and counterweight pipe should be sufficient to avoid the counterweight reaching the pulley during drought. A well-maintained float-tape gauge can be as accurate as a pressure transducer.

4.3.6.2 Manual groundwater level monitoring

Regular manual monitoring of the groundwater hydraulic head, or water table, is still needed, even where data are collected automatically. Readings of a pressure transducer or mechanical float recorder should be compared with a manual observation at least once a month. In countries where labour is not too expensive, manual monitoring is often the most practical method of collecting groundwater levels during drought (Fig. 4.6).

A popular manual method is the dipper (Fig. 4.6a). The dipper is a cylindrical probe with a hollow space at the end, which is connected to a plastic-coated tape or flexible steel cable. If the dipper reaches the water level, an audible signal is produced. The length of tape or cable used equates to the depth of the groundwater water table. If the top of the piezometer or observation well does not equal soil surface, the length has to be corrected for the height of the piezometer or observation well above soil surface.

A more sophisticated device is the two-electrode device (Fig. 4.6c), which consists of a portable reel having a plastic-coated tape, or cable, that is connected to a probe at one end. The probe has two adjacent electrodes such that, as soon as the probe reaches the water level, a circuit is made to activate a

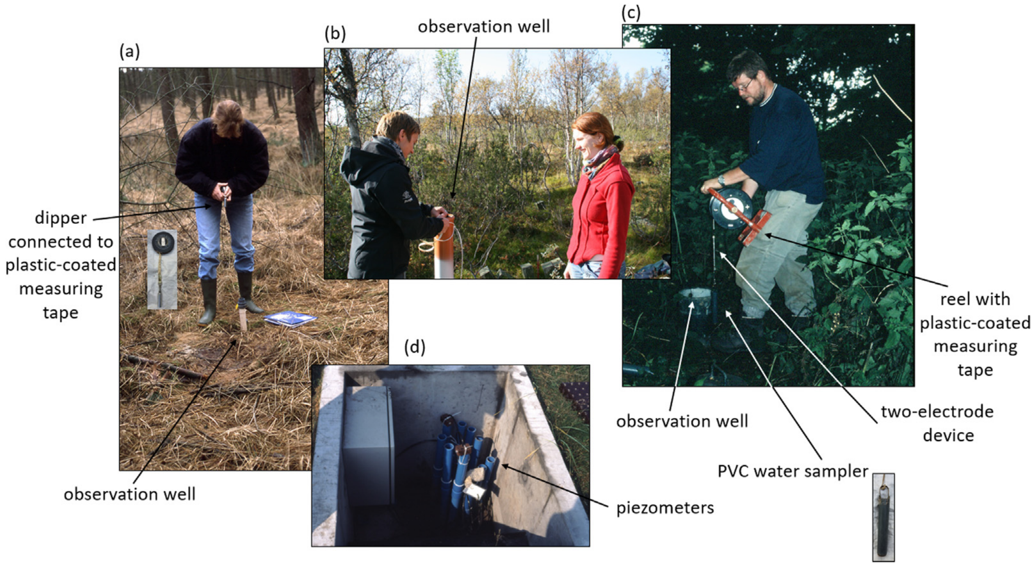

FIGURE 4.6

Manual monitoring of groundwater: (a) measurement of groundwater level in an observation well with a dipper connected to a tape measure, (b) letting the dipper down to measure the groundwater level in an observation well, (c) measurement of groundwater level in an observation well with a two-electrode device and a water sampler beneath, and (d) maintenance well with a bundle of piezometers that measure the groundwater hydraulic head at different depths of a confined aquifer. The top of the piezometers are ordered from high to low; the highest measures the groundwater hydraulic head in the topmost part of the aquifer and the lowest in the deepest part of the aquifer.

Photos from Henny van Lanen (Wageningen University, the Netherlands).

light bulb or buzzer at the reel. The depth of the water table is read from the length of tape or cable used. These instruments can also be used for artesian groundwater, where the groundwater hydraulic head rises above the soil surface, as long as the groundwater hydraulic head is not more than about 1.5 m above the surface (not exceeding the tube height). If the groundwater hydraulic head of the artesian aquifer is more than 1.5 m above the surface, a pressure transducer needs to be used. Otto (1998), Van Lanen (2003) and Hiscock and Bense (2014) review observation methods, maximum depth, accuracy, required skills and costs of each observation method, while Jousma and Roelofsen (2003) give an extensive bibliography of groundwater monitoring tools.

4.3.6.3 Estimating groundwater recharge

Assessing groundwater recharge, the replenishment of groundwater resources from precipitation, is still a major challenge when characterising the water balance of an area since there is currently no entirely satisfactory or simple direct measurement available. Recharge is usually estimated using a variety of methods that consider the fluctuation of groundwater levels in response to precipitation, including water balance approaches (Healy, 2012). A comprehensive and site-specific way to measure components of the soil water balance (Eq. A3.1.2) is using a weighable lysimeter and a nearby automatic meteorological station to measure precipitation and other weather variables. Kohfahl et al. (2019), for example, used a cylindrical lysimeter of 1 m^2 surface and 1.50 m height to measure groundwater recharge in a dry subhumid climate (Csa, Fig. 2.2) in southern Spain. Recharge was estimated as the accumulated drainage from the lysimeter over a certain period of time and found to be about two-thirds of the precipitation in the hydrological year 2016–17.

4.3.6.4 Monitoring groundwater discharge

Groundwater can be discharged either diffusely, in a brook, stream or river, or, more concentrated, in a spring. In the latter case, measurement of groundwater discharge is identical to conventional river flow measurement (Sections 4.3.1–4.3.3). When groundwater discharge is diffuse (e.g., from a riparian area, through the banks or bed), the inflow in a river during a dry period (when river flow is considered to consist of only base flow) over a certain river reach, can be measured with upstream and downstream gauging methods. The incremental flow equals the groundwater discharge over the river reach.

4.3.6.5 Groundwater storage

Groundwater storage is the volume of water stored in the aquifer that potentially can be released or stored. It is determined by the saturated thickness, the drainage base of the aquifer and storage characteristics (Section 3.4.1). Groundwater storage change is the difference between groundwater recharge and discharge over a timeframe of interest. The storage change can be derieved from the drop or rise of the groundwater hydraulic head or water table over the timeframe and aquifer characteristics. These aquifer characteristics are typically derived from a range of field tests on piezometers or boreholes and laboratory tests on core samples of aquifers (Kruseman and de Ridder, 1990). At a larger scale, regional changes in groundwater storage can be characterised using Earth Observation (EO) techniques. Data from the Gravity Recovery and Climate Experiment (GRACE) satellite missions have been used to estimate long-term regional- to continental-scale groundwater overexploitation (Rodell et al., 2009) and the response of groundwater systems to major episodes of drought (Li et al., 2019). Van Loon et al. (2017) studied groundwater anomalies derived from GRACE-Terrestrial Water

Storage (TWS) to test large-scale approaches to obtain near-real-time groundwater drought. They studied the 2003 and 2015 European droughts in eastern Netherlands and southern Germany and concluded that the spatial resolution of the GRACE-TWS-based groundwater droughts has still to be increased to satisfactorily monitor the two selected groundwater drought events. EO methods are most effective in quantifying changes in groundwater storage when the spatial scale is sufficiently detailed and accompanied by in situ ground-truthing observations.

4.3.7 Quality control

Quality control should begin well before data are delivered for processing. It should be integrated into every step of data collection, as well as in the data processing. In this section, various aspects of data quality control are considered, primarily in respect of the processing of river flow data. Nevertheless, the same general principles apply to the quality control of groundwater data and most other types of time series measurements.

4.3.7.1 The nature of errors

An error is the difference between the measured quantity and its true value. With hydrometric data, errors are usually random (or stochastic), systematic or spurious (Herschy, 2009). A random error is the type of error that is unavoidable whenever any type of measurement is made. A systematic error is the type of error that appears consistently in a set of measurements, due to a problem in the method of measurement. For example, an incorrect stage-discharge relation due to weed growth, or a problem with the instrumentation, would introduce a systematic error in a flow record. A spurious error is one that is introduced accidently into the data, most often by human error or equipment malfunction.

Little can be done to eliminate random errors, although the extent of uncertainty varies according to the method of measurement and the characteristics of the cross-section. Systematic and spurious errors, however, can be minimised with good practice. Where such errors are detected in the data, corrections should be applied and be properly recorded.

4.3.7.2 Good practice

Compliance with International Organization for Standardization (ISO) standards for data collection generally ensures good practice, thus helping to minimise systematic and spurious errors occurring in data. Some of the ISO standards commonly referred to include ISO1088 (Velocity-area methods), ISO18365 (Selection, establishment and operation of a gauging station) and ISO18320 (Determination of the stage-discharge relationship). In addition, adequate and proper maintenance of gauging structures and their instrumentation are essential to ensure that water levels are correctly recorded and are representative of flow conditions at the respective sites (Marsh, 1999).

As well as supplying raw data, it is important that those responsible for data collection in the field have a good understanding of why data are collected and are able to provide up-to-date information on methods of collection and report any deviations to those responsible for processing and storing the data. For every gauging station, a record should be kept of the gauging methods employed, changes in instrumentation and, for hydrometric data, past spot gaugings and the history of rating curves. Details should also be kept of the factors that have affected the record, such as changes to site conditions and activities in the upstream catchment.

4.3.7.3 Data validation

The 'raw' time series of stage data that are collected from the gauge is initially pre-processed into a useable format as dates, times and levels and should then be checked to see if they fall within an expected range of values and whether the difference between two consecutive readings is acceptable. These limits of allowable range and rate of change are defined according to knowledge and experience of local site conditions and may vary during the year. Visual checking of graphical plots of stage (water level) data is a very useful method of data validation that should be conducted prior to their conversion to discharge.

Application of the stage data to the relevant rating curve results in a time series of river flow data, which should then be checked prior to release. One of the initial checks is to compare the new data with past records. A hydrograph, a graphical representation of the variation in flow against time (Fig. 4.7), can be used to identify a discontinuity, or jump, between the end of the previous record and the start of the current. A hydrograph may also be used to identify spurious peaks and troughs. A useful technique is to compare the data within an envelope of the corresponding long-term daily maximum and minimum flows (Fig. 4.7); the envelope helps to direct attention to the most hydrologically significant low flows — those which approach, or exceed, the extreme previously recorded minima for the target station. Fig. 4.7 shows some typical problems that may be observed using a hydrograph, such as:

(a) missing data (in February)
(b) an isolated erroneous peak (in June)
(c) sudden drop out in flow (in March)
(d) an artificial increase in flow (in August—October) caused by weed growth, followed by a steep decrease after weed cutting in October.

