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Review

Low flow hydrology: a review

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Abstract

The paper intends to review the current status of low-flow hydrology — a discipline which deals with minimum flow in a river during the dry periods of the year. The discussion starts with the analysis of low-flow generating mechanisms operating in natural conditions and the description of anthropogenic factors which directly or indirectly affect low flows. This is followed by the review of existing methods of low-flow estimation from streamflow time-series, which include flow duration curves, frequency analysis of extreme low-flow events and continuous low-flow intervals, baseflow separation and characterisation of streamflow recessions. The paper describes the variety of low-flow characteristics (indices) and their applications. A separate section illustrates the relationships between low-flow characteristics. The paper further focuses on the techniques for low-flow estimation in ungauged river catchments, which include a regional regression approach, graphical representation of low-flow characteristics, construction of regional curves for low-flow prediction and application of time-series simulation methods. The paper presents a summary of recent international low-flow related research initiatives. Specific applications of low-flow data in river ecology studies and environmental flow management as well as the problem of changing minimum river flows as the result of climate variability are also discussed. The review is largely based on the research results reported during the last twenty years. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

A discussion of low-flow hydrology and related issues should ideally begin with a definition of what ‘low flow’ really is. This term could mean different things to different interest groups. To many it may be considered as the actual flows in a river occurring during the dry season of the year, others may be concerned with the length of time and the conditions occurring between flood events (e.g. in erratic and intermittent semi-arid flow regimes). Yet others may be interested in the effects of changes in the total flow regime of a river on sustainable water yield or riverine and riparian ecology. The latter may perceive ‘low flows’ not only as discharges occurring during a dry season, but as a reduction in various aspects of the overall flow regime.

International glossary of hydrology (WMO, 1974) defines low flow as ‘flow of water in a stream during prolonged dry weather’. This definition does not make a clear distinction between low flows and droughts. Low flows is a seasonal phenomenon, and an integral component of a flow regime of any river. Drought, on the other hand, is a natural event resulting from a less than normal precipitation for an extended period of time. Several types of droughts may be defined: meteorological, atmospheric, agricultural, hydrological and water management (Dracup et al., 1980; Rogers and Armbruster, 1990; Bogardy et al., 1994; Rao and Voeller, 1997).

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Hydrological droughts characterized by the reduction in lake storage, lowering of groundwater levels and decrease of streamflow discharge may occur over one year or over several consecutive years, and often affect large areas. Climate fluctuations is therefore the underlying natural physical factor in determining the severity of a drought but human activity can also contribute to it. Drought is normally connected with resource implications of water availability and may be defined in terms of the various uses for streamflow and the sum of the minimum low flow requirements for each (Aron and Emmanuel, 1982). Drought is therefore a more general phenomenon, and may be characterized by more factors than by just low streamflows. Droughts include low-flow periods, but a continuous seasonal low-flow event does not necessarily constitute a drought, although some researchers refer to a continuous low-flow period in one year as an annual drought (e.g. Zelenhasic and Salvai, 1987; Clausen and Pearson, 1995; Tallaksen et al., 1997).

The literature on drought analysis and management deserves a special attention and is only marginally referred to in this review. The discussion in the paper is confined mostly to the processes operating during the dry season and the techniques to quantify the various aspects of the cumulative output of these processes—the low-flow part of a continuous streamflow hydrograph.

Low flows are normally derived from groundwater discharge or surface discharge from lakes, marshes, or melting glaciers. Lowest annual flow usually occurs in the same season each year. The magnitudes of annual low flows, variability of flows and the rate of streamflow depletion in the absence of rain, duration of continuous low-flow events, relative contribution of low flows to the total streamfow hydrograph are a few of the widely used characteristics which are dealt with in low-flow hydrology in a variety of ways. Those effectively constitute the ‘temporal’ component of low-flow hydrology and require continuous streamflow time series for the analysis. ‘Spatial’ component deals with the regional distribution of low-flow characteristics and attempts to estimate these characteristics in the catchments where no observed records are available. Both components of low-flow hydrology are closely related and require understanding and consideration of physiographic factors, which affect low flows (climate, topography, geology, soils, etc.), as well as various man-induced effects. Knowledge of the magnitude and frequency of low flows for streams is important for water-supply planning and design, waste-load allocation, reservoir storage design, and maintenance of quantity and quality of water for irrigation, recreation, and wildlife conservation.

Low-flow hydrology is therefore characterised by a diversity of interrelated topics. Some previous general reviews of the subject, and studies which demonstrate that low-flow hydrology is as a multifacet and dynamic discipline with distinct physiographic basis and clear engineering applications, include Riggs (1972), McMahon (1976) and Beran and Gustard (1977). These sources covered a variety of issues including the description of existing techniques of low-flow analysis from flow records (flow duration analysis, low-flow frequency analysis, analysis of flow recessions, and storage-yield analysis), areas of application of these techniques, low-flow forecasting, principles and uses of regional low-flow analysis. McMahon and Arenas (1982) presented a compilation of methods used in different countries to compute low-flow characteristics, illustrated some of these methods with case studies and addressed some theoretical aspects of natural and man-induced factors affecting low flows. Specific aspects of low-flow analysis, management and related topics (often including comprehensive literature review) were examined by Searcy (1959), Hall (1968), Riggs (1976), Vasak (1977), Kurdov (1977), Characteristics of low flows (1980), McMahon and Mein (1986), Gustard (1989), Ponce and Lindquist (1990), Amusja et al., (1991), Heicher (1993), Demuth (1994), Tallaksen (1995) and Vogel and Fennessey (1995).

The purpose of this paper is to look at the subject of low-flow hydrology in a balanced and systematic way, to provide a recent documentation on the subject, to examine the dynamics of its physical and numerical concepts and to trace the most recent trends in low-flow related research including the emerging interactions of low-flow hydrology with other water related fields (e.g. stream environmental management). To achieve this, the paper examines the variety of recent literature sources published primarily during the last two decades.

2. Natural processes and driving forces of low-flow hydrology

A flow in a river is the result of the complex natural processes, which operate on a catchment scale. Conceptually, a river catchment can be perceived as a series of interlinked reservoirs, each of which has components of recharge, storage and discharge. Recharge to the whole system is largely dependent on precipitation, whereas storage and discharge are complex functions of catchment physiographic characteristics. During a dry season, it is those processes that affect the release of water from storage and the fate of this discharge that are directly relevant. These processes are usually operative in the vicinity of the river channel zones as opposed to the full range of hydrological processes that operate over larger parts of catchments during periods of higher discharge. The latter of course also cannot be ignored as they control the catchments ability to absorb and store water during precipitation events for later release as low flows.

The natural factors which influence the various aspects of the low-flow regime of the river include the distribution and infiltration characteristics of soils, the hydraulic characteristics and extent of the aquifers, the rate, frequency and amount of recharge, the evapotranspiration rates from the basin, distribution of vegetation types, topography and climate. These factors and processes may be grouped into those affecting gains and losses to streamflow during the dry season of the year. Anthropogenic effects on these processes and on the streamflow directly should be considered separately.

2.1. Gains to low-flow discharge

In many cases, the majority of natural gains to streamflow during low-flow periods are derived from releases from groundwater storage. This occurs where stream channels intersect the main phreatic surface in a draining aquifer. For low flows to be sustainable: (i) the draining aquifer must be recharged seasonally with adequate amounts of moisture; (ii) the water table must be shallow enough to be intersected by the stream; and (iii) the aquifer's size and hydraulic properties must be sufficient to maintain flows throughout the dry season. Some authors have illustrated that low flows may similarly be sustained by drainage of a saturated top soil zone (throughflow) rather than by deeper groundwater (Anderson and Burt, 1980).

A different example of groundwater re-emergence can occur where relatively slow moving groundwater drainage in fracture zones above the main water table has a significant lateral component which intersects the ground surface in the vicinity of channels (springs). This is most likely to occur in steeply sloping terrain and can account for prolonged baseflows following rainfall events in semi-arid areas even when the water table is well below the level of stream channels. Rates of such outflow will depend upon the fracture size and density as well as the relative importance of the lateral drainage component compared to the vertical component, which recharges the 'true' groundwater storage.

Gains to low flows can also be derived from the drainage of near surface valley bottom (or near channel) storages such as more permanently wetted channel bank soils, alluvial valley fills and wetland areas. These are areas where water becomes concentrated during and soon after precipitation events and therefore where adequate levels of storage are maintained during the dry season to ensure uninterrupted lateral drainage into channels. The water contained within these soil and alluvial storages is, strictly speaking, not the actual 'groundwater'. A distinction should be made between this source and the 'true' groundwater body which exists below the phreatic surface. It is of course possible for these two water storages to be in direct hydraulic connection, as would be the case where the phreatic surface intersects the ground surface. The distinction is then more difficult to define. However, it is not the case for most of the time (e.g. in many of the semi-arid environments) and water in these sources should possibly be referred to as 'perched' groundwater storage, alluvial water storage or channel bank water storage.

It is clear from the above, that low-flow generating mechanisms are significantly affected by catchment geology. A number of studies reported direct relationships between the geologic rock categories and discharge rate during low-flow periods (e.g. Armbruster, 1976; Smith, 1981; Musiake et al., 1984; Bingham, 1986; Aucott et al., 1987; Rogers and Armbruster, 1990). In some of these studies, streams flowing through different types of unconsolidated sedimentary rocks, were found to have normally low yields during the low-flow period. On the contrary, streams flowing through metamorphosed sedimentary and igneous rock showed markedly high flow values relative to their basin size. Whitehouse et al. (1983) illustrated the effects of differences in regolith thickness on low-flows. The role of the stratified drift as a dominant geologic structure in the generation of low-flows has been discussed by Cervione et al., (1982), Barnes (1986), Morrisey et al., (1988), Ries (1994) and Risle (1994). White (1977) showed that karst, limestone and dolomite rocks have the decreasing effect on low flows. Felton and Currens (1994) performed detailed analysis of high and low flow from a karst spring and provided some bibliography on hydrological processes in karst formations.

Low-flows in rivers may also be maintained by lakes, with which rivers have direct hydraulic connection. The adequate water level in a lake should be maintained during the dry season to allow lateral outflow into a stream. The literature which directly addresses the effects of lakes on low flows is limited, but the importance of lakes for low flows in some regions may be derived from the inclusion of lake related parameters in prediction models for low flows (Gerasimenko, 1972; Vladimirov, 1976; Kuusisto, 1987; FREND, 1989; Sakovich, 1990).

In highly seasonal climates, low flows in different dry seasons (e.g. summer and winter) may be generated by different physical processes. In cold or mountainous regions, in addition to the usual catchment parameters, low flows are subject to the special influences of ice and snow melting (Bowles and Riley, 1976; Gerard, 1981; Collins, 1982; Fountain and Tangborn, 1985; Gurnell, 1993; Hopkinson and Young, 1998). The release of water from glacier storage may greatly affect the local hydrological cycle by contributing to streamflow in otherwise low-flow periods. The principal influence of glaciers in the context of low flows is similar to that of lakes and includes a decrease in runoff variation and, consequently, more sustained low flows.

2.2. Losses to low-flow discharge

In many respects the processes involved in causing streamflow losses are the reverse of those causing gains with the addition of direct evaporation from channel water bodies. Losses to streamflow during dry weather periods may be caused by: (i) direct evaporation from standing or flowing water in a channel, other open water bodies and wetlands; (ii) evaporation and transpiration losses from seepage areas, where groundwater or channel bank soil water is draining into the channel; (iii) groundwater recharge from streamflow where the phreatic surface lies below the channel (river channels often follow lines of structural weakness and surface fracturing, offering an ideal opportunity for infiltration into the channel bed); (iv) bed losses, where unconsolidated alluvial material underlies the river channel (these losses can be substantial not only during low flows but also during the early stages of flood events); and (v) losses to relatively dry soils forming the banks of streams (these may be enhanced by the presence of dense riparian vegetation promoting evapotranspiration).

These processes are often referred to as ‘transmission losses’ or ‘river losses’. The relative importance of transmission losses within the various regions is largely unknown. Localised information from a few well-studied catchments is available (Cornish, 1961; Sharp and Saxton, 1962; Jordan, 1977; Lane et al., 1980; Morrisey et al., 1988; Walters, 1990; Hughes and Sami, 1992; Abdulrazzak and Sorman, 1994; McKenzie and Roth, 1994; McKenzie and Craig, 1998; Shentsis et al., 1998), but a more generalised and widespread impression is currently lacking.

A different source of low-flow losses, which operates in cold regions, is the permafrost. The physical side of the problem of low-flow generation in permafrost regions (including losses from drained aquifers on ice formation, phase changes of permafrost moisture) is not well understood and quantified. For large territories in high latitudes, low flows generally decrease with increasing latitude and distance from the moderating effects of the oceans (Janowicz, 1990). This trend is largely controlled by the distribution of permafrost which influences groundwater contributions to winter streamflow.

