

Chapter 2

Methodology

2.1 Principles of Drought Analysis and Assessment

2.1.1 Drought Definitions and Types

The term “drought” has nowadays a large number of definitions and it is seen from different perspectives. Drought generally starts with a lack of rainfall. Its symptoms significantly affect the intensity of evapotranspiration. It affects the air and soil moisture, runoff characteristics of the surface- and groundwater. Definitions of drought we know relatively numerous, due to its temporal and spatial variability, as well as due to different ways of perception with regard to the purposes for which it is defined. The definitions of drought, which are used in practice, determine the start, end and eventually the intensity of the impacts on various assessed fields. Any definition is not useful in all circumstances. In the literature it is divided into several types, according to the location of the occurrence in the hydrological system (Fig. 2.1).

From the Fig. 2.1 it is evident that drought is possible to assess in the hydrological cycle at different levels, where it is necessary to use different methodologies for this purpose. Equally, the time shift and different levels of drought intensity are visible in various parts of the hydrological system. Figure 2.2 shows the classification of drought. It shows that all types of drought originated from the lack of rainfall or from negative development of other climatic factors such as transpiration, evaporation, air temperature, wind speed and humidity. Other factors that affect the occurrence of drought in the hydrological system are vegetation (the nature and distribution of vegetation cover), geomorphology (slope orientation, slope degree) geological and hydrogeological conditions (e.g. hydraulic properties of the rocks massif). Due to many factors that affect the formation and occurrence of drought, the problem is relatively complex. We must also take into account that in the catchment there may occur synergy effects, combining several negative factors in the drought origin.

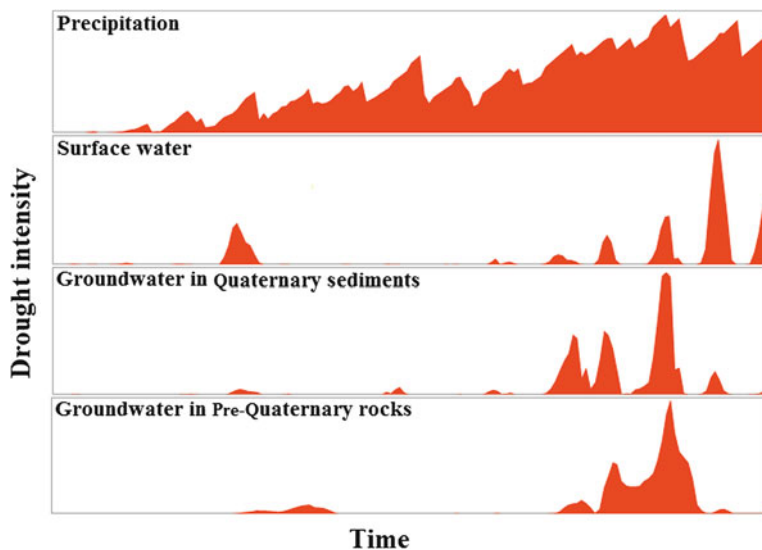


Fig. 2.1 Schematic illustration of drought occurrence in hydrological system

The degree of drought abnormality probably never will be quantitatively defined using a variety of climatic indexes for comparing with previous cases, because of the interaction complexity between meteorological, hydrological and other factors (Bagar in Rožnovský and Litschman 2003). Drought is normal, repeated state of climate that is associated with its oscillation (fluctuation). Many people believe that it is a rare and random event. Drought as a temporal climate anomaly can occur in all climatic zones (precipitation regimes).

Drought is very vague but often used term, meaning in principle the lack of water in the soil, plants and atmosphere. There is no universal and generally accepted definition of drought. Willhite and Glantz (1985) provide an overview of more than 150 published drought definitions. There are no uniform criteria for the definition of drought with respect to a variety of meteorological, hydrological, agricultural, forestry, bioclimatological and a number of other factors with regard to damage in various areas of economy. According to Fig. 2.2 we can define three basic, in literature most frequently used types of drought, namely the meteorological, agronomic and hydrological drought.

According to meteorological dictionary (Sobíšek et al. 1993) the meteorological drought is usually defined by temporal and spatial precipitation ratios, for example by the occurrence of the dry or arid period. Hulme (1992) defines a meteorological drought as the precipitation reduction compared on the basis of average conditions in the defined time period. Agronomic drought is defined as a lack of water in the soil affected by the previous or persisting occurrence of meteorological drought. Hydrological drought is defined for the surface waters by a certain number of consecutive days, weeks, months and years with the occurrence of relatively very low flow rates due to long-term monthly or annual normal values. Hydrological

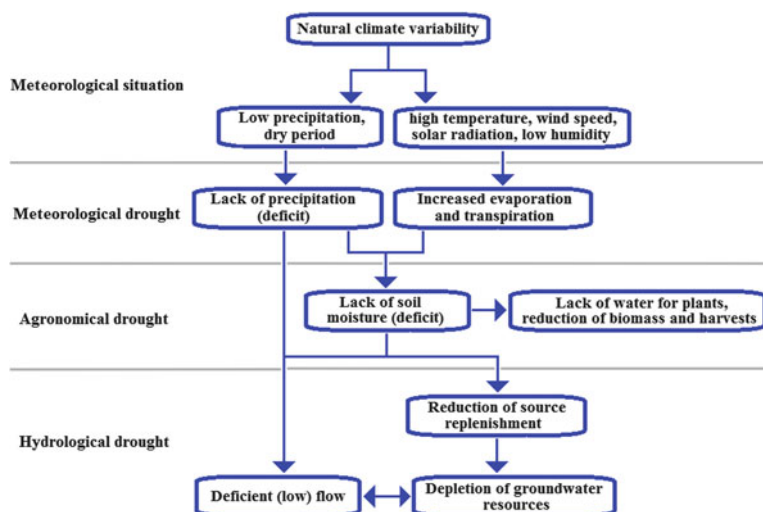


Fig. 2.2 Classification and mechanisms of drought formation (according Rasmuson et al. in Maidment 1993, adjusted)