More generally, examples of hydrometric errors and their significance are discussed by Wilby et al. (2017). The comparison of data from a gauging station on the same river, or in a nearby catchment with similar characteristics, is a valuable method for validating contemporary or historical data for a time

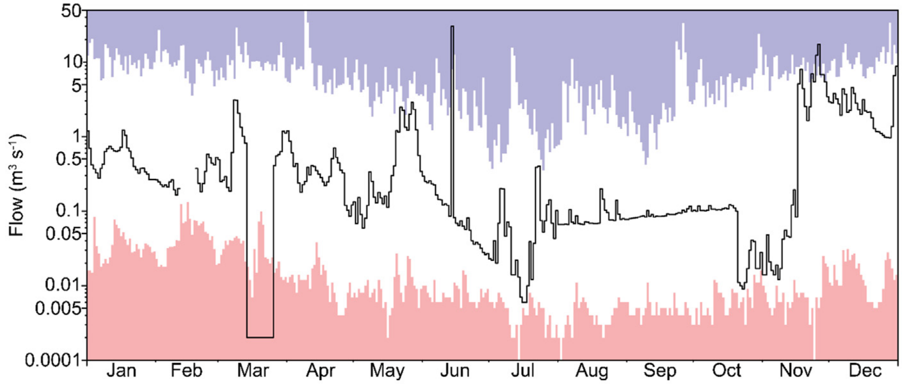

FIGURE 4.7

Data validation using an annual hydrograph for a target site (*black curve*), with examples of different types of error (see text for explanation). Red shading shows the low flow envelope (lowest flows in the previous record for that day), blue the high flow envelope.

series under review. A graphical plot of the two data records should show similar, if not identical, behaviour over the same period. Any variances between the two records indicate possible errors. Additional information for the validation can be derived from time series of catchment precipitation and other hydrometeorological variables if relevant and available.

A double-mass curve, which plots the accumulated values of two time series against each other, is another useful validation check (Fig. 4.8). The double-mass curve constructed from the flow records of two gauging stations in the same vicinity should approximate a straight line. With this method, the two time series need not necessarily be of the same variable; data from a catchment precipitation series or precipitation gauge within the catchment may also be used to check the flow record. A similar method that can be used is the residual-mass curve, which plots accumulated departures of the two time series from some datum (normally the mean).

Any anomalies and errors that are detected through these methods should be examined carefully and, if necessary, removed or corrected. Any corrections, or adjustments, should always be made in a timely manner. They may be applied manually or according to an appropriate infilling method (Section 4.3.7.4). Whenever an individual data item is altered, a simple quality control flag should be associated with it to signify that it has been changed and a comment attached to explain the change and method of correction.

4.3.7.4 Missing data

Missing data, or gaps, are a common problem that tends to cluster disproportionately in the extreme flow ranges (Marsh, 2002). Even a small proportion of missing data can greatly reduce the ability to derive meaningful summary statistics (Section 6.5.1) and indices relevant for drought or low flow (Sections 5.3—5.5). Data validation and infilling procedures should be applied vigorously to low flow data sequences, however judgement needs to be exercised when infilling missing low flow, to avoid

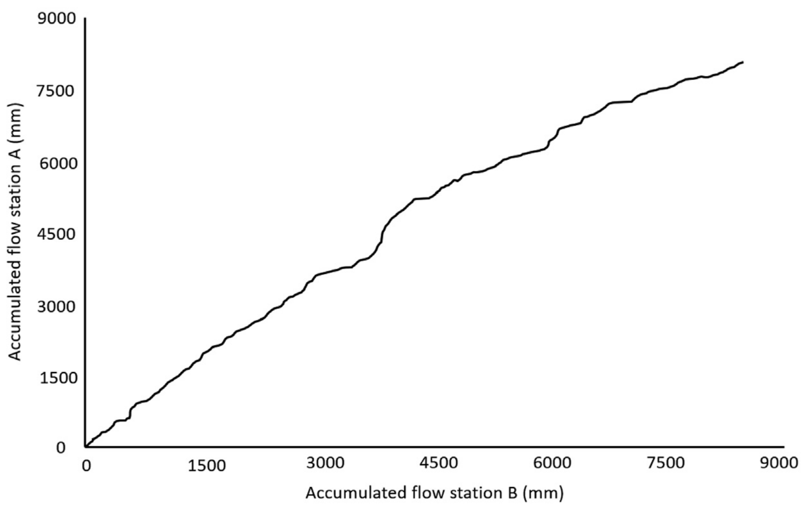

FIGURE 4.8

Double-mass curve showing accumulated flow at a Station A plotted against Station B.

archiving misleading flow estimates. Caution should also be used where missing data could be periods of zero or no-flow (Section 5.4.2), where the level in the river is below that of the staff gauge, inlet pipe or instrumentation. It will not always be possible to derive realistic flows to infill lengthy sequences of missing data, but in many circumstances, the inclusion of auditable and flagged estimates, rather than leaving a gap in the record, will produce significant benefits in relation to the overall utility of the time series.

Experience demonstrates that hydrograph appraisal undertaken by personnel familiar with the behaviour of individual rivers is the most effective means of infilling missing low flow data. Short gaps, when there is no indication of a flood event, may be filled manually (by 'eye'), by linear interpolation or by polynomial fitting with values from the time series itself. Longer gaps can be filled by use of data from an analogue (donor, Section 8.2) gauging station, or stations, together with daily precipitation totals for a representative precipitation gauge within the catchment or by simulation with an appropriate hydrological model.

An analogue gauging station would usually be upstream or downstream of the 'target' gauging station concerned or be in a nearby catchment. This resembles the approaches introduced to explore the influence of human interventions (Section 10.4) and for estimation at the ungauged site (Section 8.2). The choice of analogue stations should be determined according to the following criteria:

(a) geographical proximity of the catchments, to ensure that the catchments are in climatologically similar areas
(b) similarity of runoff generation mechanisms, that is, similar soil and hydrogeological conditions, approximately equal proportions of lake, forest, wetland or agricultural land area in the catchments, for example, as indicated by the Base Flow Index (BFI) (Section 5.3.3)
(c) similarity of catchment area, elevation and topographical relief
(d) absence of human interventions significantly affecting the natural flow regime, such as river regulation, sewage or industrial effluent or intakes for irrigation or other needs.

As well as BFI, which is an index of catchment response, the coefficient of correlation (Section 7.3.2) derived over an identical period of the target and analogue stations gives a good indication of the suitability of an analogue station.

One of the simplest methods of infilling missing data, using one or more analogue gauging stations, is to visually compare the hydrographs of both target and analogue stations and manually enter estimated values that are sympathetic with the observed behaviour. A simple, widely used mathematical method is to scale, by the ratio of the respective catchment areas (or mean flow), the data from the analogue catchment to the target (simple scaling approach, Section 8.6). A more complex, yet effective, method is the 'equipercentile' scaling approach, that involves calculating the flow percentile for each missing day from the flow record of an analogue catchment and then extracting, from the existing data record of the target gauging station, the flow values that correspond to the flow percentiles.

Various studies have compared these methods for infilling to provide general guidance on their use. Harvey et al. (2012) found the 'equipercentile' scaling approach to perform well, whereas simple catchment scaling performed poorly. All methods assume synchronicity of flows between target and analogue catchments. It would be inappropriate, therefore, to apply them to sub-daily data (e.g., 15-min or hourly flow data) or where one of the catchments is much further downstream of the other, without accounting for the lag-time between the gauging stations. Another important consideration in

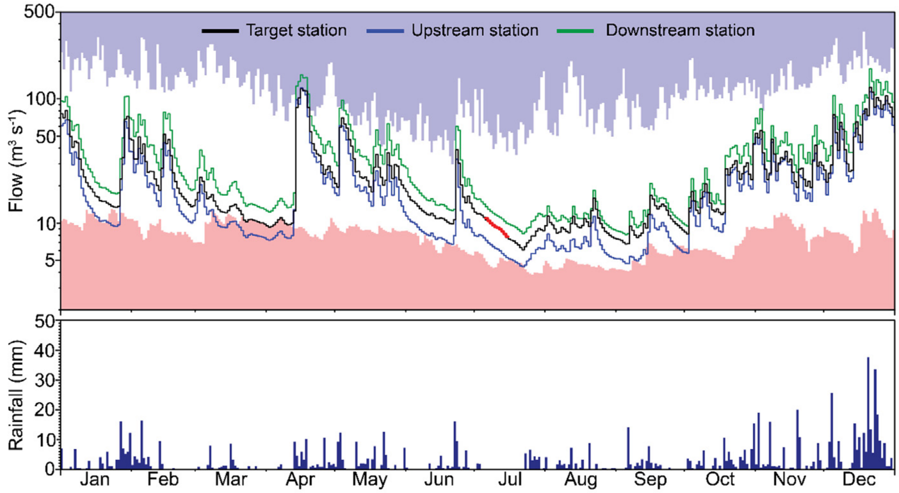

FIGURE 4.9

Infilling of missing river flow data at target site with data from analogue stations upstream or downstream along with a representative precipitation gauge. The red line shows the infilled sequence.

infilling is the length of the gap to be infilled. Clearly, longer gaps present much more of a challenge, especially in periods of substantial flow variability. It is difficult to recommend a suitable minimum gap length for infilling, although general guidance is provided by Slater and Villarini (2016) based on a numerical simulation study.

In the example shown in Fig. 4.9, a logarithmic scale has been used to help emphasise the low flow range. Flows for the station with missing data have been plotted along with a station upstream and downstream on the same river, alongside precipitation data from a nearby gauge within the catchment. The limited precipitation over the period for which flows are missing allows estimated flows to be inserted with confidence. Where precipitation may be expected to influence the recession, or where human interventions may be significant, the time series should be scanned for similar flow sequences elsewhere in the record, which would help to reconstruct the missing data.

For groundwater-level data, equipment failure (i.e., failure of the pressure transducer or float-tape gauge) leads mostly to gaps in the observed record. During drought, however, gaps can occur when observation wells run dry as a result of the base of the standpipe being shallower than the lowest level of the water table. Short gaps can readily be filled in by linear interpolation, assuming no recharge occurs to cause the water table to rise in the interim. Multiple regression (Sections 7.3.3 and 8.4) is applied to infill longer gaps, or where recharge occurs, with missing values calculated using observations from adjacent piezometers or observation wells.

4.3.8 Supporting hydrometeorological time series data

There are a variety of further data types that can be used to support low flow and drought studies. In addition to groundwater and river flow data, precipitation, soil moisture and evaporation data are often analysed to help understand how drought propagates from meteorological to hydrological drought, within catchments or across regions (Sections 2.3, 3.3 and 3.4). Spatial datasets available at different scales are further discussed in Section 4.4. A few such national datasets are already included as example datasets in the sub-sections below.