In cold regions, rivers often have their lowest flows in winter due to temporary storage of precipitation as snow. They might also have two distinct low-flow seasons (in winter and summer), however, controlled by different processes. Winter streamflow is often less than river recharge from an aquifer. The difference may be attributed to the flow losses for ice cover formation in rivers (e.g. Kravchenko and Chernykh, 1985). In permafrost zone, these losses may reach the level of 20–30 to 1000% of measured winter flow (Sokolov and Chernaja, 1984; Kravchenko, 1986).

The relevance of different 'gain' and 'loss' processes to the wide variety of climatic, topographic and geological conditions that exist naturally is difficult to determine. The literature which specifically relates to experimental studies of various low-flow generating mechanisms is rather limited. At the same time, identification of relative importance of various low-flow generation mechanisms and factors should ideally precede any low-flow analysis and also form an integral part of developing plans of catchment management.

3. Anthropogenic impacts on low flows

3.1. Impacts on low-flow generating processes

Natural gains and losses to low flows are both affected by various anthropogenic impacts which normally include:

- Groundwater abstraction within the sub-surface drainage area. This clearly affects the level of phreatic surfaces and therefore the potential for groundwater re-emergence in stream channels. Localised reductions in the level of the water table may affect either hydraulic gradients or the length of channel that intersects the phreatic surface. The effects of groundwater pumping near the head of a perennial river may result in groundwater table depletion through interception of recharge water and induced recharge of the aquifer from the river itself. This results in substantial environmental degradation of the river habitats, loss of naturally sustained fisheries, reductions in the general amenity value of the river. Different effects of groundwater abstractions on low flow are discussed by Owen (1991), Gustard et al., (1992), Bickerton et al., (1993), Clausen et al., (1994) and Fendekova and Nemethy (1994).
- Artificial drainage of valley bottom soils for agricultural or building construction purposes. This can lead to more rapid removal of water from valley bottom storage and a reduction in the sustainability of lateral drainage during dry weather (Riggs, 1976; Schulze, 1979; Smithers and Schulze, 1994).
- Changes to the vegetation regime in valley bottom areas through clearing or planting. They can modify the levels of evapotranspiration loss from riparian soils, thereby affecting gains or losses to bank or alluvial storage (Banks, 1961; Rowe, 1963; Schulze, 1979; Swank et al., 1988; Smith and Bosch, 1989; Keppeler and Ziemer, 1990; Meier et al., 1997; Wilgen et al., 1997).
- Afforestation of a whole catchment or parts thereof. Commercial plantations normally: (i) increase interception loss due to more extensive canopy cover, leaf area density and increased roughness of the surface; (ii) increase transpiration loss due to increased biomass and total leaf area, deep rooting and evergreen nature of commercial timber tree species; (iii) increase disturbance of the soil structure, infiltration and moisture holding capacity due to site preparation. All these effects modify stormflow and low-flow generating mechanisms. Bosch and Hewlett (1982), in their review of 94 catchment experiments, illustrated that afforestation may cause a significant reduction in total flow. Several studies have demonstrated (either by field experiments or by modelling) that afforestation has had a major effect on low flows reducing low-flow volumes to a larger degree than those of annual flow (Banks and Kromhout, 1963; Bosch, 1979; Trimble et al., 1987; Dons, 1986; Gustard and Wesselink, 1993; Tallaksen, 1993). Smith and Scott (1992) used a paired catchment approach to quantify the effects of afforestation with pines and eucalyptus on low flows in five South African catchments. Afforestation was found to have a significant effect on low flows in all catchment experiments, with low flows being reduced by up to 100% in some cases. The effect of afforestation generally appeared to be more marked for eucalypti plantations than for pines, and also depends upon the percentage of area afforested and climatic zone (Scott and Smith, 1997; Scott et al., 1998). Johnson (1998) has recently reviewed the UK and international

studies of forestry effects on low flows and demonstrated how these effects differ at different stages of the forest cycle (pre-planting drainage, forest growth, clearfelling, etc.).

- Deforestation often has a reverse effect on total flow and low flows. It has been demonstrated (e.g. Bosch and Hewlett, 1982), that clearfelling and timber harvesting increase annual water yield, and that in many cases this is due to increase in seasonal low flows (Harr et al., 1982; Hetherington, 1982; Keppeler and Ziemer, 1990; Hicks et al., 1991; Smith, 1991). At the same time, both increase and decrease in low flows are theoretically possible. For example, reduced evapotranspiration, interception and infiltration rates following deforestation may lead to higher soil moisture storage and increased surface runoff, which in their turn lead to reduced recharge and increased gully erosion. Eventually this may result in lowering the groundwater table and reduced low flows, which originate from groundwater storage. However, no literature sources, which illustrate this sequence have been identified.
- A wide variety of other effects which may influence the amounts or rates of accumulation of water held in storage during rainfall, and consequently the levels of storage rates of discharge from storage during periods of limited rainfall. A general example is the modification of land use over large parts of a catchment which may contribute to changes in the infiltration and/or evaporation characteristics, as well as modifications to the amount of groundwater recharge.

  One example is the catchment urbanisation. In urbanized catchments, low flows have a tendency to decrease due to the effects of urban impervious surfaces upon direct runoff, infiltration and evapotranspiration (Simmons and Reynolds, 1982; Warner, 1984; Ferguson and Suckling, 1990).

  Another example is the conservation farming. In many arid areas the natural catchment surface is over-utilized through overgrazing, collecting the firewood and burning of grasslands. These effects may result in more quick runoff as soil retention capacity is inhibited and, consequently, in increased soil erosion. The conservation strategies aimed at establishing and maintaining good ground cover include contouring, terracing and mulching. Such measures may be expected to reduce runoff volumes during both high- and low-flow periods. However, actual case studies, which specifically illustrate the reduction in runoff as a result of conservation farming, or the acceleration of runoff due to the deterioration of the natural catchments have not been identified.

3.2. Impacts directly on low streamflow

Apart from indirect anthropogenic impacts on low-flow generating processes there are human activities, which remove water directly from or add water to the stream.

- Direct river abstractions for industrial, agricultural or municipal purposes. These decrease the amount of water flowing downstream and has a more pronounced effect on streamflow during the dry season. For example, irrigation withdrawals have lead to increased frequency of occurrence of low-flow discharges (e.g. Kottegoda and Natale, 1994; Wilber et al., 1996; Eheart and Tornil, 1999).
- Direct effluent flows into river channels from industrial or municipal sources. These can significantly affect the composition of low flows leading to deterioration of water quality and therefore limiting its availability for downstream users. Pirt (1989) and Pirt and Simpson (1983) illustrated how multiple abstractions and effluent discharges may affect the dry season flow and suggested Residual Flow Diagrams (RDF) as a graphical illustration of these effects on a catchment scale.
- Irrigation return flows from agricultural fields. These are widely recognised as contributing to additional sub-surface drainage directly to the river channel or through ‘return’ canals. Irrigation return flows may constitute a large proportion of a stream’s water balance (Blodgett et al., 1992). According to some sources (Hall and Du Plessis, 1984; McKenzie and Roth, 1994), up to 40% of water initially abstracted for irrigation returns into the stream. Return flows are particularly important if the water for irrigation is imported from outside the catchment. The time lag associated with return flows remains largely unknown. Similar to effluent discharges from industrial and

municipal sources, irrigation return flows normally significantly affect the quality of water.

- Direct importation of water from outside the catchment via inter-basin transfer schemes and the use of channels as natural supply conduits (Golubev and Biswas, 1985; Davies et al., 1993).
- Construction of dams and subsequent regulation of a river flow regime. This regulation can either increase or decrease low-flow discharge levels depending on the operational management of the reservoir. It is necessary to distinguish between small impoundments such as farm dams (Warner, 1984; Maaren and Moolman, 1985; Berg et al., 1993; Davies et al., 1993) where there is little or no control over the level of storage, and larger dams where artificial releases can be made. Large artificial impoundments probably constitute the single most important direct impact on the low-flow regimes of rivers (Biggs, 1982; Muzik, 1986; Rhue and Small, 1986; Gustard and Cole, 1987; Harboe, 1988; Gustard, 1989; Sherrard and Erskine, 1991; Bonacci et al., 1992; Walker and Thoms, 1993; Finlayson et al., 1994).

Owing to the variety of direct impacts, the low-flow regimes of many rivers of the world have been significantly modified and the origin of water in a stream during low-flow conditions has been changed. Many originally perennial streams (particularly in arid regions) have become intermittent (due to various abstractions). In other cases, low flows have been artificially generated (e.g. from irrigation return flows or releases of imported water from dams for downstream users).

The relative quantitative impacts of the various anthropogenic processes and factors vary substantially in different river catchments. Each combination of both the dominating natural processes and the anthropogenic impacts has a different effect on or implications for various aspects of low-flow regime, low-flow analysis and management.

4. Low-flow measures and indices and their estimation from streamflow time series

Low-flow regime of a river can be analysed in a variety of ways dependent on the type of data initially available and the type of output information required. Consequently there exist a variety of low-flow measures and indices. The term ‘low-flow measure’ used here, refers to the different methods that have been developed for analysing, often in graphic form, the low-flow regime of a river. The term ‘low-flow index’ is used predominantly to define particular values obtained from any low-flow measure (sometimes, it is however rather difficult to separate one from the another). In this section, each low-flow technique is examined starting with its general concepts and interpretation, which is followed by recent advances in technique applications in low-flow related areas with the description of, associated low-flow indices.

4.1. Defining the low-flow domain

The arbitrary ‘upper bound’ to low-flow hydrology may be given by the Mean Annual Runoff (MAR), which is a mean value of the available flow time series of annual flow totals and one of the most fundamental hydrological characteristics. Dividing MAR by the number of seconds in a year gives the long-term mean daily discharge which is referred further in the paper as Mean Daily Flow (MDF). Various low-flow indices may be expressed as a percentage of either MAR or MDF.

A middle value in a ranked flow time series—Median Flow (MF)- may represent a more conservative upper bound for low flows, because streamflow time-series are often positively skewed and therefore MF is frequently smaller than MAR. For the same record length, the positive skewness of the data normally increases as the time resolution of the streamflow data decreases from annual to daily and therefore the gap between higher mean flow value and lower median flow value increases. Some studies speculate on the suitability of MAR and MF for the separation of droughts and low flows from the remainder of the time series (Dracup et al., 1980).

The lowest recorded daily discharge may be referred to as Absolute Minimum Flow (AMF). The information content of this index varies with the length of record and depends upon the measuring limits of streamflow gauges. Intermittent and ephemeral streams are characterised by natural extended periods of zero flow, which may generally be perceived as the 'lower bound' of low-flow hydrology.

4.2. Flow duration curve and low flows

A flow duration curve (FDC) is one of the most informative methods of displaying the complete range of river discharges from low flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equalled or exceeded, or in other words—the relationship between magnitude and frequency of streamflow discharges.

A FDC is constructed by reassembling the flow time series values in decreasing order of magnitude, assigning flow values to class intervals and counting the number of occurrences (time steps) within each class interval. Cumulated class frequencies are then calculated and expressed as a percentage of the total number of time steps in the record period. Finally, the lower limit of every discharge class interval is plotted against the percentage points. Alternatively, all ranked flows are plotted against their rank which is again expressed as a percentage of the total number of time steps in the record. The most convenient way of constructing a FDC is using the log-normal probability plot. This allows FDCs in some cases to be linearized and low- and high-flow ends of the curve to be more clearly displayed.

FDC may be constructed using different time resolutions of streamflow data: annual, monthly or daily. FDCs constructed on the basis of daily flow time series provide the most detailed way of examining duration characteristics of a river. Curves may also be constructed using some other time intervals, e.g. from *m*-day or *m*-month average flow time series. In this case, prior to FDC construction, a moving average approach is used to construct a new time series of *m*-day or *m*-month averaged flows from initially available daily or monthly data. Details on FDC construction and interpretation are provided in many sources (e.g. Searcy, 1959; Institute of Hydrology, 1980; McMahon and Mein, 1986).

The flows may be expressed in actual flow units, as percentages/ratios of MAR, MDF or some other 'index flow', or divided by the catchment area. Such normalisation facilitates the comparison between different catchments, since it reduces the differences in FDCs caused by differences in catchment area or MAR. Consequently, the effects of other factors on the shape of FDCs (aridity, geology, and anthropogenic factors) may be inspected.

FDCs may be calculated: (i) on the basis of the whole available record period ('period of record FDC' (Vogel and Fennessey, 1994)), or 'long-term average annual FDCs' (FREND, 1989; Smakhtin et al., 1997); (ii) on the basis of all similar calendar months from the whole record period (e.g. all Januaries—'long-term average monthly FDC' (Smakhtin et al., 1997) or FDC of a monthly 'window' (Mngodo, 1997)). FDCs may also be constructed using all similar seasons from the whole record period (long-term average seasonal FDCs (Smakhtin et al., 1997)), for a particular season (e.g. summer 1992) or a particular month (e.g. January 1990).

The shape and general interpretation of any FDC depend on hydrometric errors and the particular period of record on which it is based. This has been directly or indirectly illustrated by Searcy (1959), Vogel and Fennessey (1994), Hughes and Smakhtin (1996), Mngodo (1997) and Smakhtin et al. (1997).