drought usually occurs at the end of a period with meteorological drought. A similar criterion can also be used for the groundwater (groundwater levels, spring yields). Hydrological drought is often due to retardation effects which occur in a time when meteorological or agronomic drought has ended. Conversely, when the meteorological drought occurs, there does not occur the hydrological drought (Bagar in Rožnovský and Lischman 2003). Wilhite (1993) defines the hydrological drought as the impact of the rainfall reduction on the system of surface and groundwater sources due to the previous period of meteorological or agronomical drought. In various areas other terminological types of drought are used. For example the ecological drought is defined as the stress of water scarcity in the ecosystem, affecting the fauna and flora lives and development. Definition of the socio-economic drought refers to the impacts of water scarcity in economics and society. Some authors also classified the hydrological drought to drought in system of the surface water and groundwater (Tallaksen and van Lanen 2004; Fendeková and Ženišová eds. 2010). Drought can be also divided according to the occurrence period in the year to summer and winter drought. For the winter drought there has been dedicated a significant attention in the paper van Loon et al. (2010).

2.1.2 Drought Risks and Impacts

Drought is often causing large damages. Water scarcity and drought have large direct and indirect consequences. From the history, we know that a key issue for the society development has always been a sufficient quantity of the water for

Table 2.1 The examples of direct and indirect impacts of drought (modified by Tallaksen and van Lannen eds. 2004)

| Aspect | Impacts Direct | Indirect |
|---------------|--|---|
| Environmental | <ul style="list-style-type: none"> • Soil moisture • Groundwater level • Runoff • Springs' yields • Surface runoff • Water level in lakes • Available (exploitable) amounts of drinking water | <ul style="list-style-type: none"> • Water quality • Biomass development • Biodiversity • Dust storms • Desertification • Forest fires |
| Economical | <ul style="list-style-type: none"> • Exploitation of surface water • Exploitation of groundwater • Diminishing of drinking water sources | <ul style="list-style-type: none"> • Irrigation water • Water for farming • Failure of irrigation • Loss of animals on farms • Reduction of navigable rivers • Reduce of hydroelectric power production • Food prices increasing • Reduction of economic growth |
| Social | <ul style="list-style-type: none"> • Drinking water | <ul style="list-style-type: none"> • Conflicts and conflicts of interest |

consumption. In some areas of the world, drought is often the most destructive natural disaster, what may in the region occur. In the history a large number of drought disasters are documented. Table 2.1 defines the basic impacts of the drought on nature, man and society.

Drought is the limiting factor for the development of large areas in many countries. For example, in sub-Saharan part of Africa 60 % of areas is threatened by the drought impact and highly vulnerable is more than 30 % of the territory (IFAD 1994). The history described a large number of dry periods. Mostly it was a period of less than 3 years and these events have caused large economic damages and affect the life quality for the large population. Table 2.2 shows examples of the most serious droughts in recent years.

Regarding the foregoing, we can say that the risk assessment of drought occurrence and its analysis is important, because it affects not only the environment, but also has significant impact on society and can cause great damage, which assessment can be determined only approximately.

2.1.3 Methods of Drought Assessment

The choice of method for drought analysis and assessment depends on the type of available data and on the purpose for which the assessment is used. The individual types of data used in drought analysis are described in Table 2.3.

Table 2.2 Selection of the most serious drought extremes in the world with their influence (according OFDA/CRED 2002)

| Area | Period | Impact |
|-------------------|-----------|---|
| Sahel | 1980 | • >10 mil. people affected |
| Brazil | 1983 | • 20 mil. people affected by food shortages |
| India | 1987 | • 300 mil. people affected (poor harvest, lack of drinking water) for weak monsoon |
| China | 1988 | • 49 mil. people affected • 1,400 deaths • 11.3 mil. ha of agricultural crops damaged • 943 mil. loss in USD |
| Albania | 1988–1991 | • 3.2 mil. people affected |
| California (USA) | 1991 | • 1 bil. loss in USD |
| Spain | 1991–1995 | • 6 mil. people affected • 4.5 bil. in USD loss in agriculture |
| Australia | 1992–1995 | • 1.75 mil. people affected • 1.05 mld. loss in USD |
| Ethiopia | 1996–2000 | • 10.6 mil. people affected by 4-year period of drought |
| Tajikistan | 2001 | • 3 mil. people affected • 250,000 ha of damaged agricultural crops • 57 mil. loss in USD |
| Honduras (Mexico) | 2001 | • 0.8 mil. people affected • Losses recorded on 96 000 ha of agricultural land |

The principal data types that we use in the drought analysis are the time series of monitored values. It is going on the monitoring of certain characteristic in the hydrological cycle, which is measured in a defined time step for the spatially defined location. Concerning this definition, we can say that these are the point measurements. These data are constant in time and variable are only in the term of time. If we have enough measured point values from assessed area, we can obtain by the interpolation or extrapolation the spatial characteristics of the analyzed parameters. Spatial values are included in the second group of data. These data are known as thematic and are generally stored or processed in the environment of geographic information systems. Into this group there are also included data that are constant in time, like as for example geological conditions, morphological structures, etc. Thematic data are often a base for various types of modeling (e.g. modeling of the groundwater flow, transport of chemicals and heat, etc.). The last group of the data type represents metadata. Metadata have often cataloging and classification purposes and represent in fact the data about data. Their role is to describe the data from the previous two groups. They include information on the coordinates of monitored points, measurement methods, on definitions of monitored values, quality and accuracy of measurements or used units.