4.3.8.1 Precipitation

Accurate measurement of precipitation (rainfall and snowfall) amount is crucial for many areas of hydrology, and there are currently many different types of gauge in use for point measurement around the world. Precipitation measurements are made through a mixture of manual storage gauges (read by observers on a daily or monthly basis), and automatic recording gauges — using tipping bucket or weighing method — which are used to measure rainfall at a finer temporal resolution. A comprehensive overview of precipitation measurement practice is given by Strangeways (2006).

Whichever gauge type is used, this only provides a measurement of precipitation at a particular location. In order to understand precipitation inputs for the whole catchment down to the gauging station, a spatially distributed 'areal precipitation' product is needed. This can either be measured directly through radar or satellite observations or aggregated from multiple precipitation gauges within the catchment boundary. Nevertheless, the last few decades have seen a huge increase in the availability of datasets that are readily accessible, making it much easier for hydrologists to obtain comparable catchment areal precipitation series to analyse alongside river flow or groundwater data. Examples include national-scale gridded rainfall products at 1 km resolution for the UK (Keller et al., 2016) and about 4 or 5 km for the United States (Di Luzio et al., 2008; Durre et al., 2022, respectively).

Many national efforts to rescue and digitise precipitation data held in paper archives have been conducted over the past years, for example, Ireland (URL 4.5), the Netherlands (URL 4.6) and France (URL 4.7), as well as through international efforts, such as the WMO International Data Rescue (I-DARE) portal (URL 4.8) and the dedicated Data Rescue Service from the EU Copernicus Climate change Service (URL 4.9). Several such projects have used crowdsourcing, mobilising university students and members of the public to digitise millions of observations in archives dating as far back as the 17th century. This has allowed digital gridded precipitation maps to be created covering extended time periods (e.g., Hawkins et al., 2022).

Such gridded products are also very useful for drought analysis themselves, enabling hydrologists to visualise and analyse high-spatial resolution meteorological drought indices. The example from UK in Fig. 4.10 shows how a gridded rainfall data product enables (spatial) maps to be produced, along with time series shown for any selected cell of the map. This provides important context for the hydrological drought indices (river flow and groundwater, Section 5.7) that are also shown in the figure, enabling drought conditions to be tracked spatially, temporally and across the hydrological cycle. Comparable European-scale gridded precipitation datasets are available (Section 4.4, e.g., Haylock et al., 2008).

4.3.8.2 Evaporation

Evaporation is another key variable to support the interpretation of hydrological data and is of fundamental importance for drought analysis as drought can be driven by atmospheric evaporative demand as well as by deficits in soil moisture (Chapters 2 and 3). However, while evaporation is a key component of the water balance, it is difficult to measure directly. Estimates can be obtained by water balance approaches at different scales (e.g., pan, lysimeter, lake or catchment). Examples of monthly

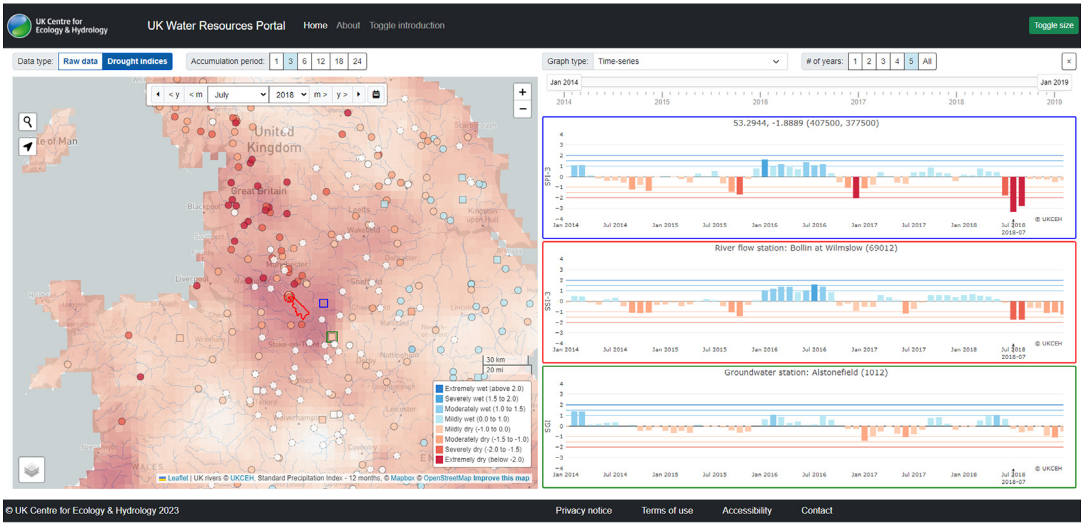

FIGURE 4.10

The UK Water Resources Portal shown during the 2018 drought (July) using a high-resolution gridded rainfall product. The map provides a view of deviations from normal precipitation in high spatiotemporal detail using a set of standardised indices (Section 5.5). The Standardised Precipitation Index (SPI), Standardised Streamflow Index (SSI, dots) and Standardised Groundwater Index (SGI, squares) are shown on the map for gauged sites, with red values depicting lower than normal values and blue wetter (see colour scale on map). The right panels show SPI-3, SSI-1 and SGI-1 monthly time series for a selected grid cell for the 2018 drought compared to recent years.

and annual time series of pan evaporation are available for Australia (URL 4.10). Direct measurements of evaporation can be obtained using eddy covariance methods on flux towers or scintillometers (Gash and Shuttleworth, 2007), but in practice, this means observations are few and far between. In practice, most datasets are therefore based on water balance outputs from hydrological models, or from land-surface models (e.g., the CHESS dataset in the United Kingdom; Robinson et al., 2020).

4.3.8.3 Soil moisture

Soil moisture is of critical importance as a drought variable representing the available water for vegetation. It is also a key factor in controlling the partitioning among latent and sensible heat, potentially intensifying an ongoing heatwave as the soil dries out (Section 3.3.1.1). While typically one may think of soil moisture being of most relevance to ‘soil moisture or agricultural drought’ rather than hydrological drought, knowledge of soil moisture is vital for understanding drought propagation and development. Like evaporation, historically soil moisture has been very challenging to monitor beyond the point scale, but the last few decades have seen significant advances in the utility and accessibility of soil moisture datasets. Traditionally, in-situ measurements have been made with time domain reflectometry (TDR) or neutron probes, which measure only a very small-scale core of the soil column. Recent years have seen the development of instruments that use incoming cosmic rays to sense soil moisture on a plot scale (around 12 ha, 0.12 km^2), between 0.1 and 0.8 m depth (depends on

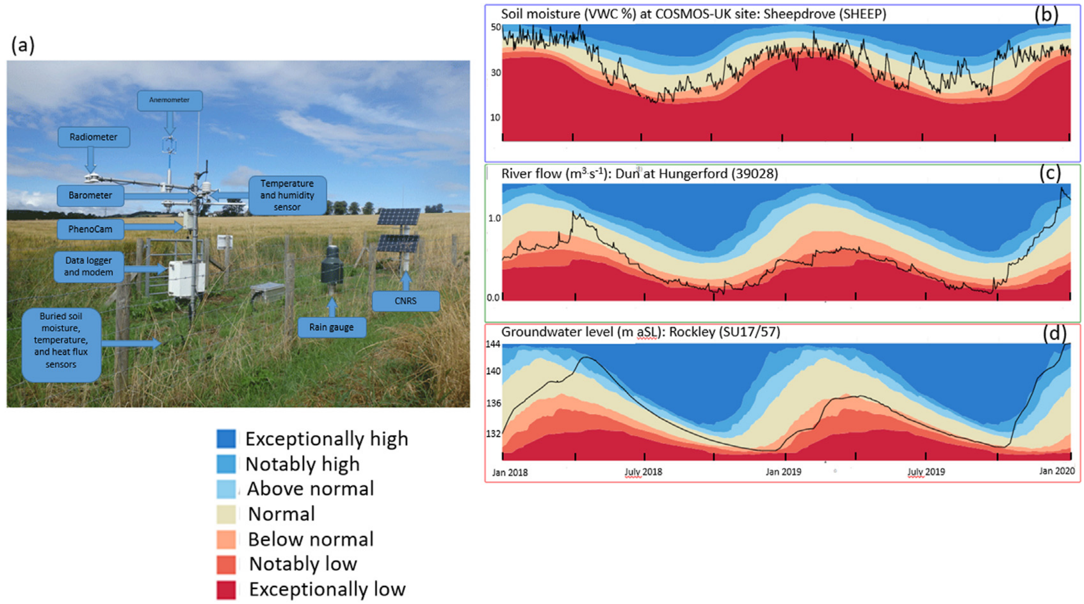

FIGURE 4.11

Monitoring site of hydrometeorological variables: (a) annotated layout of a COSMOS monitoring station, incl. a Cosmic Ray Neutron Sensor (CRNS), along with co-located meteorological and traditional in-situ soil moisture sensors. Graphs showing time series for the 2018–19 drought from nearby observation sites in the chalk aquifer in the Berkshire Downs (southern England): (b) COSMOS–UK volumetric soil moisture, (c) river flow, and (d) groundwater level. In each case the black line shows the observed daily hydrograph, and the colours show 'regime bandings' to highlight how current observations compare to the historical record according to the legend. Further information on the instrumentation can be found in Cooper et al. (2021).

soil wetness). Fig. 4.11 illustrates a typical set up of a cosmic ray neutron sensor (CRNS, typically referred to as COSMOS) observation site. The figure also demonstrates how soil moisture data from such sites can be visualised alongside river flow and groundwater data, to provide context for soil moisture dynamics during a drought event. Following the European summer drought of 2018, in the winter of 2018–19, it can be seen that soils remain relatively dry. Such periods of deficit correspond to poor winter recoveries of river flow and groundwater resulting in depressed river flows the following spring or summer despite periods of soil wetting. Well-established observatories of these sensors now exist in the US (Zreda et al., 2012) and the UK (Cooper et al., 2021), and they are also being adopted much more widely.

As noted above for evaporation, soil moisture estimates from large-scale modelling systems and measurements from satellite missions are now making high-resolution soil moisture products a possibility at local to global scales. The potential of these datasets for drought analysis is huge, given the large-scale and temporally varying nature of drought, provided that they are used with caution and awareness of their limitations. For example, soil moisture sensed from satellites typically includes only the very near-surface (<50 mm), and estimates are affected by vegetation cover – this must be borne in mind when comparing such outputs with in-situ measurements. A review of both ground-based and satellite soil moisture measurements, and their various strengths and weaknesses, is provided by Babaeian et al. (2019).

4.3.9 Human interventions

As noted in Chapter 10, the continuing development of water supply and sewerage systems, irrigation schemes, land drainage, land use change and hydro-electric power generation, all combine to disturb the pristine relation between precipitation and river flow. This means that 'drought in the Anthropocene' (Van Loon et al., 2016) requires an understanding of human interventions on hydrological responses and the feedbacks between natural and human drivers of drought.