The period-of-record FDC represents variability and exceedence probability of flow over the available (or selected) period. If the record period is sufficiently long, this interpretation is appropriate, since the FDC approaches a 'limiting' cumulative flow distribution. Vogel and Fennessey (1994) suggested a different interpretation of a FDC. It considers FDCs for individual years and treats those annual FDCs in the way similar to a sequence of annual flow maxima or minima. This interpretation allows mean and median FDCs to be estimated. Such curves represent the exceeding probability of flow in a typical year and were demonstrated to be less sensitive to the length of the record period, especially in the area of low flows. This approach also allows confidence intervals and return periods to be assigned to FDCs. Other probabilistic and parametric representations of FDC have been suggested by Quimpo et al., (1983), Mimikou and Kaemaki (1985), Fennessey and Vogel (1990) and LeBoutillier and Waylen (1993).

FDCs are widely used in hydrological practice. Vogel and Fennessey (1994) refer to several early studies related to the theory and application of FDC. Searcy (1959) was possibly the first to summarize a number of FDC applications including the analysis of catchment geology on low flow, hydropower and stream water quality studies. Warnick (1984) illustrated the application of FDCs to hydropower feasibility studies for run-of-river operations. Male and Ogawa (1984) advocated the use of FDCs in the evaluation of the trade-offs among various characteristics involved in determination of the capacity of waste-water treatment plants including flow, flow duration, water quality requirements and costs. Alaouze (1989, 1991) developed the procedures based on FDC, for estimation of optimal release schedule from reservoirs, where each release has a unique reliability. Pitman (1993) and Mallory and McKenzie (1993) illustrated the use of FDCs in design of flow diversions. Estes and Osborn (1986) and Gordon et al., (1992) illustrated the use of FDC for the assessment of river habitats in estimation of instream flow requirements. Hughes and Smakhtin (1996) suggested a non-linear spatial interpolation approach (based on FDCs) for patching and extension of observed daily flow time series, which has latter been extended to generation of flow time series at the ungauged sites (Smakhtin et al., 1997) and to the restoration of natural streamflow sequences in regulated rivers (Smakhtin, 1998). Gustard and Wesselink (1993), Lanen et al. (1997) and Smakhtin et al. (1998a)) used a FDC as a tool for rainfall–runoff model calibration and/or for the comparison of flow-time series simulated for different scenarios of development. Wilby et al., (1994) used FDC to assess the effects of different climate scenarios on streamflow with particular reference to low-flows. Hughes et al., (1997) developed an operating rule model which is based on FDCs and is designed to convert the original tabulated values of estimated ecological instream flow requirements for each calendar month into a time series of daily reservoir releases. FDCs are used in abstraction licensing (Pirt and Simpson, 1983; Gustard et al., 1992; DWAF, 1995; Mhango and Joy, 1998), in water quality studies, e.g. to indicate the percentage of time that various levels of water pollution will occur after the introduction of a pollutant of a given volume and strength into a stream (so long as there exists an adequate correlation between the quality characteristics and discharge). A recent review of numerous possible applications of FDCs in engineering practice, water resources management and water quality management is given by Vogel and Fennessey (1995).

Of most interest for low-flow studies is the 'low-flow section' of a FDC, which may be arbitrarily determined as part of the curve with flows below MF (which corresponds to the discharge equalled or exceeded 50% of the time—Q50). This entire section of the curve may be interpreted as an index of groundwater (and/or subsurface flow) contribution to streamflow from subsurface catchment storage. If the slope of the low-flow part of the FDC is small, groundwater/subsurface flow contribution is normally significant and low-flows are sustainable. A steep curve indicates small and/or variable baseflow contribution. In this sense, the shape of FDC is an indication of hydrogeological conditions in the catchment.

Various other low-flow indices may be estimated from this part of the FDC. The flows within the range of 70–99% time exceedence are usually most widely used as design low flows. Some common example indices are: one- or *n*-day discharges exceeded 75, 90, 95% of the time—e.g. Q75(7), Q75(10), Q90(1), Q95(1), Q95(10). Some less conventional indices include the percentage of time that 25% average flow is exceeded. Similarly to the ratio Q20/Q90 which may be interpreted as a measure of streamflow variability (Arihood and Glatfelter, 1991), the ratio (Q50/Q90) may represent the variability of low-flow discharges. The reverse ratio (Q90/Q50) may be interpreted as an index representing the proportion of streamflow originating from groundwater stores, excluding the effects of catchment area.

The *percentage of time the stream is at zero-flow conditions* illustrates the degree of stream intermittency and represents either the percentage of zero-flow days or percentage of zero-flow months (dependent on data resolution) in a complete record (Görgens and Hughes, 1982; Smakhtin et al., 1995). The *longest recorded period of consecutive zero-flow days* may be perceived as an indication of the most extreme drought, but the information content of this index is greatly dependent on the length of the record.

FDC illustrates the frequency distribution of flows in a stream with no regard to their sequence of occurrence. The latter falls mostly within the scope of spell analysis, which is discussed in one of the following sections. Despite the wide use of FDCs in hydrological practices, the relevant literature is rather limited. Although the recent years have seen the increased interest to FDC in hydrology, water resources and river ecology, its application potential is not yet fully explored.

4.3. Low-flow frequency analysis

Unlike the FDC, which shows the proportion of time during which a flow is exceeded, a Low-flow Frequency Curve (LFFC) shows the proportion of years when a flow is exceeded (or equivalently the average interval in years (‘return period’ or ‘recurrence interval’) that the river falls below a given discharge).

LFFC is normally constructed on the basis of a series of annual flow minima (daily or monthly minimum discharges or flow volumes), which are extracted from the available original continuous flow series (one value from every year of record). Similarly to FDCs, LFFCs may be constructed using the flow minima series of different averaging intervals. In the case of daily data, the minima of 1, 3, 7, 10, 15, 30, 60, 90, 120, 150, 180 or 183, 273 and 284 may be analysed (e.g. Characteristics of low flows, 1980; Musiake et al., 1984; McMahon and Mein, 1986; FREND, 1989; Zalants, 1992; Harris and Middleton, 1993). In the case of monthly data, averaging intervals of 1, 3, 6 and 9 months may be selected (Midgley et al., 1994). The independence of extracted annual flow minima averaged over long intervals (e.g. over 183 days) must be ensured. For seasonal low-flow frequency analysis, minimum flow values are selected from the season of interest (winter or summer low flows, e.g. Vladimirov, 1976; Whitehouse et al., 1983; Krokli, 1989). Long hydrological droughts are analysed using averaging intervals greater than 1 year. (McMahon and Mein, 1986; Srikanthan and McMahon, 1986; Midgley et al., 1994).

The available observed flow records are normally insufficient for reliable frequency quantification of extreme low-flows events and, therefore, different types of theoretical distribution functions are used to extrapolate beyond the limits of ‘observed’ probabilities and to improve the accuracy of low-flow estimation. The ‘true’ probability distributions of low flows are unknown and the practical problem is to identify a reasonable ‘functional’ distribution and to quantify its parameters. The procedure includes fitting several theoretical distribution functions to observed low-flow data and deciding, by statistically based and graphically based tests, which distribution best fits the data. Among the distribution functions most frequently referred to in the literature in connection with low-flows are different forms of Weibull, Gumbel, Pearson Type III, log-normal distributions. Many studies have examined which probability distributions are most suitable for fitting the sequences of annual minimum flows in different regions and for minima of different averaging intervals, and evaluated methods for estimation of distribution parameters (Matalas, 1963; Jozeph, 1970; Prakash, 1981; Beran and Rodier, 1985; Loganathan et al., 1985; McMahon and Mein, 1986; Singh, 1987; Waylen and Woo, 1987; Khan and Mawdsley, 1988; Sefe, 1988; Leppajarvi, 1989; Polarski, 1989; FREND, 1989; Nathan and McMahon, 1990b; Russell, 1992; Loaiciga et al., 1992; Durrans, 1996; Lawal and Watt, 1996a; Lawal and Watt, 1996b; Bulu and Onoz, 1997). In many of these papers, the emphasis is placed on the evaluation of acceptable lower limit of the distribution. Vogel and Kroll (1989) reviewed the studies which compared the fit of alternative probability distributions and parameter estimation procedures to the time series of annual 1 and 7-day minima. Pearson (1995) and Vogel and Wilson (1996) have recently performed an assessment of the probability distributions of low flows at the national scale in New Zealand and the USA. The universally accepted distribution function for low-flows, however, is unlikely to exist or ever be identified. Bardsley (1994) suggested to stop testing different distribution functions in low-flow frequency analysis and advocated a subjective extrapolation using an interactive computer graphics. Tasker (1987) and Loaiciga and Marino (1988) examined non-parametric methods for low-flow frequency analysis, which do not require the specification of a parent distribution. In general, non-parametric procedures for frequency analysis are becoming more accepted in hydrological practice. A detailed review of non-parametric functions and their applications in hydrology is given by Lall (1995).

The issue, which often arises in low-flow frequency analysis, is that the observed streamflow time series (and, consequently, low-flow time series) often contain zero flow values. In arid climates streamflow may naturally frequently fall to zero. Similar situation arises in cold regions, where the streams may be completely frozen in winter. On the other hand, the recorded zero flows are often those, which are below the measuring limit of a streamflow, gauge (censored flows). Zero values may not be ignored in statistical analysis of low-flow series. Distribution fit to series with zero flows will result in a positive probability of negative streamflows, unless the distribution is explicitly constrained to have a lower bound of zero. Such results are physically meaningless. Also, constraining some distributions to have a zero lower-bound may reduce their flexibility. Fitting a probability distribution for low-flow series containing zero values may be performed using conditional probability adjustment procedure suggested by Haan (1977). An extra parameter describes the probability of encountering a zero flow in a sample, while a continuous distribution is established for non-zero flows. The results are then adjusted to the full sample. The use of conditional probability adjustment has been illustrated in Gordon et al., 1992; Stedinger et al., 1993). Bulu (1997) suggested to use the theorem of total probability in frequency analysis of low-flow time series containing zero flows. Durrans et al., (1999) recommended that in cases when it is not clear, whether the zeroes are real or censored, they should be treated as censored values.

Numerous specific indices may be obtained from a LFFC. *The slope of LFFC* may be considered as a low-flow index. It is represented by the difference between two flow values (normalised by the catchment area), one from high and another from low probability domains. The larger this slope is, the more variable is the low-flow regime of the river and vice versa. Plots of annual low flows against recurrence interval may exhibit *a break in the curve near the modal value*. This is regarded by some authors (Velz and Gannon, 1953) as the point, where a change in drought characteristic occurs, so that the higher frequency flows are no longer ‘drought flows’ but rather flows that have a tendency to normal conditions. Though not a general feature of the LFFC, this may be interpreted as a condition at which a river starts getting water exclusively from a deep subsurface storage.

In the USA, the most widely used indices are *7-day 10-year low flow* (7Q10) and *7-day 2-year low flow* (7Q2), which are defined as the lowest average flows that occur for a consecutive 7-day period at the recurrence intervals of 10 and 2 years, respectively (e.g. Characteristics of low flows, 1980). Some studies refer to different similar indices, e.g. 3 day 20 year low flow (Hutson, 1988). A number of reports produced by the USGS contain a variety of minimum flows: annual means and extremes for selected periods ranging from 1 to 183 days and for recurrence intervals ranging from 2 to 50 years (Hughes, 1981; Armentrout and Wilson, 1987; Zalants, 1992; Cervione et al., 1993; Giese and Mason, 1993; Atkins and Pearman, 1995).

The average of the annual series of minimum 7-day average flows is known as *Dry Weather Flow* (Hindley, 1973) or as Mean Annual 7-day Minimum flow (MAM7) (Pirt and Simpson, 1983; Gustard et al., 1992) and is used in the UK by for abstraction licensing. The 7-day period covered by MAM7 eliminates the day-to-day variations in the artificial component of the river flow. Also, an analysis based on a time series of 7-day average flows is less sensitive to measurement errors. At the same time, in the majority of cases there is no big difference between 1-day and 7-day low flows.

In Russia and Eastern Europe, the widely used indices are 1-day and 30-day summer and winter low flows (either means, or flows with an exceedence probability of 50, 80, 90, 95% (Vladimirov, 1976; Balco, 1977; Szolgay, 1977; Walkowicz, 1978; Amusja et al., 1988a; Yevstigneev, 1990; Sakovich, 1990). Correction factors are introduced to convert such low-flow indices to flows of other probabilities of exceedence.

Prakash (1981) analysed flows for 66 streams in the US in an attempt to define the *probable minimum flow*. The latter is a hypothetical flow that corresponds to the smallest discharge which may occur in existing geomorphological conditions and under critical combination of reasonably possible hydrometeorological factors which determine minimum stream flows.