Regarding the diversity of input data and its different availability (precision) for the drought analysis many diverse methods were developed. It was also created a number of methods according to the purpose for that was drought assessed. In this

Table 2.3 Types of data used for the drought assessment

| Data types | Examples |
|---------------|---|
| Time series | River discharges Springs' yields Groundwater levels Water temperature Air temperature Evapotranspiration Water quality parameters Precipitation Wind direction and speed |
| Thematic data | Annual precipitation Specific groundwater runoff Average annual air temperature Geological settings Geomorphological settings Stream network density Land use Boundary conditions Vegetation cover |
| Metadata | Coordinates of monitoring points Methods of data collections for monitored parameters Definition of monitored parameters Units of monitored parameters Quality of measured data Definition of measurements' time step Other information |

chapter there will be described selected methods for the drought assessment and evaluation. The assessment of hydrological drought will be described in the following chapter.

2.1.3.1 Methods of Meteorological Drought Assessment

Meteorological drought was defined by several authors as:

- period with an average precipitation less than 0.004 mm per 48 h (Blumenstock 1942)
- period with precipitation less than specified low value (GBMO 1951)
- a period with the high-intensity wind activity, low precipitation, high temperatures and low soil moisture (Condra 1944)
- days with very to extremely low soil moisture (Bavel and Verlinden 1956)
- the period when the monthly or annual precipitations are less than long-term average value (McGuire and Palmer 1957)
- the conditions in which we can say that the lack of precipitation negatively affects normal human activity (Hoyt 1942)

Table 2.4 Classification of climatic regions according to Lang's precipitation factor (Brušková 2007)

| D_f | Area |
|--------|--------------------------|
| <60 | Dry, irrigation required |
| 60–70 | Relatively dry |
| 70–80 | Transient |
| 80–100 | Wet |
| >100 | Very wet |

As shown in Figs. 2.1 and 2.2, the meteorological drought is caused by natural climate variability and mostly by the lack of precipitation or high evapotranspiration. This type of drought occurs as the first. For its assessment there are commonly used values of daily precipitation and average daily air temperature. Several methods are built on evaluation of these parameters. The most often used are the precipitation factor by Lang (D_f), classification in terms of humidity and the average consumptive water confidence (α) by Minař (Brušková 2007).

Precipitation factor by Lang (D_f)

This method is based on the relationship between precipitation and the air temperature. It is expressed as follows (2.1). Climatic regions classified by this method are shown in Table 2.4.

$$D_f = \frac{Z}{t} \quad (2.1)$$

Total precipitations (Z) are calculated for each year (in mm) and parameter t is the average annual air temperature in individual years ($^{\circ}\text{C}$).

Classification in the terms of humidity (H_{zr})

Classification in the terms of humidity is based on comparing of a percentage of annual precipitations to the long-term precipitation normal (Team of authors 1960). Individual years are then classified according to Table 2.5.

Average consumptive water confidence by Minař (α)

By relations (2.2) and (2.3) the average consumptive water confidence α is expressed:

$$\alpha = \frac{S - Z}{t} \quad (2.2)$$

where

S precipitation amount in year (mm)

T average annual air temperature in year ($^{\circ}\text{C}$)

Z amount of annual precipitations (mm), in which the drought occurs and is the need for irrigation by Eq. 2.3

$$Z = 30(t + 7) \quad (2.3)$$

Table 2.5 Annual classification in terms of humidity (Majerčáková et al. 2007)

| Definition of moisture conditions in individual years | Relation of annual precipitation (H_{RZ}) to long term average (in %) |
|---|---|
| ED—extremely dry year | $H_{RZ} < 70$ |
| VD—very dry year | $H_{RZ} 70\text{--}80$ |
| D—dry year | $H_{RZ} 80\text{--}90$ |
| N—normal year | $H_{RZ} 90\text{--}110$ |
| W—wet year | $H_{RZ} 110\text{--}120$ |
| VW—very wet year | $H_{RZ} 120\text{--}130$ |
| EW—extremely wet year | $H_{RZ} > 130$ |

Table 2.6 Evaluation of the climatic zones by Minař (Brušková 2007)

| Climatic region | Average water security | Number of dry years |
|-----------------|------------------------|---------------------|
| Extremely dry | −4–0 | >50 |
| Very dry | 1–7 | 50–25 |
| Moderate dry | 8–14 | 25–15 |
| Transient | 15–21 | 15–5 |
| Moderate wet | 22–35 | 5–0 |
| Very wet | >35 | 0 |

where

t long-term average air temperature in assessed period

Estimating the proportion of years with precipitations equal to Z or less to the total number of assessed years, their frequency is determined, which is given in Table 2.6. The lower α is, the drought is more significant (Brušková 2007).

In the world literature numerous other methods to evaluate the meteorological drought can be found. Often different index methods are used (e.g. complex indicators of drought), based on various statistical evaluations of the time series in meteorological/hydrological cycle. The most common include:

- Analysis of cumulative precipitation anomalies (Foley 1957)
- Precipitation deciles (Gibbs and Maher 1967)
- Index of precipitation anomalies (Gibbs and Maher 1967)
- Standardized precipitation index—SPI (McKee et al. 1993, 1995)
- Hydro-thermal index—TI, KI (Harlfinger and Kees 1999)
- Palmer's index of anomaly humidity—Z index (Karl 1986)
- Palmer's index of drought intensity (severity)—PSDI (Palmer 1965)
- Index of fertile moisture—CMI (Palmer 1986)
- Specific drought index (Meyer 1993a,b)
- Pluviometric coefficient (Sobíšek et al. 1993)
- Index calculated as a percentage of annual precipitations (Brázdil et al. 1985)
- Index of dryness/aridity (Drlička 2004)