The net effect of human interventions on low flow patterns is often profound, and (unadjusted) gauged flows can be very unrepresentative of the natural response. In highly impacted catchments, the artificial component of flow may exceed the natural contribution, particularly at low flow. Information on the location, volume and timing of artificial interventions are vital for water resources managers to allocate freshwater to users and preserve the ecological quality of the rivers during periods of low flow and drought. Access to these data is useful for identifying the effect of the artificial interventions on the natural flow regime and for the management of water resources. However, it is often the case that such data are not readily available to hydrologists due to it being outside the public domain or not existing in the first place (Chapter 10 and van Loon et al., 2016), which often necessitates other approaches to estimating human impacts.

In some countries, water use is regulated within a legal framework, where licences, or consents, 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 returned) at a particular site on an annual or monthly basis. Users may be obliged to periodically submit information on the volume of water actually used to the regulatory authority. Similarly, reservoir operators are required by licence to follow a certain regime of regulated releases (compensation flows) to ensure that at least a minimum flow is retained in the river downstream. Where available, the information provided by the users on abstractions and releases are a good indication of past and future water use within a catchment and helps the water manager to determine appropriate operational responses, or strategies, for maintaining supply during prolonged drought.

4.3.9.1 Flow naturalisation

In some countries, attempts are made to adjust gauged daily or monthly flows to account for the largest and most easily quantified human interventions (e.g., non-returning abstractions above the gauging station). Normally, no attempt is made to account for the, often subtle, impacts of land-use change, but the longest of such naturalised series can be exceptionally valuable, for example, in relation to the detection of trends in low flow.

The process of distinguishing the natural flow component from the human influenced flow record is called naturalisation (Section 10.4, sometimes also called decomposition). A review and taxonomy of naturalisation methods are provided by Terrier et al. (2021). Resources are seldom available to undertake flow naturalisation for a comprehensive network of gauging stations, and the process is usually only conducted where there are good-quality flow and quantative information about the intervention (e.g. abstraction records or reservoir inflows), or where the latter are unavailable, appropriate modelling frameworks and infrastructures are available to apply the kind of estimation techniques outlined in Terrier et al. (2021).

Essentially, naturalisation involves the adjustment of the observed (human influenced) flow record according to the known human interventions upstream. The procedure requires a systematic record of the interventions, for example, times, rates and durations of abstractions, discharges and compensation flows. The data should be in compatible units and an appropriate method to temporally disaggregate the data should be applied, as necessary (e.g., 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 interventions (compensation flows plus discharges minus abstractions). It should be noted that there could be a high degree of uncertainty to the approximation; while, typically, there may be an error of $\pm 5\%$ in the observed flow, the error associated with the artificial influence can be around $\pm 40\%$, or higher. An example of a naturalised hydrograph for a heavily influenced catchment in the United Kingdom is shown in Fig. 4.12. Further details of methods to naturalise river flow data are presented in Section 10.4.

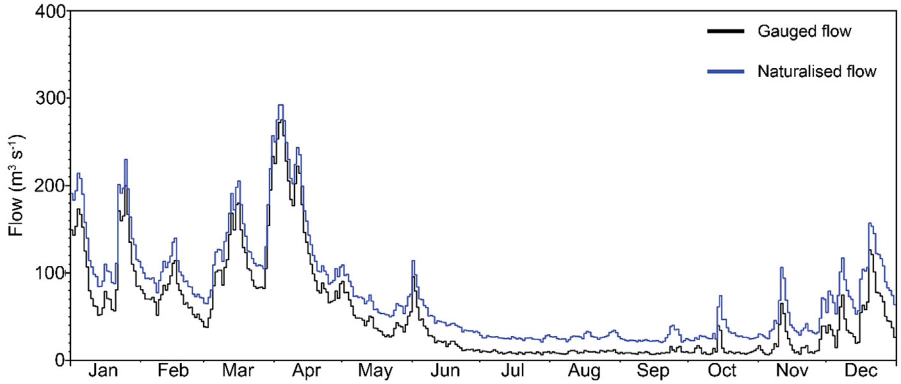

FIGURE 4.12

Disaggregation of river flows into artificial and natural components. Data are naturalised by decomposition, that is, known volumes of water abstracted for public water supply are added to the gauged data.

Data from the River Thames at Kingston for 2018.

Observed hydrographs may also be naturalised using statistical tools or hydrological models (Sections 10.4 and 10.5). Assuming the affected area is not too large, multiple regression of data from gauging stations or boreholes outside the affected area can be used to adjust data from the target site. Time series analysis can also be applied to detect a trend in the groundwater hydrographs due to human influences (Section 7.4).

4.4 Spatial and large-sample datasets

In Section 4.2, an introduction was provided to the types of spatial, or thematic, data that may be used in low flow and drought analyses. Here, further information is given on the spatial data that are typically available at local, regional and global scales.

There has been an explosion in the availability of tools for geospatial analysis, in particular in the open-source domain, which have markedly increased the ability of hydrological data analysts to process and produce large datasets within hydrological studies, and even to develop new spatial indices to improve understanding of drought (Section 5.7). In the Supporting Document 4.1 (Tables S4.1.1 – S4.1.3 on GitHub, https://github.com/HydroDrought/hydrodroughtBook), some of these spatial datasets are given; however, new datasets are rapidly becoming available, at ever-increasing spatial and temporal resolutions. Ever more, global-scale datasets are available at resolutions (e.g., ~km-scale) suitable for individual catchment studies. In fact, in some cases the best datasets available for use at the catchment scale may well be the same datasets used in global studies. For example, many global land cover datasets are produced automatically at high resolution from satellite imagery such as the 100 m resolution dataset from the Copernicus Land Monitoring Service (URL 4.11). It may, however, often be the case that such high-resolution datasets are degraded or aggregated to the global scale in order to make applications and analyses simpler at larger scales. Between these scales, many countries produce and maintain national-scale datasets that represent the highest quality and resolution readily available, particularly for soils, geology, land use and in many cases precipitation (e.g., Keller et al., 2016) and other meteorological variables. The prevalence of digital datasets in common formats, and tools and skills to rapidly access and process them, has reduced the differentiation between data used in catchment and regional to global scale hydrological analyses. The most significant distinction in scales, at which drought analysis is undertaken, may be between the local scale at which it is feasible to acquire and produce new or updated information of catchment characteristics (e.g., through field mapping of features, manual soil sampling), and the regional to global scales at which adequate digital (gridded digital) datasets are available. There remains, however, a requirement for the hydrologist to understand the limitations of digital datasets used for analysis at any scale, including to which degree these are affected by human interventions. In the following, local scale and large scale are separated; however, most spatial data are relevant at all scales. They only differ in the degree of detail, resolution and format. A catchment can be both a small, local-scale catchment (e.g., Pang, UK), as well as a large-scale river basin (e.g., Nile River).

4.4.1 Local-scale data

A wide range of spatial data is required for catchment, and local-scale studies, and may need to be manually sourced or mapped to provide insight into hydrological processes at this scale, though some national or global scale datasets may be appropriate. Land use is typically a key characteristic, and many datasets are available. In some catchments experiencing frequent change in land use (e.g., those with arable land), land use should be mapped regularly. Remote sensing can support, for example, a yearly survey.

Geological maps (e.g., lithology, depths of layers, and geological structure, such as faults, folding) are used to derive various hydrogeological maps (e.g., occurrence of aquifers), which may provide valuable information on the distribution of hydraulic parameters (e.g., conductivity, storage coefficient, transmissivity, resistance). Maps with location of observation wells and groundwater level contour lines of aquifers are useful, particularly if they represent different hydrological conditions (e.g., multiple aquifer systems, summer and winter conditions or dry years versus wet years). If groundwater exploitation occurs, a map should be compiled with the location of the abstraction wells. Maps with the groundwater table depth can be essential for computing capillary rise or recharge in thick unsaturated subsoils (Fig. 3.12). These maps also help to understand responsiveness of the groundwater system. For example, areas with deep groundwater levels respond slower — or even not — to a short-term lack of precipitation than those with shallow groundwater levels (Section 3.3.4.3). Maps with the elevation of the soil surface are useful to derive the ground water level relative to a reference (datum, e.g., m aSL), which allow construction of contour maps and estimation of groundwater flow both in horizontal and vertical direction.

For comprehensive studies at this scale, a map of the drainage network (including rivers, brooks, springs, seepage areas, lakes, and gauging stations) may need to be compiled. The highest resolution of national mapping may be sufficient, but in many cases, small streams and ditches may need to be mapped in addition. Digital elevation maps with a high resolution (e.g., 5 m) are being increasingly used to generate the drainage network or to produce maps with the slope length, slope direction and slope angle. LiDAR data may be available at higher (e.g., <1 m) resolution enabling catchment delineation even over low relief areas (topographic water divide, Section 3.4.2.1). Remotely sensed products, such as satellite derived soil moisture, radar-derived rainfall and land cover, are increasingly accessible at higher resolutions. With datasets such as these, it is becoming possible to produce some quantifiable assessments of local drought or low flow conditions from national or global datasets.

4.4.2 Regional to global scale data

Studies at scales beyond the local scale, from multiple catchments up to regional, continental and global assessments, can, increasingly, be based on the same datasets. The spatial data requirements remain similar across scales. Physiographic characteristics (geomorphologic, land cover, soil and geology) and climatic characteristics are key, and are all available, in some form, from national or global datasets. It is important when working with global data at catchment and regional scales to understand the limitations of the source data used to create the global products. The variability in primary observations may lead to significant uncertainty in some regions.

4.4.2.1 Large-scale physiographic data

Global physiographic data are derived from maps or remote sensing, though there is often little distinction between these origins; many modern maps contain elements of satellite-derived information, and many remote sensing products are improved through incorporation of surveyed ground features. There is a plethora of such data available at a variety of scales and resolution. Table S4.1.3 (Supporting Document 4.1 on GitHub, https://github.com/HydroDrought/hydrodroughtBook) lists a few physiographic datasets available at the global scale, though there are very many more available.

The availability of global-scale datasets of rivers, in which the rivers are represented as lines or as grids of flow direction (derived from Digital Terrain Models), has provided information for the derivation of spatially distributed river network and landform characteristics, some of which are relevant for low flow studies, and readily useable (e.g., river width, slope, sinuosity, Frasson et al., 2019). Such spatially distributed characteristics can be used to calculate increasingly complex catchment-level landform descriptors, such as the mean slope in the proportion of the catchment with highest altitude, or the proportion of the catchment with slope less than a defined value. Flow direction grids and available software tools can be used to create catchment boundaries, identifying the catchment as all grid cells that flow to the cell representing the catchment outlet. The ease of generating spatial datasets for hydrological studies should not belie the importance of understanding how well they represent reality. For example, digitally derived catchment areas may not always reflect the area contributing water to the stream channels (Section 3.4.2.1). In drought conditions, the size and shape of the area that actually supplies water to the stream strongly depends upon areal extent of the groundwater system, aquifer characteristics and groundwater level and gradient. In many parts of the world, the upstream part of a catchment becomes dry during a drought and does not contribute to flow in the river downstream. An estimation of the fraction of the catchment fed by aquifers is often an essential parameter in low flow and drought modelling. Data from these complex aspects of catchment hydrology may be harder to find within large-scale datasets and may require interpretation.