Low-flow frequency indices are widely used in drought studies, design of water supply systems, estimation of safe surface water withdrawals, classification of streams’ potential for waste dilution (assimilative capacity), regulating waste disposal to streams, maintenance of certain in-stream discharges, etc. (Chiang and Johnson, 1976; Refsgaard and Hansen, 1976; Male and Ogawa, 1982; Aron and

Emmanuel, 1982; Biswas and Bell, 1984; Riggs, 1985; Paulson and Sanders, 1987; Cumming Cockburn Ltd, 1990a). Lung et al., (1990) used low-flow frequency indices to calculate pollutant concentrations in estuaries. Khan and Mawdsley (1988) applied low-flow frequency analysis to obtain input recharge values for a lumpered model to simulate unconfined aquifer yield of a specified annual reliability. Heicher and Hirschel (1989) illustrated how different low-flow extremes may be used to identify existing and potential water supply problems, to identify historical extreme low-flow periods, and to determine potential water supply deficits (and other consequences) during a repeat of the most severe historical low-flow period. Prakash (1981) suggested that the probable minimum flow may find its application in designing safety related hydraulic structures for use in the nuclear power industry.

Low-flow frequency analysis forms part of the frequency analysis of extreme events and as such have been covered in many classical statistical textbooks. The papers covering specific topics of low-flow frequency analysis are numerous and those referred to above are unlikely to make a full list of recent contributions. At the same time, some authors note, that the literature on low-flow frequency analysis remains to be limited, compared, for example, with the literature on flood frequency (e.g. Vogel and Wilson, 1996). The improved ability to predict extreme low-flow events is likely to result from both the better understanding of contributing catchment processes and advances in statistical analysis. The techniques of and recent advances in the field of low-flow frequency analysis should be a subject for a detailed separate review.

4.4. Continuous low-flow events and deficit volumes

Neither FDC nor LFFC provide information about the length of continuous periods below a particular flow value of interest. The described measures also give no indication of a possible deficit of flow, which is built up during a continuous low-flow event. However, two streams with, for example, similar FDCs may have very different low-flow sequences: one may have a few long intervals below a given discharge, the other — many short intervals below the same flow rate.

There exist different ways to overcome these limitations. It is possible, for example, to analyse the durations of the longest periods which are necessary to yield a specified small percentage (1–10%) of the MAR (Velz and Gannon, 1960). These indices are similar to characteristics derived from FDC, but unlike FDC, time sequencing of discharges used in the analysis is not disturbed. Extracted from each year of record these intervals may be ranked and plotted in different ways to provide the information on consistency of low flows.

Another widely used approach uses the ‘truncation level’ or ‘threshold’ concepts, which originated from the Yevjevich’s (Yevjevich, 1967) theory of runs. A run, in a low-flow context, is the number of days (months, years) when daily (monthly, annual) discharge remains below the certain threshold flow. The choice of a threshold flow value is dictated by the objective of the study and/or the type of the flow regime. For hydrological drought characterisation in perennial rivers, meaningful threshold flows may be in the range of discharges with 70–90% exceedence on FDC. But for ephemeral rivers, which flow only after significant rainfall events, the discharges as high as those with 20% exceedence are not unreasonably high drought thresholds (Tate and Freeman, 2000). Also, different water resource practices and water users have different water requirements and may not have a common opinion on what threshold should be used to define a drought event.

The three main low-flow characteristics normally considered in the theory of runs are the *run duration, the severity (cumulative water deficit or the negative run sums) and the magnitude (the intensity)* which is calculated as severity divided by duration. If the focus of the study is the longest run duration for each year of record, such runs are often interpreted simply as annual hydrological droughts (Clausen and Pearson, 1995; Tallaksen et al., 1997; Stahl and Demuth, 1999). Other associated characteristics in this case may be the start date of the longest run (e.g. Woo and Tarhule, 1994) and the end of the run (e.g. Tlalka and Tlalka, 1987). The set of longest run durations (or deficits, intensities, run start dates, etc.), one value from each year of record, form a sample of extreme value data. These data can be ranked, assigned a probability or return period using a plotting position formula, and plotted against the assigned return periods (probabilities) for a given value of the threshold flow. As in the case of low-flow frequency analysis, various theoretical probability distribution functions are used.

A detailed example of run theory application to low-flow and drought analysis from the observed daily streamflow records is given by Zelenhasic and Salvai (1987). All important components of continuous low-flow events such as deficit, duration, start date, number of continuous events in a given time interval, the largest streamflow deficit and the largest duration in a given time interval are taken into account. The authors presented a stochastic model for analysis and interpretation of the most severe low-flow events.

A similar approach with a different terminology was adopted by the Institute of Hydrology (1980). The run duration becomes a *spell duration*, and the total volume of flow that would be required to maintain the flow at a given threshold is called *deficiency volume* (or simply, deficit as above). The threshold values are set corresponding to 5, 10, 20, 40, 60, 80% (or any other percent) of the MDF. From a given flow series of N years *the frequency of spells for a given duration* and *the number of spells greater than a given duration* may be calculated. These are then plotted against the duration of spells below a given threshold. Similarly *the frequency of deficiency volume* and *the number of deficiency volumes greater than a given volume* may be extracted and plotted against the values of deficiency volumes for a given threshold. This approach deals with all the spell events in the record period, and not just the largest ones from each year.

Beran and Gustard (1977) suggested to analyse a distribution of continuous low-flow spell durations below low-flow threshold discharges from a FDC. A similar approach, applied for both spell durations and deficits is followed by Smakhtin and Watkins (1997). The durations (or deficits) and number of spells below a threshold flow, are calculated and the results are displayed in the form of a histogram and/or a cumulative frequency curve. No theoretical distribution function is fitted to the data because both methods intend to give a quick impression of how responsive the river is on the basis of the available record. The cumulative spell frequency curves may be perceived as showing the probability that a low-flow spell below the selected threshold will last for a given duration (or longer), and the deficit of this spell will be equal or will exceed a given value. Additional characteristic included in the analysis is the actual flow volume (as opposed to the deficit) during a continuous low-flow period.

The run or spell analysis has been widely used for the identification, characterisation and management of annual and multiyear hydrological droughts (Weisman, 1978; Dracup et al., 1980; Sen, 1980a,b; Kosinsky, 1984; Tlalka and Tlalka, 1987; Chang and Stenson, 1990; Wijayaratne and Golub, 1991; Clausen and Pearson, 1995; Moye and Kapadia, 1995; Burn and DeWit, 1996; El-Jabi et al., 1997; Ciğizoğlu and Bayazit, 1998). The type of information obtained from low-flow spell analyses is required for different purposes—domestic water supply, irrigation, power generation, dilution of industrial pollutants, recreational planning, fish migration etc—which are all dependent on the continuous availability of prescribed river discharges.

The theory of runs is extensively used to assess the storage capacity of a reservoir which is necessary to provide a given yield at certain levels of reliability. The literature on storage–yield (or storage–draft) relationships and the relations between the theory of runs and reservoir storage is extensive and several review papers and books have been written on both of those subjects. Reviews and details about storage–yield analysis may be found, in Pegram et al., (1980), McMahon and Mein (1986), Klemes (1987) and Midgley et al., (1994).

If the river regularly falls to zero-flow or ‘cease-to-flow’ conditions, the frequency of durations of continuous zero-flow periods may be analysed by common statistical procedures. Continuous zero-flow period analysis is effectively a specific case of run analysis which indicates the likelihood of extended periods of no flow or drought (e.g. Armentrout and Wilson, 1987).

Spell analysis is applicable not only to low flows but to the periods of high flow as well (Prudhomme and Gilles, 1997; FRIEND, 1997). It may also be useful for the study of even more specific events, like short-term freshes (small peaks caused by occasional rains during prolonged low-flow periods) which may have important ecological implications.

4.5. Base flow and baseflow measures

Baseflow is an important genetic component of streamflow, which comes from groundwater storage or other delayed sources (shallow subsurface storage, lakes, melting glaciers, etc.). Through most of the dry season of the year, the streamflow discharge is composed entirely of baseflow. In a wet season, discharge is made up of baseflow and quickflow, which represents the direct catchment response to rainfall events.

Baseflow may be characterised by its hydrograph which is derived from the total streamflow hydrograph by various *baseflow separation techniques*. Reviews of these techniques may be found, for example, in Hall (1971). The majority of these methods concentrate on baseflow separation from a flood hydrograph (event based methods) and are often eventually directed to the estimation of the surface runoff component of a flood. They may be grouped into two main types: those methods that assume that baseflow responds to a storm event concurrently with surface runoff, and those that account for the delaying effects of bank storage. The quantitative aspects of these techniques are rather arbitrary mostly due to the difficulties related to the estimation of timing and rate of baseflow rise and identification of the point on a storm hydrograph at which surface runoff is assumed to cease. In general, these methods are of rather little relevance to low-flow studies.

Other types of baseflow separation techniques are directed to generate baseflow hydrograph for a long-term period—a year, several years or for the whole period of observations. These techniques normally make use of a certain kind of digital filter, which allows daily streamflow time series to be disintegrated into quickflow and baseflow. The most well-known techniques of that kind are UK ‘smoothed minima’ method (FREND, 1989 and ‘recursive digital filter’ (Nathan and McMahon, 1990a; Chapman, 1991) although other methods to separate baseflow on a continuous basis have been reported (Sittner et al., 1969; Birtles, 1978; Boughton, 1988; Smakhtin and Hughes, 1993). The USGS automated standardised physically based algorithm for separating baseflow is based on the original work by Pettyjohn and Henning (1979) and is computerised by Sloto and Crouse (1996). Sokolov (1974) recommended a method for deriving average baseflow discharge during low-flow period from a single discharge measurement. This idea is also developed by Potter and Rice (1987) who suggested the method of baseflow volume calculation based on a single discharge measurement provided that this measurement is properly centered in the baseflow period. Continuous baseflow separation techniques do not normally attempt to simulate baseflow conditions for a particular flood event, nor are they appropriate for the identification of the origin of baseflow. These methods are rather aimed at the derivation of objective quantitative indices related to long-term baseflow response of a catchment.

Such indices may include, for example, *mean annual baseflow volume* and long-term *average daily baseflow* discharge. Conventional frequency analysis may be used to estimate baseflow characteristics of duration and frequency of interest. Of primary importance to low-flow studies is the *base flow index* (BFI). This concept was, effectively, first introduced by Lvovich (1972) and then further developed by the Institute of Hydrology (1980) to describe the effect of geology on low flows. BFI is sometimes also referred to as ‘reliability index’ (e.g Beran and Gustard, 1977). It is a non-dimensional ratio which is defined as the volume of baseflow divided by the volume of total streamflow (or alternatively, as the ratio between the average discharge under the separated baseflow hydrograph and the average discharge of the total hydrograph). BFI may be estimated for every year of record or for the entire observation period (e.g. FREND, 1989; Gustard et al., 1992). In catchments with high groundwater contribution to streamflow, BFI may be close to 1, but it is equal to zero for ephemeral streams. Some sources list characteristic values of BFI for a number of rivers in certain regions (FREND, 1989; Smakhtin and Watkins, 1997). BFI was found to be a good indicator of the effects of geology on low-flows and for that reason is widely used in many regional low-flow studies, which are examined in one of the following sections. In some cases, for example, lake regions, or if the dominant source of the river flow is melt-water from snow as opposed to rainfall, the origin of baseflow may be different, which makes hydrogeological interpretation of the BFI difficult or inappropriate.

Knowledge of baseflow regime is important for development of catchment management strategies, (especially for drought conditions), establishing relationships between aquatic organisms and their environment, estimation of small to medium water supplies, water quality and salinity management, calculating water budgets of lakes, etc. Some studies report the use of baseflow separation procedures in the context of estimation of groundwater recharge (Rutledge, 1993; Rutledge and Daniel, 1994; Fröhlich et al., 1994). Baseflow analysis is closely related to the analysis of streamflow recession characteristics.

4.6. Recession analysis

During the dry weather periods, water is gradually removed from the catchment by evapotranspiration and groundwater/soil water discharge into a stream. A depletion of streamflow discharge during these periods is known as ‘recession’, and is reflected in streamflow hydrograph by a *recession curve (recession limb).*

Streamflow recession rates and consequently, the shape of recession curves depend primarily on catchment geology (e.g. transmissivity, storativity of the aquifers), and on the distance from stream channels to basin boundaries. Different runoff components: overland flow, interflow and groundwater flow have their own characteristic recession rates, but the ranges of these rates may overlap which reflect the fact that the distinctions between surface flow and interflow and between interflow and baseflow are not always clear (e.g. Klaassen and Pilgrim, 1975). Initially, the recession curve is steep as quickflow (made up of overland flow and/or interflow in a topsoil) leaves the basin. It flattens out with delayed flow supply from deeper subsurface stores and may eventually become nearly constant if sustained by outflow from a glacier or from groundwater storage.