- Šatansky's hydrothermic index (Drlička 2004)
- Končko's irrigations index (Sobíšek et al. 1993)
- Brádka's typing index (Brádka et al. 1961)
- Index of climatic water balance (Škvarenina et al. 2002)
- Monger's index (Drlička 2004)
- Kincer's index (Drlička 2004)
- Marcovitch's index (Drlička 2004)
- Thornwait's precipitation efficiency index—PE index (Drlička 2004)
- Blumenstock's index (Drlička 2004)
- Index of previous precipitations (Drlička 2004)
- Precipitation anomalies index—RAI (Drlička 2004)
- Keetch-Byram's drought index—KBDI (Drlička 2004)
- Drought areas index (Drlička 2004)
- Precipitation reliability index (Sobíšek et al. 1993)
- Precipitation index (Sobíšek et al. 1993)
- Budyko dryness index (Sobíšek et al. 1993)

The currently used index methods have a number of weaknesses, which Byun and Wilhite et al. (1999) notice. Most of the used indices is not able to determine the drought start and end enough precisely. They often work only with monthly average or cumulative values and not include the factor of the water supply loss at a time, which is a function of runoff and evapotranspiration. The disadvantages of certain methods consist of a need of numerous input data. For the purpose of index calculating often must be a number of parameters forecasted or calculated (e.g. runoff or evapotranspiration). The basis of the estimated parameters is the precipitation. Some authors consider that using only precipitation measurements for the meteorological drought assessment is better than the use of complex indices. None of the indices take into account the fact that the effects of drought in different part of environment occur with delay. Therefore, the authors propose new drought indices, which solve the shortcomings of current methods. Daily loss of water resources represent an effective precipitation (EP), to determine which only daily precipitations are needed (Eq. 2.4). Loss of reserves in time represents time dependent reductive function, from which we estimate the current water deficit (Blinka 2002).

$$EP_i = \sum_{n=1}^i \left(\frac{\sum_{m=1}^n P_m}{n} \right), \quad or \quad EP_i = \sum_{m=1}^i \lambda_m P_m \quad (2.4)$$

where

- i summation time
- P_m precipitation before m days
- λ_m weight of precipitation

A series of other indices is based on EP method, which allows the estimation of drought duration and intensity, the accumulated precipitation deficit (deviation d from normal), the necessary precipitation amount to return to normal and standardized index of drought intensity, which allows comparison between different temporal and spatial points. There are also used some simple balance-equilibrium models such as:

- FAO model (Allen et al. 1998)
- Normalized differential vegetation index—NDVI (Kogan 1995; Peters et al. 2002)
- DSSAT model (Tsuji et al. 1998)
- GRAM model (Eitzinger and Trnka 2006)

2.1.3.2 Methods for Assessment of Agronomical Drought

According to the simplest definition, about the agronomical drought we are talking when the amount of the soil moisture is insufficient for the plants needs. Thus, the agronomic drought is referred mainly to soil water deficit. It occurs after meteorological drought, but before the hydrological drought. Agriculture sector is often the first of all sectors in economy, which is affected by the drought.

For the assessment of water in soil (Šútor et al. 2007), in the vegetation cover there are chosen by convention the following characteristic points of the soil retention line (characteristic states of retention—water content in soil):

- Wilting point (WP) corresponding to the value $pF = 4.18$ (it is the soil moisture at which plant cover is consistently undersupplied with water from the soil and consequently it is wilting).
- Point of reduced availability (RAP), corresponding to the value $pF = 3.3$ (characterized by the soil moisture content at which plant cover physiological processes are limited by the lack of water).
- Field water capacity (FWP), corresponds to the value $pF = 2.0 - 2.7$ (characterized by the soil moisture, which is maintained in the soil profile over a relatively longer time, while the aeration of soil is still sufficient for the plant cover development).

Evaluation approach for the classification of the soil hygrometry is agronomical classification (Benetin and Šoltész 1988). It is based on the determination of evaluation ratio coefficient A by Eq. 2.5.

$$A = \frac{1}{n} \sum_{i=1}^n (\Theta_i - \Theta_v) / (\Theta_{PK} - \Theta_v) \quad (2.5)$$

where

Θ_i average soil moisture of active root zone in the i -day of balanced period ($m^3 \cdot m^{-3}$)

Θ_v wilting point of the active root zone ($m^3 \cdot m^{-3}$)

Θ_{PK} field water capacity of the active root zone ($m^3 \cdot m^{-3}$)

Table 2.7 Types of hygrometry regime by agronomic classification (Šútor et al. 2007)

| Levels of soil water content | Coefficient A | Type of moisture regime within the balanced period |
|---------------------------------|---------------|--|
| Lack of soil water for plants | <0.11 | Extreme dry |
| | 0.11–0.20 | Very dry |
| | 0.21–0.30 | Significantly dry |
| | 0.31–0.40 | Dry |
| Optimal water content of plants | 0.41–0.50 | Alternately dry |
| | 0.51–0.60 | Alternately wet |
| | 0.61–0.75 | Wet |
| | 0.76–0.90 | Significantly wet |
| | 0.91–1.00 | Very wet |
| Excess of soil water | >1.00 | Waterlogged |

To evaluate the types of soil hygrometry regime under this equation is used Table 2.7.

Agronomic drought is often assessed also by hydrothermal Seljanin's coefficient CHT, which is defined by:

$$K_{HT} = \frac{\sum H_z}{0.1 \sum t_{10}} \quad (2.6)$$

where

$\sum H_z$ sum of precipitation for evaluated period ($t > 10^\circ\text{C}$) in mm

$\sum t_{10}$ sum of average daily air temperatures for evaluated period in $^\circ\text{C}$

The evaluated period is then characterized by Table 2.8.

2.1.3.3 Methods for Hydrological Drought Assessment

The study of hydrological drought means to study the low flow phase in the river and its parameters. Knowledge of the lower extreme flow phase—minimal river discharges is in our country at a relatively high level. It forms a good basis for evaluation of further parameters in the low flow phase—its evaluation in terms of water scarcity, either the size or duration. In this context we are talking about assessing the hydrological drought (Demeterová 2000).