Land cover has an important influence on runoff generation and low flow behaviour in a catchment. Interception, infiltration and evaporation, in particular, depend strongly on land cover characteristics (Section 3.3.4.2), such as the proportion of catchment area under urban development, the proportion of forest and the proportion of agricultural land. During a prolonged drought, a high fraction of forest area can significantly affect low flow, as the roots of trees, if suitably deep, can accelerate the drying process of a catchment. Further, high interception losses normally associated with forests may reduce the overall water balance of the catchment. In Nordic countries, Canada and Siberia, the proportion of catchment occupied by lakes and wetlands is especially important. The effect of lakes, by providing storage, is similarly important for maintaining low flow (Section 3.5.2). The role of different land covers, in particular the effect of lakes, can be parameterised, for example, the ratio between the area of the lakes and the catchment area, for statistical analyses, or incorporated into more process-based distributed models (Section 9.4).

In many catchments, the geology and soils control low flow response (Sections 3.3 and 3.4). However, data that characterise these features remain difficult to establish and quantify, despite the availability of large-scale, extensive, geological and soil maps, due to the problem of quantifying the impact of geology or soil on catchment runoff. In addition to physical catchment characteristics, climatic characteristics, especially precipitation and evaporation, are important when analysing low flow and drought (Section 3.3.2). Usually, at the regional scale, the characteristics are derived from aggregations of national datasets or from subsets of global datasets.

4.4.2.2 Large-sample hydrological data

Obtaining datasets with time series of observed groundwater data can be challenging, as data availability at the global scale is limited. However some regions have extensive records, and more data are becoming available as open-source. For example, the Netherlands provide data from more than 12,000 observation wells (URL 4.12) and the United States Geological Survey (USGS, URL 4.13) makes groundwater level data of more than 13,500 observation wells available. Current conditions can be retrieved for about 2000 wells (data are transmitted to the USGS every hour). For a given well, time series can be plotted for selected periods showing past and current observations and summary statistics presented (e.g., the minimum and maximum level (Fig. 6.2), the mean and percentiles ranging from the 5th to the 95th). Furthermore, mean monthly and annual statistics are available.

River flow is recorded by many national organisations that collect and quality assure observed river flow data. For example, the USGS provides daily river flow country-wide. A colour-coded national map shows, for about 13,500 gauging stations, river flow near real time relative to historical conditions. Gauging stations have at least 30 years of data (URL 4.14). Extensive search functions are available to build a summary table or a time series for one or more stations. The Global Runoff Data Centre (GRDC) collects national river flow records into an international archive that holds discharge data from over 9500 stations worldwide (URL 4.15). GRDC also runs a number of special datasets that are region specific, such as the Artic Region Dataset and the European Water Archive (EWA), or thematic specific, such as the GRDC Climate Sensitive Stations. The EWA collated daily flow data and catchment information from more than 4000 river gauging stations in 30 countries (URL 4.16). In 2014, the dataset was frozen. The climate sensitive stations dataset contains daily river flow data of over 1200 gauging stations worldwide (URL 4.17). National Hydrological Services have identified these gauging stations on request of the World Meteorological Organisation (WMO) to explore climate change and variability. Particular attention should be given to the quality of data held by such archives, and metadata should be carefully examined to assess suitability to study low flow or possible anthropogenic influences on discharge.

4.4.2.3 Large-scale hydrological data

Datasets with spatial modelled river flow data provide an alternative for observed data (Section 4.4.2.2). These datasets are also called simulated observed data or proxy observed data (see Glossary, Box 9.1). On the global scale, river flow is derived from large-scale models (Global Hydrological Models and Land Surface Models, Section 9.4.2) as part of large-scale modelling studies, such as the EU WATCH (Haddeland et al., 2011), ISI-MIP (Warszawski et al., 2013), and EDgE projects (Samaniego et al., 2019). These projects used modelling to create spatially coherent records of reasonable length (up to 50 years) of past hydrological time series (e.g., runoff, Section 9.4) that allow analyses at ungauged locations as well as projected hydrological time series that permit exploration of the impact of climate change in a consistent way. For example, the EU WATCH gridded runoff data (0.5 degrees resolution) were used to compare simulated annual time series of low flow percentiles derived from the multi-model mean runoff against observed flow over the period 1963–2000 across Europe (Fig. 11.8). With ISI-MIP gridded runoff data, the influence of climate change on streamflow drought by the end of the 21st century was assessed for several regions across the world (Fig. 11.10). Example datasets with large-scale hydrological data are described in Table S4.1.2 (Supporting Document 4.1 on GitHub, https://github.com/HydroDrought/hydrodroughtBook).

Contrary to the gridded runoff flow data, large-scale reconstructions of groundwater levels to obtain gridded global maps are still in an early phase. De Graaf et al. (2017) present a global map with simulated average water table depths (averaged for the period 1960–2010) in the upper aquifer under natural conditions. They combined the PCR-GLOBWB model (Section 9.4.2) to simulate recharge for the two-layer groundwater model MODFLOW (McDonald and Harbaugh, 2000) at a global-scale and for a high-resolution (5′ resolution).

4.4.2.4 Large-scale climatological data

Global climatological spatial data (Table S4.1.1, Supporting Document 4.1 on GitHub, https://github.com/HydroDrought/hydrodroughtBook) are generally derived in three ways: from interpolating observation-based, meteorological point measurements to the grid scale (gridded observed, see Glossary, Box 9.1), from satellite observations, or through reanalysis processes, combining available observations with global scale circulation modelling (simulated observed, Box 9.1). Variables that are described globally include precipitation, air temperature, vapour pressure, sunshine hours, cloud cover and wind speed. Sun et al. (2018) provide a review of global precipitation datasets, whereas Zhang et al. (2016) review remote sensor-based estimates of actual evapotranspiration. The CRU TS dataset (monthly temperature and precipitation, 0.5°, Harris et al., 2020) is an example of a gridded observed datasets built by spatially interpolating station observations. Such datasets require a high density of observations to have a sufficient degree of reliability. Continental-scale examples include the E-OBS pan-European dataset (temperature and precipitation), which now comes as an ensemble product to reflect the uncertainty in interpolating station data (Cornes et al., 2018).

Several large climate laboratories, such as the National Oceanic and Atmospheric Administration (NOAA in USA) and the European Centre for Medium-Range Weather Forecast (ECMWF), produce global climatological datasets: the 0.25−0.5° CFSR dataset (URL 4.18) and the 0.25° ERA5 dataset (URL 4.19), respectively. NOAA, among others, also supports the CHIRPS dataset (URL 4.20), a quasi-global precipitation dataset, which uses high-resolution (0.05°) satellite data and ground station data to capture small and intense storms in a variety of topographic settings, and currently has widespread use for drought monitoring (e.g., Funk et al., 2014). As part of large-scale modelling studies, global climatological datasets have been created and fine-tuned to drive hydrological models. An example is the WATCH Forcing Data (WFDE5, Cucchi et al., 2020), which is based on surface meteorological variables from the ERA5 reanalysis (Hersbach et al., 2020) in combination with ground observations, that is, CRU TS4.03 data (URL 4.21). The latter served as basis for bias correction of multiple meteorological variables (e.g., air temperature, radiation terms), whereas the GPCCv2018 dataset (URL 4.22) was used to bias correct precipitation. The WFDE5 has a spatial resolution is 0.5° and a sub-daily temporal resolution. The data are adjusted for elevation differences and updated regularly.

4.4.2.5 Satellite data

Satellites can also provide additional observations to help understand changes in the hydrological cycle over time, though many are derived datasets based on proxy observations. Satellite-mounted temperature and radar sensors can provide information that can be used to produce estimates of surface temperature and near-surface soil moisture. Groundwater is monitored at very large scales through use of gravimetric sensors, such as aboard the GRACE satellite (Section 4.3.6.5). Topographic sensors are starting to enable measurement of lake and river levels from space (albeit currently only for rivers of $>\sim$50m in width), which can be combined with historical flow measurements to provide satellite-based flow estimates, i.e., blending satellite observations with gauge measurements. Tables S4.1.1 and S4.1.2 (Supporting Document 4.1 on GitHub, https://github.com/HydroDrought/hydrodroughtBook) list several datasets of additional hydrometeorological observations, but again, this is a rapidly evolving area, and the increasing range and accuracy of sensors together with new methods for processing satellite datasets, continue to produce new products at higher temporal and spatial resolutions.

4.4.3 Spatial data access

4.4.3.1 Data catalogues

Many global, regional, national and even local scale spatial datasets are now freely available over the web. The huge range and number of datasets available can make it difficult to identify the most appropriate datasets to use for specific studies. As well as information on the spatial and, where relevant, temporal resolution, users need to understand the data sources, how the product is produced and uncertainties deriving from this, in addition to the licensing under which the dataset is made available. Online metadata catalogues can provide this information, usually through a readily searchable interface providing standards-based information. Such catalogues exist at national scales (e.g., the USA data catalogue, URL 4.23) or are provided by international organisations (e.g., the UN FAO, URL 4.24), as well as through commercial platforms (e.g., Google Earth Engine, URL 4.25). Many satellite datasets are developed by international research organisations, which provide catalogues of their own products (e.g., ECMWF, URL 4.26; NOAA, URL 4.27).

4.4.3.2 Data access

Many of the organisations providing data catalogues also provide data. These can be research data centres, which often exist for specific domains, for example, NOAA in the United States (URL 4.27). Access to datasets is usually facilitated by these data centres through provision of file download facilities, for users to process and use on local computing facilities. Datasets are given digital object identifiers, which are guaranteed to provide a persistent link to a specific version of a dataset, meaning datasets remain accessible in future and analyses can be reproduced if required. Increasingly, in particular for larger datasets, data centres are providing tools for sub-setting datasets spatially and/or temporally, prior to downloading files, minimising the volumes transferred and reducing data handling effort for the user.

Furthermore, access to datasets is often enabled from programming and GIS tools directly over the Internet, using a range of technologies collectively known as Application Programming Interfaces, or APIs. A data API simply provides a protocol by which a dataset can be called by a program over the internet, often allowing for specification of parameters such as the date, bounding box (selected areal unit), or variable required, enabling the program to access specific subsets as and when required. APIs are increasingly standardised and supported by GIS software products, for example, the Web Map Service (WMS) standard, which is used to deliver tiled map images over the web, that is, a map in which each region is represented by a single tile of the same shape and size.