In a low-flow context, baseflow is the most important component and consequently baseflow recession is of primary interest. Baseflow recession is described mathematically by various recession equations (e.g. Toebes and Strang, 1964; FREND, 1989; Clausen, 1992; Wittenberg, 1994; Griffiths and Clausen, 1997), of which the exponential recession equation (model) is, perhaps, the most common. The parameter of such recession model is known as *recession constant.*

The baseflow recession constant for a particular site may be estimated from the slope of a *master recession curve* which is normally defined as an envelope to various individual recession curves. One of the most commonly used techniques for the construction of a master recession curve is known as the *correlation method* (Knisel, 1963; Hall, 1968; Brutsaert and Neiber, 1977; Beran and Gustard, 1977; Institute of Hydrology, 1980; FREND, 1989). In this approach, a plot of ‘current flow’ (‘today’s flow’) against the ‘flow *n* days ago’ is constructed for all low-flow recession periods longer than *N* days. The envelope can be rather objectively defined if the number of individual recessions is large enough to delineate the region of their highest density. Recession constant is easily calculated from recession equation if the slope of the envelope is known. The value of *n* is usually in the range of 1–5 days and the threshold value of *N* must be reasonably long to have a suitable number and duration of individual recessions. Another technique, *the matching strip method* includes superimposing individual recession curves to construct a master recession curve (Nathan and McMahon, 1990a; Sugiyama, 1996). Most of the methods of recession constant estimation remain rather subjective. Some authors suggested that master recession curve does not give an adequate representation of recession flows (Jones and McGilchrist, 1978), and attempts to construct alternative mean and enveloping recession curves were reported (e.g. Petras, 1986). Bako and Hunt (1988) attempted to increase the objectivity of estimation by using the statistical approach which employs analysis of covariance.

Another method of recession analysis includes the consideration of ratios of current flow to flow *n* days ago. These ratios are calculated for every day when discharge is below the mean flow. A cumulative frequency diagram is then constructed to estimate recession indices, for example, median recession ratio REC50. Some studies (FREND, 1989) use this index as a substitute for a ‘true’ recession constant. Smakhtin and Hughes (1993) and Smakhtin et al., (1998b) suggested to use the ‘recession ratio’ method to evaluate the quality of flow time series simulated by deterministic rainfall–runoff daily models.

The higher the recession constant (or REC50) value, the more efficient is the long-term basin storage factor and hence the closer is the relationship between long-term average storage input (e.g. normal annual rainfall) and baseflow at any time during normal recession. In this context, the other useful measure of flow recession is the *half-flow period* (HFP, or *half-life*), introduced by Martin (1973). It is interpreted as the time (in days) required for the baseflow to halve. For unsustained, quickly receding baseflows, HFP may be in the range of 7–21 days, while for slowly receding streams it may be as large as 120–150 days. Some authors consider it to be more physically meaningful than the recession constant and more sensitive to differences in recession rates for slowly receding streams (Nathan and McMahon, 1990a).

The streamflow recession curve effectively represents the storage–outflow relationship for the river catchment. Griffiths and Clausen (1997) suggested the approach whereby flow recession is modelled as the result of depletion in a multistorage catchment, which may include depression storage (lakes, ponds, marshes, depressions on the ground surface), detention storage (channel storage in a stream), channel bank storage, aquifer storage, underground storage in karst terrain, etc. They derived the general equation that describes flow recession assuming the dominant type(s) of storage in any given catchment. Similar idea was examined by Moore (1997), who suggested a two linear reservoir recession model and illustrated that the shape of the recession curve depends not just on the volume of subsurface storage, but also on its initial distribution between reservoirs.

The recession analysis is widely used in many areas of hydrological research, water resource assessment, planning and management. The most common application is a short-term forecasting of low-flows for irrigation, water supply, hydroelectric power plants and waste dilution, estimating groundwater resources in a catchment, and hydrograph analysis (Anderson and Burt, 1980; Collins, 1982; Bako and Owoade, 1988; Radczuk and Szarska, 1989; Curran, 1990; Griffiths and Clausen, 1997; Moore, 1997). Integrating the recession curve gives an estimate of available drainage storage (Boughton and Freebairn, 1985; Korkmas, 1990). East and Colesc (1982) used recessions as the basis for low-flow forecast to improve trout farm management. Kelman (1980) used recession constants for fitting stochastic daily streamflow model and recently Kottegoda et al., (2000) applied recession characteristics for the generation of continuous daily streamflow time series. Bates and Davies (1988) applied recession constants for hydrographs separation and modelling surface runoff. Vogel and Kroll (1996) examined several different estimators of the baseflow recession constant in an attempt to evaluate the most physically based one with a view to include recession constant in regional regression model for prediction of other low-flow indices (incorporation of recession constant into regional prediction models could improve their predictive ability). A comprehensive recent review of streamflow recession analysis and its various applications has been compiled by Tallaksen (1995).

4.7. Interaction between low-flow indices

Although various low-flow indices describe different aspects of low-flow regime of a river, most of them are obviously strongly intercorrelated. Perennial rivers with large contribution from subsurface stores normally have high baseflow indices, low recession rates (indicated by large recession constants), low variability of daily flows and, consequently, relatively large (compared to MDF) low-flow values with different probability of exceedence. The picture changes for intermittent rivers with unsustainable seasonal baseflow contribution and reaches its extreme in ephemeral streams with zero low flows.

The issue of interdependence of different low-flow indices is directly or indirectly addressed in many studies. Several studies (Balco, 1977; Drayton et al., 1980; Amusja et al., 1988a; Gustard et al., 1992) use the principle of conversion of some selected basic (primary) low-flow statistic into low-flow statistics of a different extremity or duration. Loganathan et al., (1986) suggested a physically based approach for low-flow frequency analysis considering extreme low-flows as part of the recession limb of streamflow hydrograph and illustrated the applicability of his method for both perennial and intermittent streams. Gottschalk and Perzyna (1989) derived low-flow frequency distribution function with parameters estimated from traditional recession analysis and analysis of dry weather spells (periods during which precipitation was less than an assumed threshold). Gottschalk et al., (1997) suggested to use recession equations (describing the streamflow decay during rainless periods) to derive theoretical expressions for low-flow distribution functions. This was, effectively, the first attempt to combine recession analysis and low-flow frequency analysis, which have been traditionally treated as separate fields.

Tallaksen (1989) illustrated that low-flow discharges are dependent on the recession constant and BFI. Curran (1990) demonstrated the calculation of Q95 using a recession equation. Kachroo (1992) showed the relation between recession constant and spell deficit volume. Clausen and Pearson (1995) investigated the relationship between low-flow spell characteristics on one hand, and BFI and catchment parameters on the other, as well as the relationship between spell duration and deficit. The later issue has also been addressed by Zelenhasic and Salvai (1987) and Chang and Stenson (1990).

Smakhtin and Toulouse (1998) provided the explicit illustration of the correlation between a number of different types of low-flow indices and characteristics extracted from 1-day annual FDC. The study used the database of low-flow indices calculated from the observed records of more than 200 rivers in South Africa. A strong relationship was established between Q75 on one hand and MAM7, 7Q10 and 7Q2, on the other. The MAM7 and 7Q2 flow values, if placed on the 1-day FDC, were found to exceed by 80–91% of the time and 83–93% of the time, respectively. 7Q10, as an index, of more extreme low-flow conditions was found to be exceeded by 95–99.5% of the time and consequently, better correlated with Q95. The relationships of BFI and REC50 with low-flow discharges extracted from FDC were found to be less explicit and affected by the limitations of calculation procedures used to determine these characteristics of the catchment subsurface storage. Weak correlation was found between the duration of low-flow spells and any FDC discharges (a low-flow spell may be interrupted by minor flow fluctuations and consequently, the duration of a continuous low-flow period is more dependent on variability of daily flows then on any particular low-flow discharge). On the other hand, strong relationships were established between low-flows from FDC and deficit volumes, since the former effectively determine the magnitude of flow deviation from the specified threshold flow during a low-flow period.

The relationships, which exist between low-flow indices of different type and extremity imply, amongst the others, that one low-flow index may often be derived from another using regression models. Consequently, only one ‘primary’ low-flow characteristic may need to be initially estimated from the available observed time-series data sets. The estimated primary low-flow values may then be used to construct the base map, while regional regression models (described in one of the sections below) with the primary statistic may be used to calculate other required low-flow indices. This approach is adopted in some studies. Very often, the BFI is selected as a primary low-flow index (e.g. Hutchinson, 1993; Pilon and Condie, 1986; Green, 1986; Meigh, 1987; Nathan and McMahon, 1992), but other examples are also available from the literature (Q75(10)—Drayton et al., 1980; Q20/Q90—Arihood and Glatfelter, 1991). It should be stressed, however, that wherever an observed flow record of good quality is available, it should be used directly to obtain a variety of different low-flow indices.

5. Methods of low-flow estimation in ungauged catchments

Most of low-flow measures and calculation methods described above require adequate observed streamflow records which can only be provided for gauged catchments. Ungauged catchments pose a different problem. Possible approaches for low-flow estimation in ungauged catchments may be arbitrarily classified, for example, into: (i) those which aim at the prediction of either specific low-flow indices (e.g. Q95 or 7Q2) or composite low-flow measure (e.g. low-flow frequency curve) using techniques of hydrological regionalisation (regional methods of low-flow estimation); and (ii) those which allow any low-flow characteristic to be estimated from synthetic flow time series. The later case implies the application of simulation methods which aim at the generation of a continuous flow time series (at an ungauged site or multiple sites in a river catchment), which may subsequently become a subject to low-flow analyses, described in the previous sections.

On the other hand, it is also possible to distinguish between: (i) mathematical methods (regional regression models of some low-flow index with catchment physiographic characteristics); (ii) graphical methods (construction of regional prediction curves); (iii) techniques of spatial interpolation (low-flow maps, grids, profiles); and (iv) low-flow estimation from synthetic flow time series. Any classification is however rather arbitrary, and many low-flow estimation techniques incorporate elements of several approaches.

5.1. Regional regression approach

This is perhaps the most widely used technique in low-flow estimation at ungauged sites. It normally includes several subsequent steps which are briefly described below.

5.1.1. Selection of a low-flow characteristic for regression model

In many cases, the choice is dictated by the engineering or water resources planning traditions of a particular country (Characteristics of low flows, 1980; Gustard et al., 1992; Vladimirov, 1976; Amusja et al., 1988b). In other cases, the choice is not that critical or obvious either due to variable user requirements, limitations of existing streamflow database, research objectives or because of the extreme spatial variability of river low-flow regimes (Drayton et al., 1980; Nathan and McMahon, 1992; Smakhtin et al., 1995; Mhango and Joy, 1998).

5.1.2. Delineation of hydrologically homogeneous regions

The regionalisation of streamflow characteristics in general is based on the premise that catchments with similar climate, geology, topography, vegetation and soils would normally have similar streamflow responses, for example, in terms of unit runoff from the catchment area, average monthly flow distribution, duration of certain flow periods, frequency and magnitude of high and low-flow events in similar sized catchments, etc. The delineation of regions may be accomplished using convenient boundaries based on geographic, administrative or physiographic considerations. The regions that result using such an approach may not always appear to be ‘sufficiently’ homogeneous. However, this pragmatic approach may appear to be suitable in conditions of limited data availability. Geographically contiguous regions may be established on the basis of residuals from a regional regression model developed to estimate flow characteristics at ungauged catchments. The regions are then delineated by grouping catchments with residuals of a similar sign and magnitude (e.g. Hayes, 1992). Even two adjacent river catchments may have rather different topography, soils or other local anomalies. A homogeneous region may therefore be viewed as a collection of catchments, which are similar in terms of catchment hydrological response, but not necessarily geographically contiguous. Development of a separate regression model for each of the identified homogeneous regions is likely to improve the predictive ability of the final prediction equation.

Classification of catchments into groups may be based on standardised flow characteristics estimated from the available observed or simulated streamflow records (Wiltshire, 1986; Hughes, 1987; Haines et al., 1988; Hughes and James, 1989; Joubert and Hurly, 1994; Midgley et al., 1994). Alternatively, the regions are delineated using catchment physiographic and climatic parameters (Acreman and Sinclair, 1986; Krokli, 1989; Hayes, 1992) obtained from maps and hydrometeorological data (rainfall, evaporation). This last approach has more relevance to the estimation of flow characteristics at ungauged sites since an ungauged catchment for which, for example, low-flow estimation is undertaken, should first be assigned to one of the identified groups/regions and this can only be done on the basis of catchment physiographic information.

Several authors delineate regions for some specific purpose. Wiltshire (1986), Burn and Boorman (1993) and Burn (1997) attempted to establish regions for regional flood analysis, Mimikou and Kaemaki (1985)—for regionalisation of FDCs; and Nikitin and Zemtsov (1986) and Gutnichenko and Sedov (1988)—for low-flow analysis. Other researches tried to establish regions which are ‘homogeneous’ in more general hydrological terms. Hughes and James (1989) delineated regions in Australia on the basis of general flow and low-flow characteristics, Midgley et al. (1994) established 80 hydrological zones in South Africa for the prediction of deficient flow-duration frequency and storage—yield characteristics. Tucci et al., (1995) delineated regions in Brazil for the prediction of low flows, mean flows and floods.

Grouping of catchment is often performed by means of multivariate statistical analyses (e.g. Tasker, 1982; Nikitin and Zemtsov, 1986; Gutnichenko and Sedov, 1988; Gordon et al., 1992; Solin and Polacik, 1994). Nathan and McMahon (1990c) tested several different approaches to hydrological regionalisation, which were variably based on a combination of cluster analysis, multiple regression, principal component analysis and the graphical representation of multidimensional data and did not assume the geographical contiguity of resultant homogeneous catchment groups. Nathan and McMahon (1991, 1992) illustrated how the catchments may be grouped using trigonometric curves with parameters related to catchment and climatic characteristics.