Hydrological drought can be evaluated in several ways, using multiple parameters of the hydrological cycle, using number kinds of methods. Drought in surface waters is defined by low or zero flow. Similarly, groundwater drought and its symptoms we can identify by long-term measurements of water levels and measuring the yield of springs. For the hydrological drought characteristic derivation we usually use a series of measured parameters.

Table 2.8 Period definition according the hydrothermic coefficient (Juva 1959)

| Hydrothermic coefficient | Period characterization |
|--------------------------|---|
| <0.3 | Catastrophic drought |
| 0.31–0.50 | Drought |
| 0.51–0.99 | Lack of water |
| 1.00 | Precipitation equal to evapotranspiration |
| 1.01–2.00 | Water sufficiency |
| >2.00 | Excess of water |

Figure 2.3 provides the basic methods of deriving hydrological characteristics from time series of average daily river discharges. Hydrological drought assessment methods can be divided into two groups. The first group consists of the low flow characteristics. The second way of drought assessment is the use of the analysis of deficits characteristics. Most methods of hydrological drought assessment are based on analysis of original time series of hydrological parameters. In the derivation of hydrological characteristics of low flow we choose minimal discharges by different methods, identified by the long-term observations and as the result is usually a low flow index. Contrary, in determining the deficit characteristics the values from measured time series are taken, being below a defined threshold level. From these results, we compile a time series of deficit characteristics (e.g. length of deficit period, deficit volumes, etc.) and from them the deficit index of drought is counted. On the base of two defined indices there can be then evaluated the vulnerability of interest area with regard to the risk of drought (Tallaksen and van Lanen 2004).

Low Flow Characteristics

This subchapter describes the characteristics, indicators and methods for the low flow determining, which are derived from discharge time series. The variation in climatic conditions combined with different catchment properties forms of different types of water runoff from the catchments. The amount of methods, developed for determining low flow indicators, was developed for rivers and streams with constant non-zero discharge. In contrast, other methods have been developed for intermittent streams or streams with very unstable discharge regime. The basic methods of the low flow analysis include that by Tallaksen and van Lannen (2004):

- Flow duration curves (determining discharge values percentile—e.g. Q90)
- Determination of the average annual minimum N-daily discharge
- Base flow separation (techniques targeted at identifying and separating the various runoff components from catchment discharge)
- Recession curves analysis (focused on analysis of decreasing sections of hydrogram—defining and analyzing the recession coefficients).

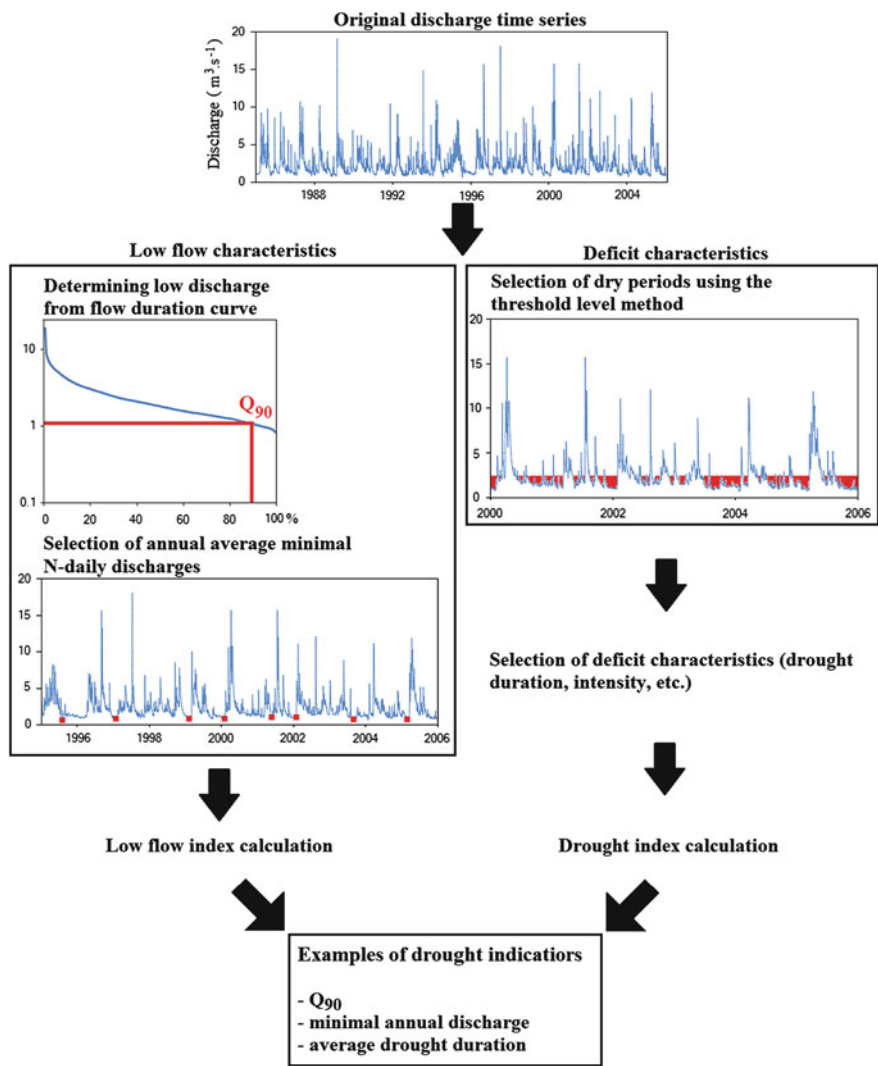


Fig. 2.3 The types of methods for hydrological drought characteristic assessment (according Hisdal et al. 2004, adjusted)

Analysis of flow duration curve

The flow duration curve can be defined as a flow dependence on the probability of achieving or exceeding. Flow duration curve example is shown in Fig. 2.4.