Other standards, such as Web Feature Service for point-, line- or polygon-based spatial datasets, and Web Coverage Service for grid-based (raster) datasets, enable access to the data themselves. The OpenDAP (Open-source Project for a Network Data Access Protocol) is widely used in Earth Sciences for delivering data over the web, particularly for gridded time series formats, and is often implemented by climate data centres. Many programming tools can readily access OpenDAP APIs, making access to a wide range of datasets from data centres all over the world relatively simple for users with knowledge of these tools.

Such tools, however, do not reduce the volume of data required for analysis, and many analyses simply require too much data to be transferred over the Internet to be feasible. In this case, where computer-processing power is sufficient, downloading entire datasets for local analysis may be the most suitable approach. For large-scale analyses with huge datasets, for example, the calculation of drought indices from long periods of high-resolution precipitation data, a new paradigm is emerging. Data centres and cloud-based computing platforms are increasingly providing services for analysing large datasets close to where the datasets are held. Google Earth Engine is an example of such a service for Earth Observation data analysis.

4.4.3.3 Spatial data sharing, integration and dissemination

As discussed, advances in technology have enabled data sharing across the internet to become common practice. Many data providers are able to host spatial (and non-spatial) data services to deliver outputs to data users, including drought and low flow data. Standards such as the Web Map Services described above are enabling seamless use of data across the web. Within hydrology, standards such as WaterML2 (URL 4.28) have made progress in enabling sharing of river flow time series data between organisations, and other innovations (such as the WMO Hydrological Observing System) are pointing the way toward a joined-up web of hydrological datasets. The increased availability of web-based datasets and technologies for creating data services has led to a proliferation of applications in all aspects of hydrology.

Organisations monitoring drought, whether through meteorological and hydrological observations, the production of drought indices, or the collation of information on drought impacts, are now increasingly able to disseminate drought information online, often in near real time. In addition to simply providing access to information, many organisations are providing tools for interacting with drought data, producing visualisations, data explorers and decision support dashboards. The US Drought Monitoring Centre (NDMC, URL 4.29) allows users to view national-scale maps of drought intensity and drill-down to county level metrics (Section 13.3.3). The Australian Government National Drought Map (URL 4.30) allows map-based visualisations integrating physiographic data (e.g., land cover) with monitored meteorological information and multi-sectoral drought impacts. The UK Water Resources Portal (UKCEH, URL 4.31, Fig. 4.10) allows users to explore near-real time precipitation, river flows, soil moisture and groundwater level observations and transform these into drought indices providing longer-term contextual information to drought events.

Tools such as these are enabling the ever-increasing volume of environmental data to be synthesised and delivered to improve the understanding of drought for experts and the public alike.

4.5 Example datasets

This section describes several datasets that are used in a number of the following chapters to illustrate methodologies and approaches presented. The International Dataset (Section 4.5.1) is a collation of flow time series from across the world reflecting different climatic and physiographic conditions. Some of these time series are affected by human interventions. The International Dataset is used for several worked examples in Chapters 5, 6, 7 and 10. Section 4.5.2 presents the Regional Dataset of Eastern Austria. The regional dataset contains data from 30 catchments that are located in four different geological settings. The dataset is used for worked examples in Chapters 5 and 8. Two local datasets are introduced in Section 4.5.3, i.e., the Upper-Guadiana catchment (Spain) and the Stonor Park well (UK). Time series of groundwater levels are provided in both datasets. In addition, time series of flow data are available at the outlet of the Upper-Guadiana catchment and catchment-averaged precipitation and potential evapotranspiration. Upper-Guadiana data are used in Chapter 10, whereas the groundwater data from the Stonor Park well are used in Chapters 3 and 5. All datasets are online available (https://github.com/HydroDrought/hydrodroughtBook).

4.5.1 International Dataset

The International Dataset comprises long-term daily river flow data from many gauging stations around the world. It demonstrates the large variability of hydrological regimes globally (Section 2.2.2) and gives an opportunity for the reader to practice low flow and drought analyses on information that is, quite literally, foreign to any he or she may have encountered before. As such, the reader will be exposed to the challenges of hydrological analysis and the applicability (or limitations) of certain methods, with data from different regions.

The flow records were selected to typify some of the key regime types that are found in different parts of the world. The list of selected catchments, shown in Table 4.1, is by no means exhaustive because the range of possibilities is vast. Nevertheless, as can be seen in Fig. 4.13, the International Dataset comprises data from catchments in both the Northern and the Southern Hemisphere. There are catchments from cold regions (e.g., Breelvi, Chusovaya) and tropical regions (e.g., Honokohau), others from moist, temperate regions (e.g., Huruni, Bagamati) and some from dry, arid (e.g., Dawib) and semi-arid regions (e.g., Arroyo Seco, Pecos, Sabar). Analysis of these data shows that low flow and drought occur at different times of the year and with varying intensity all over the world (Section 5.3). Processes other than climate also affect the low flow and hydrological drought. The soil and hydrogeological conditions of a catchment (Sections 3.3 and 3.4) and the degree of human intervention (Section 10.5) modulate river response, especially during periods of low flow. To illustrate this, data from three contrasting catchments, that is, Lambourn (permeable), Ray (impermeable) and Lindenborg (mixed) in northern Europe are included in the dataset. Three catchments are affected by human intervention (Göta River, Upper-Guadiana River and Sächsische Saale) to offer the reader the opportunity to investigate human-modified drought (Sections 10.4 and 10.5) or non-stationarity (Section 6.5.4). The dataset also contains a large river (Rhine), whose catchment comprises a variety of climatic (cold, humid and temperate) and physiographical features (e.g., mountains, lowlands). Some catchments have time series of 100 years of data or more (Göta älv, Lågen, Arroyo Seco and the Rhine River) to enable analysis of changes and trends over time.

The river flow data for the International Dataset were collated from a number of disparate sources. Most of the earlier data (until 1990s to 2003) were provided from:

(a) databases of the UNESCO regional FRIEND-Water (Flow Regimes from International Experimental and Network Data) projects of northern Europe (URL 4.15), southern Africa and the Hindu Kush-Himalaya (Gustard and Cole, 2002)

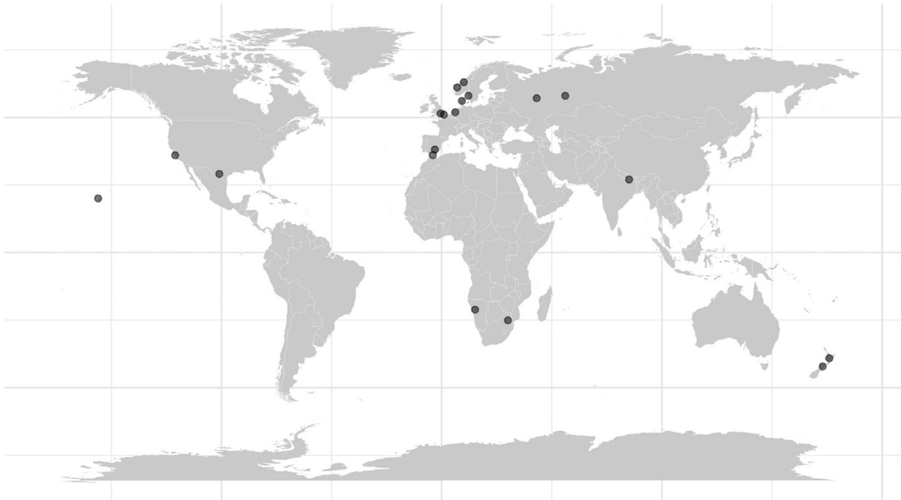

FIGURE 4.13

Location of the selected catchments in the International Dataset.

Table 4.1 Summary of the International Dataset.

Country	River	Site	Period of record		Catchment area (km^2)	Station altitude (m aSL)	Mean flow ($m^3\ s^{-1}$)	Basis of selection
			Start	End				
Denmark	Lindenborg	Lindenborg Bro	1925	2018	214	5	2.39	Northern European catchment having mixed response to rainfall; flow is affected by vegetation during summer, which is cut several times.
Spain	Sabar	Alfartanejo	1963	1993	39	n/a[a]	0.19	Southern European river, having zero flows that persist for months at a time
Spain	Upper Guadiana	Site 4008	1957	2001	18,816	558	9.87	Heavily exploited catchment in southern Europe
Namibia	Dawib	Dawib	1978	1993	560	n/a[a]	0.02	Ephemeral stream in southern Africa where zero flows predominate
The Netherlands	Rhine	Lobith	1901	2019	160,800	9	2209.91	Large catchment in western Europe featuring many climate types
Norway	Breelvi	Nigards-brevatn	1962	2017	65	285	6.40	Snow and glacier (73%) influenced catchment in northern Europe
Norway	Lågen	Rosten	1917	2017	1833	320	32.44	Snow-affected, northern European river with distinct winter low flow
Nepal	Bagamati	Sundurijal	1970	1995	17	1600	1.04	South Asian, rain-fed catchment having a monsoon dominated regime
New Zealand	Ngaruroro	Kuripapango	1963	2019	370	n/a	17.37	Southern Hemisphere river, temperate regime with no distinct dry season
New Zealand	Hurunui	Mandamus	1956	2019	1060	n/a	52.28	Southern Hemisphere river, temperate regime with no distinct dry season
Russia	Chusovaya	Liamino	1956	2002	21,500	n/a[a]	224.45	Continental, East European river with low flow in summer and winter, runoff regime is supposed to be natural

Russia	Unzha	Makariev	1936	2010	18,500	n/a[a]	175,45	Continental, East European river with low flow in summer and winter
South Africa	Elands	Elands River Drift	1963	1992	690	n/a[a]	3.10	Perennial river in southern Africa, having distinctly seasonal regime
United Kingdom	Ray	Grendon Underwood	1962	2018	19	66	0.10	Impermeable upland catchment in northern Europe
United Kingdom	Lambourn	Shaw	1962	2020	234	76	1.75	Permeable lowland catchment in northern Europe
United States of America	Pecos	Girvin	1940	2019	76,560	692	1.58	River in arid part of North America having Rocky mountains tributaries
United States of America	Arroyo Seco	Soledad	1902	2019	632	103	4.62	Catchment in semi-arid part of North America having 10% of time zero flows
United States of America	Honokohau	Maui, Hawaii	1922	2019	11	265	1.07	Tropical island regime with no dry season
Sweden	Gőta älv	Vargöns krv	1850	2018	46,886	44	528	Scandinavian river; strongly affected by dam construction in 1937
Germany	Sächsische Saale	Hof	1921	2011	522	467	5.39	Non-stationary time series: change of low flow likely to be connected to the implementation of the Förmitz barrage in 1978.

[a]n/a, *not available.*

(b) the web, in particular data from the United States of America
(c) directly from national hydrometric agencies (e.g., United Kingdom, Spain, New Zealand).