The identification of homogeneous regions is normally required for large territories (countries, large regions/catchments) or areas with varying physiographic condition and may be skipped for smaller regions. It may also be argued that the application of even highly sophisticated statistical techniques may not necessarily result in a more physiographically meaningful and practically applicable set of regions/groups than that obtained using some combination of scientific judgement and convenient geographic or administrative boundaries.

5.1.3. Construction of regression model

The regression model is a relationship between dependent low-flow characteristics and independent catchment and climatic variables. To establish a usable regression relationship, a certain amount of observed streamflow data should be available to adequately represent the variability of flow regimes in a region and to allow required low-flow characteristics (dependent variables) to be estimated for further use in regression analysis. The streamflow data used should represent natural flow conditions in the catchments: the approach will most probably not work or will be misleading if flow regimes analysed are continually changing under man-induced impacts.

Technically, regression model is constructed by means of a multiple regression analysis. This step includes selection of type of regression model, estimation of regression model parameters, assessment of estimation errors. The ‘best’ regression model is commonly estimated using stepwise regression approach when the model is derived one step—one independent variable—at a time. The procedure is described in many textbooks (e.g. Yevjevich, 1972; Haan, 1977; Gordon et al., 1992) and at present may be performed using statistical software packages. The parameters of the regression models have been traditionally estimated using the principle of ordinary least squares—OLS (e.g. Thomas and Benson, 1970; Hardison, 1971), in which it is effectively assumed that all observations of the variable being predicted are equally reliable at different sites in a region. In practice, however, it is seldom the case, because the accuracy of measured streamflows and the lengths of observations at different gauges vary. To account for unequal lengths of observation periods, Tasker (1980) developed a weighted least squares (WLS) procedure and demonstrated that by using the WLS approach the accuracy of regression models may be increased. Later, Stedinger and Tasker (1985, 1986) developed generalized least squares (GLS) regression procedures, which account for different record length and the cross correlation between concurrent flows. More recently, Moss and Tasker (1991) and Kroll and Stedinger (1998) have demonstrated the advantages of GLS techniques over OLS and examined, amongst the others, cases when OLS procedures are adequate and when GLS are preferable. The GLS regression methods are currently used widely in low-flow regressions in the USA.

It is not an easy task to uncover a true physical relationship between dependent and independent variables without some prior knowledge of which basin characteristics should be included in the regression equation. However, in some cases the world-wide or local experience may suggest the required set of independent physiographic variables. Occasional attempts to a priory ‘fill’ a future regression model with physical meaning have been reported. Downer (1981) has shown that developing a better physical understanding of the components affecting low flows before choosing the regression variables, may significantly reduce estimation errors. Vogel and Kroll

(1992) adapted the conceptual catchment model to identify primary low-flow generating factors and found that low-flow characteristics are highly correlated with catchment area, average basin slope, and base flow recession constant, with the base flow recession constant acting as a surrogate for both basin hydraulic conductivity and soil porosity. It was concluded that a simple physically based catchment model could suggest variables and the functional form for regional regression equations that estimate low-flow statistics at ungauged sites. However, Nathan and McMahon (1992) explicitly stated that regression models "…are in effect a 'black-box' solution to the problem… where only inputs and outputs have any real significance".

Basin and climate characteristics (independent variables) which are most commonly related to low-flow indices include: catchment area, mean annual precipitation, channel and/or catchment slope, stream frequency and/or density, percentage of lakes and forested areas, various soil and geology indices, length of the main stream, catchment shape and watershed perimeter, mean catchment elevation. Armbruster (1976) suggested the use of an infiltration index (based on a simple numerical weighting of soil infiltration capacities) for predicting equations for low-flows in regolith based catchments. Kuusisto (1987) found that winter flow minimum in Finland was significantly explained by lake percentage and basin area. The effects of lakes were also explicitly accounted for by Gerasimenko (1972) and Sakovich (1995). Some researchers emphasise the dominant effect of various characteristics of catchment and river elevation on low-flow discharges (Sakovich, 1995). Hutchinson (1990), Clausen (1992) and Clausen and Pearson (1995) refer to the use of several composite non-dimensional catchment indices: hydrogeology index (which can vary from 1 to 8 for low to high infiltration capacities), percentage of bare land, soil drainage index (from 1 to 7 for poor to excessive drainage), vegetation index (from 1 to 2 for low vegetation to forest) macroporosity and minimum porosity (%). Lacey and Grayson (1998) examined the influence of a set of geology-vegetation groups and a number of non-dimensional catchment properties (including topographic and climatic indices) on the BFI in Australia. Smith (1981), Nathan and McMahon (1991) and Kobold and Brilly (1994) used similar approaches to index catchment geology in regional low-flow analysis.

Garcia-Martino et al., (1996) examined the relationships of low-flow frequency characteristics with 53 different catchment and climatic parameters estimated using GIS technology. The most significant parameters were found to be the drainage density, the ratio of length of tributaries to the length of the main channel, the percent of drainage area with north-east aspect and the average weighted slope. It was also demonstrated that the accuracy of estimates had improved compared with the best regression model based on catchment parameters that could be measured without a GIS. Skop and Loaiciga (1998) illustrated the usefulness of GIS in spatial hydrological analysis and presented examples of low-flow estimation based, amongst the others, on groundwater contributing areas determined using GIS.

A large number of regional models for low-flow estimation at ungaged sites have been developed in different parts of the world in the last several decades and the list of such studies will hardly ever be complete. The examples, which concentrate predominantly on regression models for low flows of different frequency of occurrence include: Balco (1976, 1977) and Szolgay (1977) in Slovakia; Leith (1978), Pol (1985), Hamilton (1985), Pelletier et al., (1986) and Cumming Cockburn Ltd (1990b) in Canada; Chang and Boyer (1977), Downer (1981), Armentrout and Wilson (1987), Barnes (1986), Tasker (1989), Risle (1994), Ries (1994), Ludwig and Tasker (1993), Cervione et al., (1993), Hayes (1992) and Dingman and Lawlor (1995) in USA; Mimikou (1984) in Greece; Lundquist and Krokli (1985) in Norway; Institute of Hydrology (1987) in Scotland; Pirt and Simpson (1983) and Gustard et al., (1992) in UK; Demuth (1994) in Germany; FREND (1994) in Western Europe; and Kobold and Brilly (1994) and Brilly et al., (1997) in Sovenia. Gustard et al., (1997) reported the results of a European study of Q90.

Regional studies of spell characteristics, often referred to as annual or seasonal droughts, have been carried out by Kachroo (1992), Clausen and Pearson (1995), Tallaksen and Hisdal (1997), Tallaksen et al., (1997) and Stahl and Demuth (1999).

A number of studies investigated the relationships between the catchment geology and recession characteristics and/or BFI. Browne (1981) attempted to represent catchment storage by means of recession characteristics. Tjomsland et al., (1978), Pereira and Keller (1982) and Demuth (1989) illustrated relationships of baseflow and recession constant with catchment morphology and climatic characteristics. Bingham (1986) illustrated the significance of geology and drainage area in estimating low-flow recession rate. Ando et al., (1986) derived regional values of recession constant in Japan. Zecharias and Brutsaert (1988) examined regional distribution of recession parameters. The use of baseflow index in regional studies has been illustrated by: Hutchinson (1993) in New Zealand; Pilon and Condie (1986) in Canada; Green (1986) in Fiji; Meigh (1987) in Zimbabwe; and Lacey and Grayson (1998) in Australia.

Nathan and McMahon (1991, 1992) conducted a comprehensive regional low-flow analysis in Australia. The study used different types of regression models and a large number of catchment characteristics. Regression models have been established for several catchment groups for baseflow index, half-flow period, FDC, low-flow frequency curves (for several *n*-day low-flows), low-flow spell duration and deficit curves and storage-draft characteristics. The study represents perhaps the most detailed known example of regional regression approach and also in a certain sense — the attempt to illustrate the powerful abilities of multiple regression combined with new methods of regionalisation.

Gustard et al., (1992) and Gustard and Irving (1994) described the approach which combined a soil database with the national hydrological data base to classify soils of the UK into 29 Hydrology of Soil Types (HOST) classes. The HOST classes were then assigned to12 low-flow HOST groups to be used in low-flow regression models. This allowed the accuracy of prediction of the MAM7 and Q95 (two most widely used low-flow indices in the UK) to be improved. The most recent low-flow studies in the UK have resulted in the development of the estimation procedures for artificially influenced streams (Bullock et al., 1994). These procedures were aimed at the estimation of MAM7, Q95 and FDCs at ungauged sites in catchments where streamflows were affected by surface water abstractions and discharges, impounding reservoirs and groundwater abstractions.

Schreiber and Demuth (1997) attempted to estimate MAM10 from indices of geology, pethrography, hydrogeology and land-use using the river network approach as opposed to the complete catchment approach. The difference was that only the main characteristics of the narrow ‘corridors’ immediately adjacent to the stream channel were considered as independent variables in regression analysis.

The accuracy of low-flow estimation by means of regional regression models is often complicated by censored data (e.g. Kroll and Stedinger, 1999) and in general may range from ‘very poor’ to ‘very good’ depending on the quality and amount of streamflow data used to construct regression model, accuracy of estimation of independent catchment parameters and amount of time spent on experimenting with different types of regression models. The combination of limited data availability (or their insufficient quality) and high spatial variability of physiographic conditions and flow regimes may limit the possibilities for development and application of regional regression models. Thomas and Benson (1970) found that average prediction errors in low-flow estimation may be at least twice as large as for flood estimation in the same catchment. Standard errors of regression model estimates also depend upon the complexity of regional low-flow generation mechanisms and the type of dependent low-flow variable. Such errors may range from about 30% (Chang and Boyer, 1977) to 172% (Hayes, 1992).

5.2. Regional prediction curves

As opposed to the estimation of a single low-flow characteristic for which regression model has been constructed, this approach allows the range of low-flow indices of a similar type to be estimated. Flow duration curves, low-flow frequency curves and low-flow-spell curves from a number of gauged catchments of varying size in a homogeneous region can be converted to a similar scale, superimposed and averaged to develop a composite regional curve. To make curves from different catchments comparable, all flows are standardised by catchment area, mean or median flow or other ‘index’ flow. A curve for ungauged site may then be constructed by multiplying back the ordinates of a regional curve by either catchment area or an estimate of the index low-flow depending on how the flows for the regional curve were standardized. The index flow is estimated either by means of regression equation or from regional maps.

The first attempt to construct regional FDCs belongs, perhaps, to Lane and Lei (1949). They have designed the *variability index*—a measure of streamflow variability specifically related to FDC and calculated as the standard deviation of the logarithms of 5, 15, 25, …, 85 and 95 exceedence flow values. Lane and Lei determined the average value of variability index and corrections to this index which are dependent on the physiography of the individual ungauged river catchment.

Regional FDCs have been constructed in several states in USA (Singh, 1971; Dingman, 1978), in Philippines (Quimpo et al., 1983), Greece (Mimikou and Kaemaki, 1985), Northern Ireland (Wilcock and Hanna, 1987). Fennessey and Vogel (1990) used a different approach, approximating the lower half of 1-day annual FDCs using log-normal distribution and developing regression equation for distribution parameters with catchment characteristics. LeBoutillier and Waylen (1993) suggested another probabilistic representations of a FDC combining the principles of order statistics and traditional flow frequency analyses. The model was applied to FDCs for rivers in British Columbia, Canada, where streamflows are generated from a number of distinct physical processes operating in highly variable environments. In European FREND (1989) study, non-dimensional 1-day annual FDCs were averaged for each of several pre-defined catchment groups. The shape of the whole curve in each group appeared to be dependent on only one point: the flow exceeded 95% of the time (Q95). Smakhtin et al., (1997) constructed seasonal regional FDCs for one of the primary drainage regions of South Africa and used them to generate a continuous daily streamflow hydrographs at ungauged sites.

The construction of other types of regional curves is in principle similar to that of a regional FDC. Regional LFFC may be constructed using annual minima standardised by MAM flow or other similar low-flow index (FREND, 1989; Gustard et al., 1992; Pilon, 1990; Vogel and Kroll, 1990; Tucci et al., 1995). Midgley et al., (1994) constructed regional Deficient Flow—Duration—Frequency curves and Storage—Yield curves for about 80 hydrologicaly homogeneous zones in South Africa. Regionalisation of storage-yield characteristics has also been examined by Gan et al., (1988), Domokos and Gilyen-Hofer (1990) and Kachroo (1992).

Nathan and McMahon (1991, 1992), used the assumption of linearity of various flow prediction curves (FDC, LFFC, low-flow spell curve) in log-normal space and defined full curve (of each type) for ungauged sites by estimating only two points on a curve: one from the area of low probability of exceedence and one from high. In case of FDC these two points were represented by discharges exceeded 10% and 90% of the time (Q10 and Q90; for intermittent rivers the latter point was replaced by percent of time with zero flows). In case of LFFC, the two points were the 2 and 50-year return period low flows. In case of spell curves, these were durations (or deficits) of 2 and 50-year events. In each case, the two base points were estimated by means of regression models.