This curve characterizes catchment runoff variability in time. For better readability, the axis showing the discharge is often in logarithmic scale. Flow duration curve is often created from the whole observed period in the river profile. Alternatively, there is possible to compile a curve from specified time periods, such as from the summer seasons, selected days of year or from individual years. The low

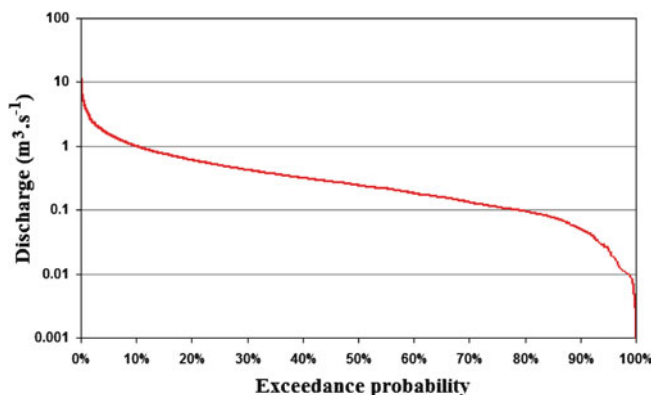


Fig. 2.4 Example of flow duration curve for river profile No. 8740—Slavkovský potok—Brezovica

flow indicators are frequently derived directly from the flow duration curve as the frequency of exceeding of the low discharges. For this index there is well established the statistical term—percentile. Percentile obtained from duration curve defines the percentage probability with which a given discharge was exceeded (Tallaksen and van Lannen 2004). For the analysis of the low flows there was established 90-percentile (Q_{90}). This percentile tells as about the value of discharge, which was in the time series of observed discharges exceeded for 90 % of observed time. For example, for profile No. 8740—Slavkovský potok—Brezovica the Q_{90} value is equal to $0.05 \text{ m}^3 \cdot \text{s}^{-1}$ (Fig. 2.4). The percentile calculations of low flows are well established and used method in many sectors of water management, such as drinking water supply, the design of hydroelectric power, irrigation planning, determining minimum discharges for treated rivers, water withdrawals from the surface water, etc. In the case of multiple flow duration curves construction in one chart is possible to analyze and evaluate differences in the runoff from several profiles in one catchment or from several catchments.

Figure 2.5 shows three flow duration curves from three different Slovak catchments. From the first perspective the differences between the catchments are evident. For the comparability of individual results there are the discharge values ($\text{l} \cdot \text{s}^{-1}$) from catchments recalculated (standardized) to the specific discharge ($\text{l} \cdot \text{s}^{-1} \cdot \text{km}^{-2}$).

The graph shows that the highest specific discharge is in the Belá river catchment (No. 5400—profile Podbanské) and the lowest in the Litava river catchment (No. 7600—profile Plášťovce). It is also possible to characterize the discharges variability from flow duration curve. This variability reflects differences in climate and hydrological conditions between catchments. Low variability in discharges is demonstrated by the curve flatness. On the other hand, the catchment runoff is time-changing with the steeper curve. In the practice, except the percentile Q_{90} there are used also other—lower percentiles. For example, in basins

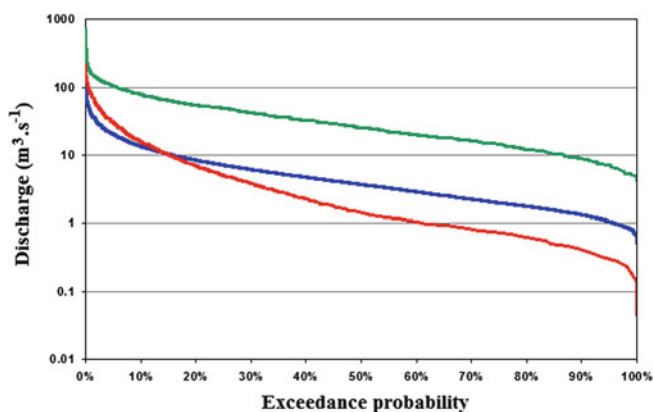


Fig. 2.5 Example of flow duration curves comparing in different catchments (*red*—No. 7600/Litava/Plastovce; *blue*—8780/Torysa/Prešov; *green*—5400/Bela/Podbanske)

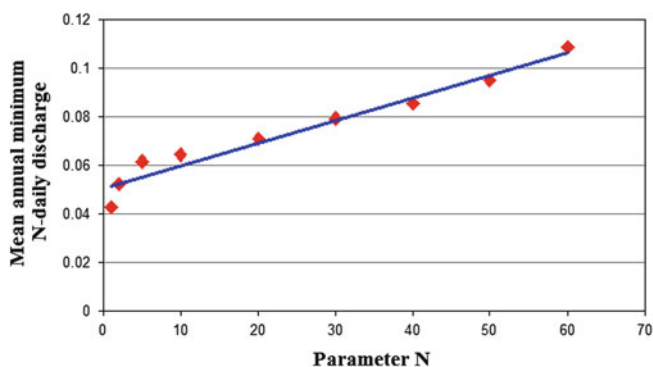


Fig. 2.6 Graph showing the relationship between the average annual minimum N-daily discharges and N parameter in the river No. 8740—Slavkovský potok—profile Brezovica

with intermittent rivers and streams there are used to determine the index of low flow percentiles Q_{80} , Q_{70} , Q_{50} (Tallaksen and van Lannen 2004).