Update of the river flow data (some up to 2019) came from similar sources. Updated flow data from United States of America and Spain came from the web (URLs 4.32 and 4.33, respectively). Although only records of reasonably good quality were selected, the data are real, and, as would be expected in reality, does feature errors, missing values and some imperfections. No attempt has been made to correct the data, as it was considered that exposure to such problems would be of benefit to the reader. One can find more time series of observed flow data in, for example, the GRDC database (Section 4.4.2.2).

4.5.2 Regional Dataset of Eastern Austria

Throughout the book, a series of drought studies refer to a nation-wide Austrain dataset, comprising 325 gauged catchments. A subset of 30 stations situated in Eastern Austria, referred to as the 'Regional Dataset of Eastern Austria' is used in worked examples in Chapters 5 and 8. It comprises catchments situated in the federal states Lower Austria, Burgenland and Styria (Fig. 4.14).

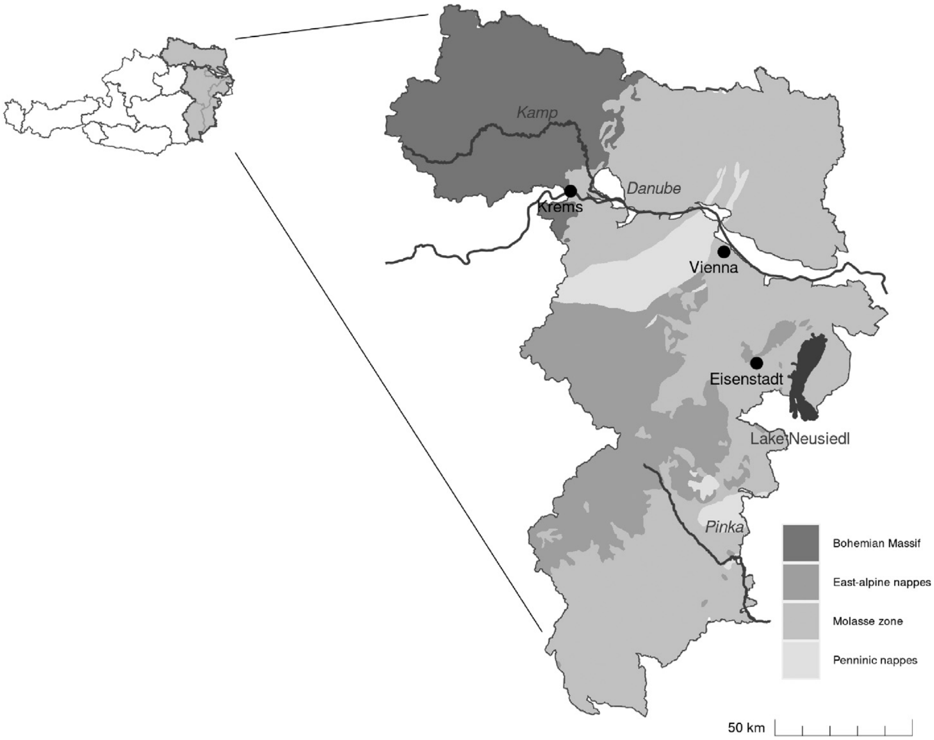

FIGURE 4.14

Map of Austria with details of the Eastern Austria region with its main geological units.

The region is hydrologically more homogeneous than the whole of Austria, but still encompasses several landscape types and exhibits a wide range of morphometric, hydrogeological, soil and land use features.

The eastern part of the study area belongs to the Molasse zone. It is composed of lowland plains and tectonic, sediment-filled burial basins (such as the Vienna Basin and the Pannonian Basin) in combination with hilly terrain. The catchments are typically composed of Tertiary and Quaternary sediments, often in combination with a shallow or deep aquifer. In the western part, low mountain ranges are found. These include the highlands of the Bohemian Massif made of crystalline rock north of the River Danube, the Pennine ranges of Flysch in the centre and the Eastern-alpine ranges of limestone and crystalline rock in the south. Catchment altitude ranges from 159 in the east to almost 2000 m aSL in the west. The lowest part is the region around Lake Neusiedl, which is mainly fed by precipitation and to a lesser extent by small streams. The lake is endorheic, so it has no outflow to other water bodies. The rest of the region drains to the Danube, but for the rivers south of Lake Neusiedl, the mouth lies outside the study area. Agriculture is the predominant land use of the region, followed by forests in the low mountain ranges.

Eastern Austria has a continental, cold climate with warm summers and no dry season (Dfb, Fig. 2.2) and is one of the warmest and driest regions within Austria. The low annual precipitation (800 to less than 600 mm) combined with long, warm summers, high sunshine duration and strong wind exposure, make the study area one of the most drought-prone regions in Austria. Consequently, the rivers exhibit pronounced summer low flow regimes. Low flow typically occurs between July and October and is triggered by persistent dry weather with evaporation exceeding precipitation. Because of a relatively low altitude and low winter precipitation, snow storage and freezing processes have a subordinate influence on the low flow regime.

The Regional Dataset of Eastern Austria consists of several elements with different type of information. The first, ‘Austria_30.txt’, is a multivariate dataset containing catchment information of 30 sub-catchments (sub-catchments refer here to the area between gauges along the river network) and headwater catchments. In addition to annual and seasonal low flow indices, it also contains 31 climate and catchment descriptors (Table 4.2). These descriptors relate to seven categories representing sub-catchment area (A), topographic elevation (H), topographic slope (S), precipitation (P), geology (G), land use (L) and stream network density (D). Each group is further subdivided into classes as indicated by a subscript.

For geostatistical models, so-called shapefiles are used containing the (overlapping) catchment polygons (areas) of the entire catchments, together with an attribute table containing their low flow indices and other catchment information. The geospatial data are provided by two files. The first file, named ‘File1.shp’, contains time series of river flow for the 30 observed sub-catchments. Corresponding low flow indices and climate and catchment descriptors are summarised in Table 4.2. The second file, named ‘File2.shp’, contains a wider dataset (403 target catchments, incl. observed catchments), which is used in Section 8.5.2 for performing low flow estimation at ungauged sites by top-kriging (Worked Example 8.2). Low flow indices derived from observed time series of river flow are in Section 5.9 used to study the relationship (correlation) between indices (Worked Example 5.8).

Table 4.2 Climate and catchment descriptors of Regional Dataset of Eastern Austria. Summary statistics refer to the 30 gauged sub-catchments contained in the 'Austria_30.txt' dataset.

Category	Acronym	Descriptor	Unit	Min.	Mean	Max.
Low flow indices						
	q_{95}	Specific low flow	$l\ s^{-1}\ km^{-2}$	0.09	1.36	4.08
	q_{95s}	Specific summer low flow	$l\ s^{-1}\ km^{-2}$	0.33	1.20	4.32
	q_{95w}	Specific winter low flow	$l\ s^{-1}\ km^{-2}$	0.12	1.69	5.40
Catchment area (*A*)						
	A	Sub-catchment area	$10^1\ km^2$	6.15	18.93	51.49
Catchment elevation (*H*)						
	H_0	Altitude of stream gauge	10^2 m	1.59	2.76	5.33
	H_+	Maximum altitude	10^2 m	2.98	6.57	12.35
	H_r	Range of altitude	10^2 m	1.1	3.81	9.73
	H_m	Mean altitude	10^2 m	2.32	4.11	6.27
Catchment slope (*S*)						
	S_m	Mean slope	%	2.8	6.47	13.20
	S_{sl}	Slight slope	%	23.7	74.9	99.40
	S_{mo}	Moderate slope	%	0.6	24.99	76.00
	S_{st}	Steep slope	%	0	0.11	2.40
Precipitation (*P*)						
	P	Average annual precipitation	10^2 mm	4.67	6.47	7.99
	P_s	Average summer precipitation	10^2 mm	3.03	4.25	5.29
	P_w	Average winter precipitation	10^2 mm	1.55	2.22	2.79
Geology (*G*)						
	G_b	Bohemian Massif	%	0	16.22	100.00
	G_q	Quaternary sediments	%	0	6.49	30.40
	G_t	Tertiary sediments	%	0	47	97.30
	G_f	Flysch	%	0	3.65	35.40
	G_l	Limestone	%	0	4.02	63.20
	G_c	Crystalline rock	%	0	9.91	70.10
	G_{gs}	Shallow groundwater table	%	0	8.99	48.00
	G_{gd}	Deep groundwater table	%	0	3.57	40.00
	G_{so}	Source region	%	0	0.17	5.00

Table 4.2 Climate and catchment descriptors of Regional Dataset of Eastern Austria. Summary statistics refer to the 30 gauged sub-catchments contained in the 'Austria_30.txt' dataset.—cont'd

Category	Acronym	Descriptor	Unit	Min.	Mean	Max.
Land use (L)						
	L_u	Urban	%	0	1.1	7.80
	L_a	Agriculture	%	16.2	54.01	89.30
	L_c	Permanent crop	%	0	1.22	20.30
	L_g	Grassland	%	0	4.41	19.00
	L_f	Forest	%	5.5	39.16	68.70
	L_r	Wasteland (rocks)	%	0	0.02	0.20
	L_w[a]	Wetland[a]	%	0	0	0
	L_{wa}	Water surfaces	%	0	0.08	1.00
	L_{gl}[a]	Glacier[a]	%	0	0	0
Stream network (D)						
	D	Stream network density	10^2 m km^{-2}	3.57	8.07	10.63

[a]*Variable not contained in the Regional Dataset of Eastern Austria, as it is always zero for the study area.*

4.5.3 Local datasets

4.5.3.1 Upper-Guadiana catchment (Spain)

The Upper-Guadiana catchment is located in central Spain, south of Madrid (Fig. 4.15). It covers an area of 16,130 km^2. The catchment has a semi-arid climate (Csa, Csb and Bsk, Fig. 2.2) with a mean annual precipitation varying from 350 mm yr^{-1} in the centre to 580 mm yr^{-1} in the southeast. Peak rainfall occurs in spring and the driest period is towards the end of the summer, leading to a strong seasonality in river flow. Variation in precipitation between years is large. The mean annual temperature is 14.1°C with a winter mean of 5°C and a summer mean of 25°C. Mean potential evapotranspiration is 1250 mm yr^{-1} and clearly exceeds mean precipitation of 450 mm yr^{-1}, resulting in a relatively low mean discharge of 16 mm yr^{-1} (Van Loon and Van Lanen, 2013). Highest river flow occurs in winter, and the dominating low flow season is summer.