Prediction curves at ungauged sites may also be established if only a few discharge measurements are made at this site during low-flow period. The measured discharges are then related to concurrent discharges of a nearest gauged stream for which the required curve (FDC or LFFC) has been established on the basis of observed record. The discharges from this curve are then transferred through the relation curve to obtain corresponding flows at the ungaged site (Riggs, 1972; Hayes, 1992; Telis, 1992; Giese and Mason, 1993; Atkins and Pearman, 1995). The estimates of low-flow characteristics at short-record sites may be improved by using the information from other gauged sites with longer records (e.g. Durrans and Tomic, 1996). Also, various streamflow record augmentation procedures may be employed to increase the effective record length (Vogel and Stedinger, 1985; Vogel and Kroll, 1991).

5.3. Regional mapping and other methods of spatial interpolation of low-flow characteristics

Mapping of flow characteristics is based on a principle of existence of a ‘field’ of flow and its relationship with physiographic zonation of natural factors. In this context, regional mapping is similar to regional regression approach. Similarly to regression relationships, flow maps are constructed on the basis of flow characteristics estimated from gauged data. The denser the gauging network with usable flow data, the more reliable will be the estimates derived from maps (as well as from regression models). The size of catchments used for mapping ideally should reflect the zonal type of flow regime. Consequently, very small rivers (where flow regime is normally a result of small-scale local factors) and very large rivers (flowing through several geographical zones) should not be selected for the purpose of mapping of flow characteristics. The choice of upper and lower threshold catchment areas for both regional regressions and/or maps is often rather arbitrary and may differ in different physiographic environments (e.g. Kurdov, 1977; Armentrout and Wilson, 1987; Arihood and Glatfelter, 1991; Ludwig and Tasker, 1993; Risle, 1994).

The most widely used approach in flow mapping is the construction of flow contour maps (Drayton et al., 1980; Belore et al., 1990; Telis, 1992; Vladimirov, 1990; Vandewiele and Elias, 1995; Smakhtin et al., 1995). A flow characteristic estimated at any gauged location in a region is assumed to be representative for the whole catchment above the gauge. Therefore, calculated flow values are usually assigned to the centroids of gauged catchments. Flow contour lines are then constructed either manually or by available computer packages. Automated contouring has advantages of efficiency and reproducibility, whereas manual contouring allows the exercise of potentially more accurate expert local knowledge, where it exists.

The alternative way of mapping is to delineate spatial units (subareas) with constant values or narrow ranges of low-flow characteristics (Arihood and Glatfelter, 1991; Gustard et al., 1992; Smakhtin et al., 1998a).

The examples of mapped low-flow indices include Q75(10) (Drayton et al., 1980), Q20/Q90 (Arihood and Glatfelter, 1991), 7Q2 and 7Q20 (Belore et al., 1990), 7Q10 (Telis, 1992), Q95(7) and MAM(7) (Gustard et al., 1992), spell duration of and average runoff during continuous periods below mean flow (Tlalka and Tlalka, 1987), 30-day low flow with 95% probability (Amusja et al., 1988b).

The reliability of flow estimates obtained from maps depends upon a number of factors: the already mentioned density of gauging network and quality of flow data used, variability of flow characteristic being mapped in time and space, the scale of the map and the contour interval, etc. At the same time, maps of flow characteristics provide an easy way of estimating required flows at ungauged sites, indicate the quantity of water resources available in a region, and may be a valuable water resource planning tool (e.g. Arnell, 1995).

Alternative ways of presenting spatially changing low-flow characteristics normally concentrate on the river itself, rather then on a catchment or region. Perhaps the most well known of such methods is the Residual Flow Diagram (RDF) described by Pirt and Douglas (1982) and Pirt and Simpson (1983). RFDs show the total quantity of water at any point along a stream. The vertical axis represents distance downstream from the river source, the horizontal axis is for natural and artificial flow data. The total flow in a stream at every point along the vertical axis is represented by the distance between natural and artificial flow lines. The main advantage of RFDs is a very convenient and straightforward presentation of flow data. Different low-flow indices derived from FDCs or LFFCs may be plotted using RFD. Such diagrams are certainly more informative if detailed flow data are available.

Similar ways of presenting low-flow characteristics plotted against distance along a stream channel are sometimes referred to as ‘flow line technique’, ‘low-flow profiles’ etc. (Riggs, 1972; Browne, 1980; Characteristics of low flows, 1980; Carter et al., 1988; Domokos and Sass, 1990; Gottschalk and Perzyna, 1993).

5.4. Low-flow estimation from synthetic streamflow time series

The alternative approach to low-flow estimation at ungauged sites is to utilise a time-series simulation method to generate a satisfactorily long length of streamflow data and to calculate a set of low-flow indices from the simulated series. Two simulation approaches may be employed: stochastic and deterministic. The first produces a time series with ‘realistic’ statistical properties but does not intend to simulate the actual flow sequences at a site (Huthman and Liebscher, 1978; Kelman, 1980). The second, deterministic approach, normally involves some rainfall–runoff model which converts actual rainfall data in a simulated catchment into a continuous flow time series. Both approaches may be used successfully, but the latter has, perhaps, a potential for wider application in ecohydrological studies, where the real historical sequences of flows are preferred.

The difficulties with rainfall–runoff simulation method are associated with the reliability or representativeness of the model employed and the ability of the user to satisfactorily quantify the parameter values for the specific catchment under investigation. If the user has to rely upon calibrating the model against observed data, the constraints are similar to those that might apply to the regionalisation approach described above. The question then concentrates on whether there exists enough faith in the ability to construct models which do not rely upon calibration to produce satisfactory results. These models would then require regional techniques for estimation of model parameter values which, especially in the case of a daily time step model, is a very difficult task even if the model is explicitly physically based.

The model employed should be flexible enough to adequately conceptualise and simulate various low-flow generation mechanisms. Therefore extensive testing is requited to ensure that a model can be reliably applied over the range of physiographic conditions for the purpose of simulating different aspects of low-flow regimes. Methodological aspects of model calibration with specific regard to low flows are currently not well developed. Most of the goodness-of-fit criteria used in deterministic rainfall–runoff modelling focus on how well the simulated hydrograph shape, flood peaks and flow volumes match with corresponding observed features (e.g. Green and Stephenson, 1986). These criteria therefore provide relatively little information about the quality of low-flow simulations and it is necessary to consider other criteria, which reflect the model performance in the low-flow domain of a continuous daily streamflow hydrograph.

The unconventional approach in this regard (also in principle applicable in a low-flow context) was suggested by Khan (1989), who described the technique for evaluating rainfall–runoff model performance between or above prescribed flow rates. In the first case, the range of the observed discharges is divided into bands, whose limits are defined in terms of fractions of the highest recorded peak. For a given band, the model performance is calculated considering only the observed discharge values occurring within that band, and comparing with the corresponding simulated discharges. In the second approach, the model performance is evaluated by considering only the discharge values above each threshold level and the corresponding computed discharges. Within each band, or above each threshold, any standard criterion of fitting may be used. To be more meaningful in a low-flow context, the second case may be slightly modified to consider discharges below certain thresholds.

Gustard and Wesselink (1993) and Smakhtin et al., (1998b) suggested to use various existing low-flow measures and indices as criteria of daily model performance in a low-flow context. The model simulations may be evaluated by comparing observed and simulated 1-day FDCs (annual, seasonal or monthly), frequency and duration of low-flow spells below certain reference discharges, the frequency and duration of small increases in flow during a dry period, hydrograph recession rates and baseflow volumes.

One advantage of the modelling approach which makes it very attractive in many water related problems including low-flow studies, is that, if an ‘appropriate’ model is used, it gives a complete flow time-series from which various low-flow characteristics can be extracted. Another advantage is that various scenarios of water use development, land-use change and even climate change can be easily incorporated into the parameter set used to simulate the time-series and to examine their effects on the derived low-flow indices. Duba and Pitchen (1983) used the Streamflow Synthesis and Reservoir Regulation (SSARR) model to check the reliability of extremely low-flow values, which occurred within a sequence of monthly flows used for firm energy estimates for a Bolivian river basin. Clausen and Rasmussen (1993) used the numerical model to obtain an understanding of the hydrogeological effect on the temporal variation of runoff and estimation of low-flow statistics in small catchments in Denmark. Clausen et al., (1994) used modelling approach to investigate the impacts of groundwater abstractions on low-river flow. Lanen et al., (1993) examined the interactions between low flows and catchment hydrogeology simulating spatially distributed nature of recharge and pearmeability. Smakhtin and Watkins (1997) demonstrated the application of daily rainfall–runoff model for the generation of flow time series representative of ‘present-day’ and natural catchment conditions. These time series have then been used to illustrate the spatial variability of selected low-flow characteristics in several catchments in South Africa.

Despite the fact that rainfall–runoff models have a long history and ‘successful carrier’ in hydrological science, their application specifically in low-flow studies to date has been relatively limited. This is most likely going to change in the nearest future with the increasing pressure on water resources and more emphasis on environmental importance of low flows.

6. International initiatives in low-flow research

The traditional methods of low-flow estimation and analysis differ significantly in different parts of the world. Since the last successful attempt to present an overview of methods used in different countries for low-flow estimation (McMahon and Arenas, 1982), the significant efforts in low-flow research have been concentrating on the identification of the best low-flow characteristics to be used in different regions and water related fields and on the improvement of the accuracy of predictive techniques, using the expanded national flow databases and advanced computer technology. Low-flow research in some regions of the world, for example, the republics of the former USSR and countries of Eastern Europe, until recently remained mostly unknown to the broad hydrological community due to the language barrier and limited participation of the former ‘socialist camp’ in international projects. However, the low-flow related research in these countries has been significant and worth a separate review (the same in fact applies to scientific contributions of this region to other directions of hydrological science).

In the past decade, there emerged prominent international research activities that break the national boundaries and encourage participating countries to communicate and exchange their national flow databases for research purposes, including low-flow studies. These activities are mostly associated with rapidly developing international cooperation within the framework of the FRIEND projects. The first project of this kind, FREND (Flow Regimes from Experimental and Network Data) was initiated by the Institute of Hydrology (UK) and represented a contribution to UNESCO’s International Hydrological Programme-III for 1985–1988 (FREND, 1989). It was the practical example of cooperation involving 13 European countries. Its main focus was on the use of international flow databases for the application of regional methods of analysis with the primary emphasis on high and low-flow prediction. The study of the low-flow regimes of 1350 rivers of north-west Europe was conducted as part of the FREND project (Gustard and Gross, 1989). The relationships between low flows and catchment characteristics were analysed with particular reference to the role of soil type in determining catchment response. Flow frequency analysis identified consistent relationships in the region between the mean and the variability of annual minima and between low flows of different durations. Clear regional patterns of seasonal runoff were identified and the spatial variation of low flows appeared to be larger than that of the flood statistics. Analysis of the frequency of occurrence of low flows revealed a regional consistency of the relationship between the magnitude of annual minimum flows and the variability of low flows (e.g. it has been shown that estimates of the annual minima of different return periods could be derived from a knowledge of the MAM10).

The first European FREND project employed an extensive database of daily flow data and catchment characteristics from national network and research basins throughout western Europe. At further stages, FRIEND (Flow Regimes from International Experimental and Network Data Sets) activities (FRIEND, 1994, 1997) have developed horizontally (involving countries of the former Eastern block) and vertically (expanding into scale problems and methodologies, assessment of catchment land-use changes on high and low flows, water quality studies, etc).

The FRIENDS initiatives are currently rapidly expanding into other regions of Europe as well as into the other parts of the world: Alpine and Mediterranean Region, Western and Central Africa, Nile countries, Southern Africa, Hindu Kush Himalayan region. Some of the most recent results of ongoing FRIEND projects have been summarised in FRIEND (1997). This source presents amongst the others, the summaries of recent FRIEND studies of low flows and droughts in Northern Europe, regional water resources and drought assessment methods in Southern Africa, the analysis of long-term effects of rain shortage on low flows in Western and Central Africa, analyses of low-flow time series with zero discharges, discussion of emerging principles of regional ecohydrology and integrated water management.

International collaboration in FRIEND hydrological projects allowed a variety of analytical techniques to be applied to large regional data sets not confined by national boundaries, and currently represents perhaps the most powerful driving force of development in regional low-flow hydrology studies.

7. Low flows in river ecology studies and environmental flow management

The major problem in the management of rivers has been how to balance the tradeoffs between instream (e.g. aquatic life, and recreation) and out-of-stream (e.g. reservoir regulation) uses. Management problems normally exacerbate during low-flow periods and with on-going water resources development resulting in gradual reduction of flow available for instream uses.