Determination of annual minimal N-daily discharge

For the analysis of low flow, the authors—for example Fleig (2004), use the annual minimal N-daily discharges (AMN-day). The simplest expression of the minimal discharge is the determination of annual minimal 1-day discharge (AM_1), when from the time series the lowest annual values are selected. Unless we get N-daily minimal values (AM_n), we use for this purpose a moving average value. If calculated the N-daily minimal values for several years, we can find by averaging them the average annual minimal N-daily discharge (MAM_n). The most frequent in the study of low flows are average annual minimum 1, 10 and 30-daily discharges (MAM_1 , MAM_{10} and MAM_{30}). In Fig. 2.6 there is an example of the

relationship between the values of the calculated discharges and actual parameter N. It is evident that the longer time step for parameter N is chosen, the higher average annual minimum N-daily discharges we get.

Base flow separation

To identify the individual runoff components from the total runoff the number of separation techniques was established. The individual components represent different paths of the water runoff in the hydrological cycle of the river catchment and are characterized by variability and dynamics of properties in time and space. Total runoff is traditionally divided into surface, sub-surface and groundwater runoff component. It is also used for separation of runoff components in the term of base flow, which is determined as component of total runoff, formed by the groundwater inflow with delayed hypodermic flow into the river (Hanzel et al. 1998). Nathan and McMahon (1990) in their work dealing with different methods focused on the continuous separation of individual runoff components from the catchment. In addition to traditional hydrological separation methods, various isotopic and geochemical methods are used. Their principle is to identify the sources and ages of river water. Another way is recession curve analysis (Bates and Davies 1988). The methodology of the recession curves analysis will be presented in the next subchapter.

For the basic hydrological separation of the base flow from the total runoff, the most often used is the automated—time-based separation method, named *local minimum method* (Institute of Hydrology 1980). The other two methods include HYSEP program developed in USGS. It is the *fixed interval method* and *sliding interval method* (Sloto and Crouse 1996). In the first method (local minimum method) it is in the specified time steps finds the lowest river discharge value. The found value is then multiplied by filter value (usually is set to 0.9). Such a value is then compared with the lowest values from the previous and next time steps. If it is less or equal to both values, then it is leaved in the series, otherwise it is deleted. The entire river discharge time series is processed by this procedure and filtered gaps in series are filled by linear interpolation. Newly formed time series of values form the separated base flow in time (Fig. 2.7a). When using the next method (fixed interval method) the lowest value of discharge is searched in a specified time step and with this value all cells in time step are filled (Fig. 2.7b). The last method (sliding interval method) is based on the same simple principle as the previous one, except that in the separation process it does not shift in time series of the length of evaluated time step, but only one day (Fig. 2.7c).

In addition to the described methods, the recursive digital filters are often used for the separation. Table 2.9 presents the most common filters. There are used from the simple one-parameter filters to various composite multi-parameters or more physically based filters and algorithms. We get the time series of filtered base flow by setting the parameters of digital filters. Changing the parameters in filters changes the resulted base flow and therefore their use requires a sufficiently deep knowledge of this problematic.

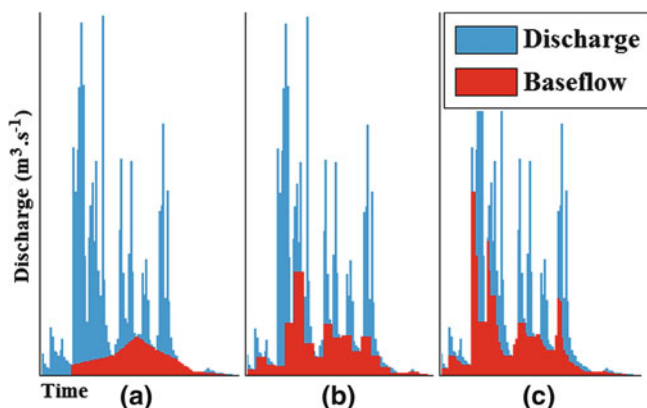


Fig. 2.7 Example of the basic hydrological separation methods used for catchment No. 8740—Slavkovsky potok—profile Brezovica in 2005 (a—local minimum method; b—fixed interval method; c—sliding interval method)

Time series of separated base flow serves mainly for the assessment of the dynamics of groundwater in catchment. For proportional analysis of the base flow to total discharge there is in practice used the BFI index (Institute of Hydrology 1980). BFI index expresses the ratio between the base flow and total discharge. BFI index can be expressed as a time series of daily, monthly, annual or long-term average values. High long-term average value of BFI index reflects a high proportion of the total groundwater runoff in catchment, while low values are typical for the catchments with low influence of the base flow on total runoff. Stojković (2007) calculated specific base flow in 33 catchments and her results determined the average values and range of base flow values for individual geological units in the Western Carpathians.

As mentioned in the literature, there are number of hydrological separation methods and new procedures and methods are still produced. Their use is quite simple (just long enough time series of river discharges) and for the separation there were developed numerous simplification programs. But the problem is that the filtered base flow does not always reflect the real situation. This issue treated in details for example by Xu et al. (2002). Example of this problem is shown in Fig. 2.8, which shows variable hydraulic relationship between surface waters and groundwater in the discharge hydrogram.

For this reason, also other methods of the base flow separation have been developed, such as the method of isotopic and geochemical indicators—*tracers* (Hercold et al. 1995). Natural tracers such as dissolved ions and isotopes, create a direct method for observing interactions between the surface water, groundwater and precipitation. Time series of chemical and isotopic analysis are an appropriate tool for the runoff components separation. The tracers can be divided into conservative and nonconservative according to whether their presence or form in hydrological cycle is changed or altered. The nonconservative tracers include ionic