Catchment altitude varies between 600 and 1100 m aSL. The central part (Mancha Occidental region, Fig. 4.16a) is relatively flat and relatively low lying, whereas the southern region (La Campo de Montiel) and the northwest region (Sierra de Altomira) are elevated. In the catchment, five hydrogeological units can be found (Fig. 4.16a). The Mancha Occidental hydrogeological unit (H.U. 04.04) and the Campo, the Montiel unit (U.H. 04.06), are the two most important aquifers. The Mancha Occidental is the aquifer with the highest transmissivity. Groundwater is a key resource in the Upper-Guadiana and is mainly abstracted from the Mancha Occidental aquifer. This has led to deep water tables, and all groundwater and surface water from neighbouring aquifers and regions disappear at the interface of the aquifers into the Mancha Occidental. In the middle of the Mancha Occidental, groundwater used to surface into the Ojos del Guadiana before major abstractions started in 1970s

FIGURE 4.15

Location (*marked in red*) of the Lower Guadiana catchment (LG, Spain and Portugal) and the Upper-Guadiana catchment (UG, Spain).

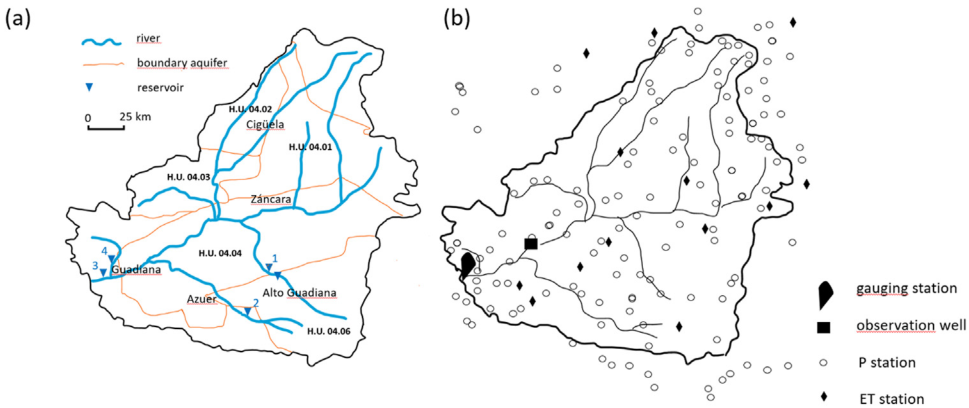

FIGURE 4.16

Upper-Guadiana catchment: (a) hydrogeological units, main rivers and reservoirs, and (b) location of the flow gauging station, groundwater observation well, precipitation (*P*) stations and evaporation (*E*) stations in and near the catchment. Hydrogeological units (Fig. 4.16a): H.U. 04.01 Sierra de Altomira, H.U. 04.02 Lilo-Quintanar, H.U. 04.03 Consuegra-Villacañas, H.U. 04.04 Mancha Occidental, and H.U. 04.06 Campo de Montiel. Reservors (Fig. 4.16a): 1 Peñarroya, 2 Vallehermoso, 3 El Vicario, and 4 Gasset.

(Van Loon and Van Lanen, 2013). The presence of these aquifer systems makes Upper-Guadiana a slowly responding catchment (Van Loon and Van Lanen, 2012).

The main rivers discharging into the Mancha depression are the Cigüela, Záncara, Azuer and Alto Guadiana River (Fig. 4.16a). The Cigüela and Záncara Rivers and their tributaries are draining the Sierra de Altomira region (H.U. 04.01) and the Rivers Azuer and Alto Guadiana (High Guadiana) drain the Campo de Montiel aquifer (H.U. 04.06).

Some rather small-scale reservoirs can be found in the Upper-Guadiana catchment. Since 1959, the discharge from the Campo de Montiel aquifer has been collected in the Peñarroya reservoir (reservoir 1, Fig. 4.16a), and is used for irrigation in the Mancha depression. In the Azuer River, the Vallehermoso reservoir (constructed in 1988, reservoir 2, Fig. 4.16a), is used for water supply. Downstream in the Guadiana River, one find the El Vicario reservoir (constructed in 1973, reservoir 3, Fig. 4.16a) and the Gasset reservoir (constructed in 1909¸ reservoir 2, Fig. 4.16a), both located in a tributary of the Guadiana River. The El Vicario reservoir is used for irrigation purposes and water from the Gasset reservoir is used for both irrigation and water supply of the city Ciudad Real (Fig. 4.15). The El Vicario and Gasset reservoirs provide an artificial stable minimum flow in the Guadiana River. The reservoirs simply act as additional (surface water) storage. Their influence can be regarded similar to natural stores in the catchment, that is, aquifers and wetlands.

Until about 1970, the Castilla-La Mancha region, in which the Upper-Guadiana catchment is located, was a typical agricultural region with mainly dryland farming and some small-scale irrigation. This changed in the 1970s when new irrigation cropping systems were introduced. Annual groundwater abstraction substantially increased up to 10 times in 1988 relative to the pre-1970 volume, which led to severe over-exploitation of groundwater resources. Groundwater levels showed a significant decline. In the Mancha Occidental aquifer, the average regional drawdown of the water table was 22 m, with a maximum of over 50 m (Martínez-Santos and Martínez-Alfaro, 2010). This drawdown resulted in a total disconnection of groundwater and surface water by the early 1980s and therefore declining wetland area, decreasing discharge, changes in water quality, decreasing evapotranspiration, and spontaneous combustion of peatlands. In the 1990s, there was a large shift in agriculture practise that required less irrigation, although it was still higher than the historical abstracted volumes. The hydrological situation before 1980 is regarded as 'undisturbed' and provides a benchmark situation for simulations of near-natural conditions. In the 1970s, the hydrological system became severely disturbed by groundwater pumping. The effect depended on the location and type of variable investigated. The period following is called the 'disturbed period' (Van Loon and Van Lanen, 2013).

Observed hydrological data of the Upper-Guadiana catchment consist of discharge and groundwater level. Daily discharge is measured at the outlet of the catchment (Fig. 4.16b, gauging station Balbuena, station no. 4008). Groundwater level is measured at a number of locations in the catchment. Data from one representative groundwater measurement station (Fig. 4.16b, station no. 1929 70002) are selected for illustration purpose. The station measures groundwater levels in the Mancha Occidental aquifer. Monthly observed groundwater levels are available for the period 1973–97. This groundwater observation station was chosen because it has a long and relatively continuous hydrograph, although it has not the largest drawdown.

Observed discharge and groundwater level data from the Upper-Guadiana catchment and the outcome from lumped process-based model HBV ('undisturbed' time series) are used in Worked Example 10.1 to quantify the effect of groundwater abstraction after 1980. Drought characteristics for the observed (disturbed) and simulated (undisturbed) can then be compared. The HBV model (Section 9.3.2) that simulated the 'undisturbed' time series needs as input daily catchment-averaged observed temperature and precipitation, and potential evapotranspiration. These data were taken from precipitation and climate stations within and surrounding the Upper-Guadiana catchment (Fig. 4.16b) (Veenstra, 2009; Van Loon and Van Lanen, 2013). Potential evapotranspiration was calculated using the FAO Penman-Monteith method. All time series of meteorological data used in Worked Example 10.1 are online (https://github.com/HydroDrought/hydrodroughtBook) available on a daily timescale. The same holds for the time series of discharge at the outlet and monthly aggregated groundwater levels of the selected well (Fig. 4.16b).

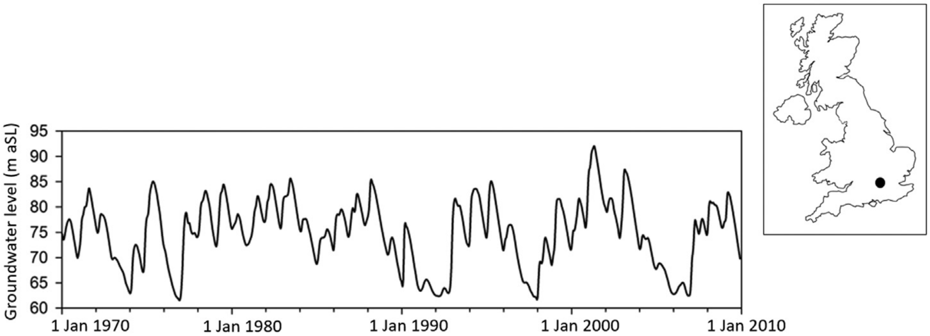

FIGURE 4.17

Monthly groundwater levels observed in the Stonor Park well, UK (*location marked black insert on the map*).

Source: British Geological Survey (URL 4.34).

4.5.3.2 The Stonor Park well, Henley on Thames (UK)

The Stonor Park well (SU78/45A) measures groundwater level in the Chalk aquifer above Henley on Thames, northwest of Reading (UK) (Fig. 4.17). The observation well is located in a temperate oceanic climate with no dry season and a warm summer (Cfb, Fig. 2.2). It monitors the water level in the Berkshire Downs Chalk (Cretaceous), which is an unconfined aquifer. On top of the chalk, predominantly permeable deposits lie consisting of a complex of vertically and laterally varying gravel, sand, silt and clay (Lambeth Group, Lower Eocene). Fig. 4.17 shows the observed groundwater levels for the period 1970—2010. The well it is often labelled as a 'typical' chalk observation well (URL 4.34), given the absence of major abstractions in its neighbourhood. The top of the well is at 121 m aSL and the bottom is at 87.5 m depth, which means that the well can capture the aquifer's full range of fluctuation, although there may be a slow drop because of lower permeability at the bottom of the well. The groundwater level varies between about 60 and 90 m aSL. The groundwater hydrograph shows long multi-year dry periods. The observed time series is used in Section 3.4.1 to illustrate drought-generating processes and in Section 5.5.2 to derive the Standardised Groundwater Index (Worked Example 5.7).

4.6 Summary

This chapter has provided an overview of the hydrological data that are typically used in low flow and hydrological drought analysis. Section 4.1 introduced the subject with an overview of the different uses of hydrological data, including operational and academic applications. A classification of data was given in Section 4.2, with three generic types described: time series data, spatial data and metadata. In Section 4.3, information was provided on the collection and processing of river flow data and groundwater data. Hydrometric practices were outlined, with details given on the types of gauging stations, methods of the measurement of stage (water level) and the derivation of the stage-discharge relation. Methods of obtaining groundwater data were then described, including manual and automatic measurement of groundwater levels and the monitoring of groundwater discharge. Supporting hydrometeorological data were covered, focusing on precipitation, evaporation and soil moisture, before human interventions were considered. Issues of data quality control and management were addressed at the end of the section by firstly describing errors as being random, spurious or systematic, then considering good practice, methods of data validation, approaches to the hydrological validation of data and techniques for dealing with missing data. Further detailed information was given in Section 4.4 on the spatial data that are typically available for hydrological studies at global, regional and local scales, with advice given on potential data sources and the types of data that can be obtained or derived. Section 4.5 described the example datasets available on Github (International, Regional and Local), which enables the reader to work through the Worked Examples of subsequent chapters.

4.7 Further reading

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