Heicher (1993) outlined a number of possible environmental effects caused by instream flow reduction. Such reduction may lead to increased sedimentation that changes the morphology of the stream channel and flood plain. Changes in stream morphology may potentially affect the distribution and abundance of stream biota. Streamflow reduction can also aggravate the effects of water pollution. Winds, bank storage, spring seepage, tributary streams, and the warming effect of the sun usually have a greater effect on stream water temperatures during low-flow periods. With the overall reduction in flow, the influence of these factors increases. Lowering the water table and/or reducing overbank flooding may result in changes in the density, productivity, and species composition of wetland and riparian vegetation. Streamflow reduction may cause changes in the relative abundance of algae, allochthonous material and organics, which may influence the abundance and distribution of benthic macroinvertebrates. Changes in aquatic habitat caused by extended low-flow periods may result in long-term changes in species distribution and abundance. Increased siltation and adverse water quality effects associated with unnaturally persistent low flows can alter the distribution and abundance of fish, etc.

Traditionally, the problem of balancing instream and out-of-stream uses has been addressed by optimizing the economic benefits of flow diversions and reservoir releases with instream uses as a flow constraint. An alternative approach is to analyse different types of flow patterns, resulting from, for example, reservoir regulation and to determine their potential instream impact (e.g. Gustard and Cole, 1987; Flug and Montgomery, 1988). Some sources state that the majority of present day compensation discharges were set to satisfy river interests which no longer apply or were based on inadequate hydrological or biological information (Gustard, 1989).

Previous methods of environmental flow assessment had a focus on the most sensitive or economically/ecologically important user. Hooper and Ottey (1982) examined the impacts of low and high discharge fluctuations on benthos communities. Singh (1983) suggested the method based on fish preferences and incremental costs to provide extra storage to meet the environmental low-flow releases. Tsai and Wiley (1983) focussed their attention on fish species diversity and composition. Williams and McKellar (1984) illustrated the trade-offs between hydro energy and aquatic ecosystem productivity. Some researchers reported the attempts to identify particular low-flow indices of ecological significance (King et al., 1995; Clausen and Biggs, 1997).

Well-known techniques of ecological flow assessment include Tennant (or Montana) method which displays required seasonal flows for fish and wildlife as percentages of the mean annual flow, and the wetted perimeter technique which estimates a desired low-flow value from a habitat index that incorporates stream channel characteristics (Tennant, 1976; Lamb, 1989). A more widely used method of environmental flow assessment is Instream Flow Incremental Methodology (IFIM—Nestler et al., 1989; Stalnaker et al., 1994). A primary component of IFIM is the Physical Habitat Simulation System (PHABSIM). It is used to relate total habitat area for particular species to river discharges. This is then combined with a FDC and a habitat duration curve is produced. The IFIM method is best adapted for use in tradeoff analyses but is also very complex and requires considerable time, money and technical expertise. Orth and Maughan (1982) claimed that IFIM applications are limited in many situations because the required input quantitative biological information is scarce. King and Tharme (1994) indicate that in traditional IFIM, the emphasis is placed on target species and not on the management of the complete instream and riparian components of river ecosystems. The output of IFIM is not a recommended modified flow regime as would be required for the whole river management plan. Karim et al., (1995) classified the variety of previously developed instream flow assessment techniques into: (i) historic flow methods; (ii) hydraulic rating methods; and (iii) habitat rating methods and analysed these methods in detail.

Management of rivers for some specific purpose (e.g. to satisfy fish requirements) is no longer viewed as an entirely valid approach. Rivers are now considered as balanced ecosystems and recommendations are often required as to instream flows which would ensure fish passage, temperature levels, different habitats maintenance, sedimentation control, recreation etc. Narayanan et al., (1983) suggested that instream flows should be evaluated in the context of multiple uses where each use has water requirements that vary over time in a unique way. The largest should determine the overall instream requirement at any given time and must be considered in competition with the demand for municipal and agricultural uses.

With the increasing pressure on water resources came a recognition that the aquatic environment is not a user of water in competition with other users, but is the base of the resource itself, which needs to be actively cared for if development is to be sustainable. This principle received particular attention in countries with limited water resources, like South Africa and Australia. The Australian ‘Holistic Approach’ (Arthington et al., 1992) and the South African Building Block Methodology (BBM—King and Tharme, 1994; King and Louw, 1998) are both aimed at the determination of the required nature of a river’s modified flow regime. In BBM, this regime is described in terms of month-by-month daily flow rates (Instream Flow Requirements—IFR) which should maintain the river in a prescribed ecological condition (and/or satisfactory status for downstream users) after any water resource development is taking place. The process normally involves a multidisciplinary team of specialists from aquatic ecologists to water engineers and is implemented in any river system where such water resource developments are planned.

The components of a flow regime which are considered important for the estimation of IFR include low flows, small increases in flow (freshes) and small and medium floods. Large floods, which cannot be managed, are normally ignored. More specifically, the instream flow assessment process has the following objectives:

- To establish low-flow and high-flow discharges for ecological river maintenance for each of the 12 calendar months of the year. Additional information that describes the required duration of high-flow events and the severity of low-flows (in terms of their probability of occurrence) is often also included.
- To determine minimum flow requirements during drought years. These are also determined as a set of month-by month daily flow rates and are viewed as the flows which could prevent the irreversible damage to the river system during extreme droughts.
- To estimate the total water volume (ecological reserve), which will be required to maintain the desired ecological state of the river after the water resource development has been implemented.

The process requires the description of (preferably) natural flow regime and the streamflow time-series data with daily time resolution. IFR are estimated at several different sites below the proposed impoundment or other water resource development. The estimation of IFR is an information consuming process where the hydrological information (including low-flow data) is a basic need and at the same time a primary component for final recommendations. The recent development related to the IFR estimation includes the work by Hughes et al., (1997) where the technique to convert tabulated monthly IFR values into continuous daily modified flow time-series (e.g. daily reservoir releases) has been suggested. Hughes (1999) has further suggested to use this technique to estimate the assurance levels, or frequency of exceedence, for different BBM components. This extension of the IFR methodology opened the way to implement the ecological flow recommendations within the context of a water resource plan or management scheme for the river.

The reviews of ecological flow assessment techniques (which also include the role of low flows) are provided by Estes and Osborn (1986), Karim et al., (1995), Tharme (1996) and Petts and Maddock (1997).

One direction which is receiving increasing attention in the recent years is the economic aspect of low-flow management. Postle et al., (1997), Willis and Garrod (1999) and Moran (1999) investigated the benefits of low-flow alleviation for different purposes, reviewed the techniques which ensure that a balance is achieved between financial costs of low-flow alleviation and environmental benefits and analysed the techniques based on benefit transfer, whereby the economic values of low-flow alleviation estimated for one project are transferred to another.

8. Low flows and climate variability

The issue of possible climate change impacts on streamflow have been extensively investigated in recent years. However, the studies, which address this problem normally focus on changes in long-term means of climatic and hydrological characteristics. The studies are normally performed in two distinct directions: either through the analysis of available historical flow records or by investigation of the effects of various possible climate change scenarios on streamflow by means of hydrological models.

Schaake and Chunzhen (1989) reported the evidence of probable greater effects of climate change on low flows than on high flows. Liebscher (1983) has demonstrated different effects of climatic variability on high and low flows. He also illustrated regional differences in the effects of climatic variations on streamflow in different portions of the Rhine river basin using the longest historic hydrological records dating back into early nineteenth century. The decreasing trend in mean annual minima of rivers in Slovakia in the recent period have been identified by Majercakova et al., (1995, 1997). Using the data from the Mississippi catchment, Telis (1990) has demonstrated that cyclic patterns of streamflow correspond to cyclic patterns of rainfall and suggested a method for improvement of low-flow characteristics estimation for climatic cycles.

Wood (1987) identified some evidence that the weather in the UK is becoming more variable, with a tendency for drier summers and wetter autumns. He also stated, however, that this pattern has been observed only over the past 10 years and probably represents a small perturbation in the long-term cycle of climatic change. It was suggested that engineering hydrologists should consider using paleo-hydrological data to improve the estimates of flood and drought severity.

Arnell (1989) investigated the possible changes in frequency of hydrological extremes in Europe. He stated that the problem of identification of such changes from observed data is complicated by the short periods of records. The detected increase in dry and warm summers does not appear to have resulted in lower low flows. Low flows were lowest over much of Europe during the mid-1970s, and only in parts of northern Britain and Denmark the lowest flows were experienced in the 1980s. The observed changes seem consistent with, but do not necessarily confirm, the possible effects of global warming associated with the greenhouse effect. It was concluded that the conventional approach of using flow records from the past as a reasonable model for the future is unrealistic. Determining the effects of temporal change on estimates of events with high return periods is difficult because such estimates have a high sampling variability even under stationary conditions.

Wilby et al., (1994) have used the modelling approach to translate the climate change predictions produced by general circulation models at the macro scale into hydrological concerns at the catchment scale. A range of synoptic scenarios has been used and the effects of these scenarios on several indices from a FDC with particular emphasis on low flows have been illustrated using example catchments in UK. It appeared that the most affected flow indices are Q10 and Q50, while extreme low flows (e.g. Q90) are affected mostly by land-use rather then by climate change.

Querner et al., (1997) have studied the impact of land-use, climatic change and groundwater abstractions on streamflow droughts using four different physically-based models operating with daily and monthly time step. Several climatic scenarios have been used (temperature increase by 2 and 4°C in combination with precipitation increase and decrease by 10%) and the model have been applied to five small European catchments. A drought has been defined as the continuos low-flow event below Q70, characterised by its duration and deficit. It has been found that both duration and deficit are increasing in most of the catchments as a result of possible climate warming. In catchments with lower precipitation and higher storage capacity, the drought duration is increasing substantially. An increase in precipitation would be able to compensate the effect of an increase in temperature.

In general, despite the obvious importance of the issue of climate related low-flow change, the literature, which specifically investigates such effects, is relatively scarce at present. The concepts of low-flow prediction in non-stationary climate conditions should also receive more focus.

9. Conclusions

- Despite the significant amount of specialist knowledge that has been accumulated in the field of low-flow hydrology in the past decades, the understanding of specific low-flow generating mechanisms and relevance of different gain and loss processes to the wide variety of climatic, topographic and geological conditions remains rather limited. This is probably the result of limited experimental low-flow studies. At the same time, identification of relative importance of various low-flow generating mechanisms and factors in a particular catchment and/or region should ideally precede any low-flow analysis.
- Due to the variety of direct or indirect anthropogenic impacts on streamflow in river catchments, the low-flow regimes of many rivers have been significantly modified and the origin of water in a stream during low-flow conditions has been changed. In many cases, low flows have been effectively either removed from the streamflow, (due to various abstractions) or artificially generated (from irrigation return flows, discharges, reservoir releases for downstream users). At the same time, the impacts of some anthropogenic processes on low flows (e.g. deforestation, groundwater pumping, conservation farming) are not always properly understood and quantified and need to be investigated.
- Each combination of both the dominating natural processes and the anthropogenic impacts has a different effect on or implications for various aspects of low-flow regime, low-flow analysis and catchment management. Most of the low-flow studies, however, still investigate the relationships between low-flow characteristics and natural catchment conditions. While this is clearly a very important point of departure, more attention should be paid to the development of methods which quantify the individual and combined effects of various anthropogenic processes on low-flow characteristics. Possible approaches may include both: (i) development of databases of anthropogenic impacts and their subsequent analysis; (ii) scenario modelling.
- With the increasing general pressure on water resources, more emphasis will be placed on: (i) finer temporal resolution of hydrological data; and (ii) utilisation of resources of small catchments. Both statements imply that temporal and spatial downscaling of hydrological data is likely to form a promising direction of future low-flow research. The use of daily streamflow data is effectively already a prerequisite for any detailed low-flow study. The methods for low-flow estimation in small ungauged catchments should be in the focus of future research.
- Understanding of low-flow processes and reliable low-flow information will attract more focus from the side of integrated and environmentally sustainable catchment management. In the context of such management, low flows should rather be viewed as a dynamic concept and not described by just one single low-flow characteristic. The preference should therefore be given to the time series of flows, from which the variety of low-flow indices may be extracted to satisfy different management and engineering purposes. Alternatively, more emphasis should be placed on the application of condensed information general measures of catchment flow response, such as FDCs.

- In the view of increased attention to low-flow studies at small scales and to the accuracy of low-flow prediction methods, the use is expected to be made of larger regional databases of flow characteristics. Consequently the efforts should be concentrated on regional international hydrological projects which imply the exchange of hydrological information.
- In the view of growing attention to climate variability, additional research is required regarding the specific issue of low-flow changes under changing climate conditions. The concepts of low-flow prediction in non-stationary climate conditions for engineering and management purposes should receive more focus.

The paper intended to look at the subject of low-flow hydrology in general, considering the variety of its research directions, practical applications and emerging trends. Although the paper has examined a number of (primarily) recent literature sources, it seems to be virtually impossible to include in a review all relevant publications, even those, which have appeared during the last two decades only. It is possible that some aspects of the subject have either been overlooked or only briefly referred to. Some of the aspects of low-flow hydrology have been deliberately only marginally considered here and they deserve a more comprehensive, special review. It is expected that these gaps could be filled by subsequent contributions and that there is a scope for further discussion about the current status and prospects of low-flow research, possibly in the broader context of future development of the entire hydrological science.

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