Table 2.9 The most common recursive digital filters for base flow separation

| Filter name | Filter equation | Notice |
|---|--|---|
| One-parameter algorithm (Chapman and Maxwell 1996) | $q_{b(i)} = \frac{k}{2-k} q_{b(i-1)} + \frac{1-k}{2-k} q_{(i)}$ | $q_{b(i)} \leq q_{(i)}$ Simple filter |
| Boughton's two-parameter algorithm (Boughton 1993; Chapman and Maxwell 1996) | $q_{b(i)} = \frac{k}{1+C} q_{b(i-1)} + \frac{C}{1+C} q_{(i)}$ | $q_{b(i)} \leq q_{(i)}$ Simple filter with includes other parameters such as tracer test by setting the C parameter. |
| IHACRES—three-parameter algorithm (Jakeman and Hornbarger 1993) | $q_{b(i)} = \frac{k}{1+C} q_{b(i-1)} + \frac{C}{1+C} (q_{(i)} + \alpha_q q_{(i-1)})$ | Extension of Boughton two-parameter algorithm. |
| Algorithm of Lyne—Hollick (Lyne and Hollick 1979; Nathan and McMahon 1990) | $q_{f(i)} = \alpha q_{f(i-1)} + (q_{(i)} - q_{(i-1)}) \frac{1+\alpha}{2}$ | $q_{f(i)} \geq 0$ The recommended value of α is 0.925, base flow is calculated by formula |
| Chapman's algorithm (Chapman 1991; Mau and Winter 1997) | $q_{f(i)} = \frac{3\alpha-1}{3-\alpha} q_{f(i-1)} + \frac{2}{3-\alpha} (q_{(i)} - \alpha q_{(i-1)})$ | $q_b = q - q_f$ Base flow calculated by formula: $q_b = q - q_f$ |
| Filter of Furey and Gupta (Furey and Gupta 2001) | $q_{f(i)} = (1 - \gamma) q_{b(i-1)} + \gamma \frac{c_3}{c_1} (q_{(i-d-1)} - q_{b(i-d-1)})$ | Physically based filter, using volume balance equation for base flow calculation. |
| EWMA algorithm (Tularam and Ilahee 2008) | $q_{b(i)} = \alpha q_{(i)} + (1 - \alpha) q_{b(i-1)}$ | Exponential smoothing applied for base flow calculation |

$q_{(i)}$ —total runoff

$q_{b(i)}$ —filtered base flow

$q_{f(i)}$ —filtered direct runoff

k —digital filter parameter, obtained from the recession coefficient

α , α_q —digital filter parameters

C —parameter affecting the shape of the separated base flow curve

γ , c_1 , c_3 —physically based parameters of digital Furey—Gupta filter

composition of dissolved water substances. Changes in form and concentration of ions in water within the hydrological cycle help us to identify the environment in which the chemical composition of dissolved substances of water was formed or altered.

From the stable isotopes there are monitored and used mainly the oxygen and hydrogen isotopes (^2H , ^{18}O). These tracers are considered as conservative (Sklash

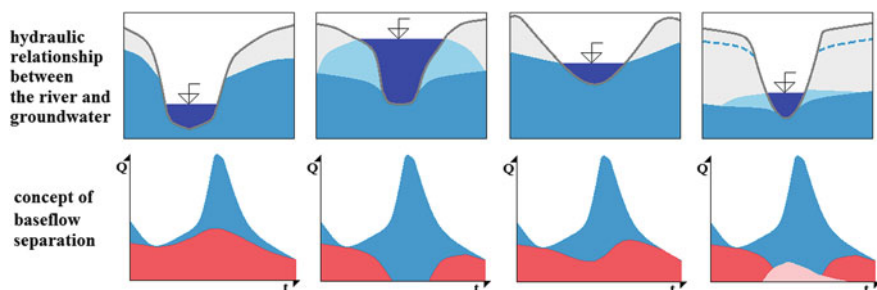
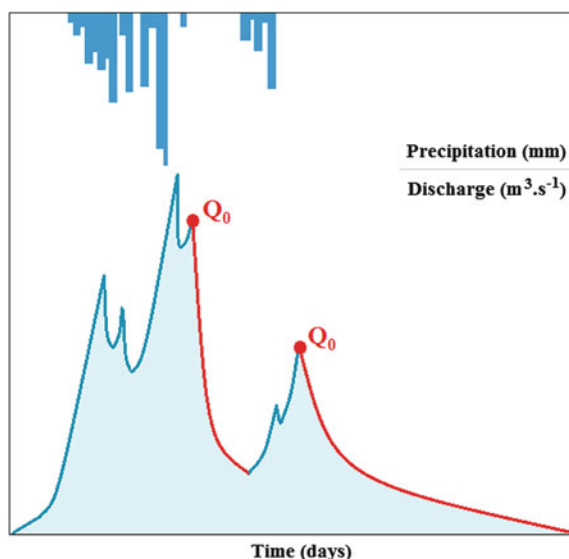


Fig. 2.8 Effect of hydraulic relationship between the surface water and groundwater and resulting expression for the relationship between the base flow and a total discharge in hydrograph (according Xu et al. 2002, modified)

Fig. 2.9 Schematic representation of the recession curve



et al. 1975) and are often used for the assessment of mixing of the various components of total runoff. Their main and evident disadvantage in comparison with the conventional hydrologic separation methods is especially financially, technically and time consuming process of acquisition of the measured values.

Analysis of recession curves

The gradual depletion of accumulated sources of the water in catchment in the period with little or no precipitation causes a gradual lowering of the groundwater levels, springs yields and rivers discharges (Fig. 2.9). In the discharge hydrograph, this fact is represented by chronological segments decreasing curves. These sections in hydrograph are called the recession curves.

Studying the recession curves and its practical use was done by many authors. From the international works it is mainly the work by Kiraly (2003) and Kovacs (2003). Both authors solve an analysis of recession curves and their mathematical simulation and modeling.

From the Slovak authors, the recession curves were dealt mainly by Kullman and Petráš (1977, 1979) who have emphasized the reflection of filtration coefficient on the practically all lithological, tectonic and spatial characteristics of the rock massif, as well as properties of the hydrogeological structures. They also pointed to the possibility of using the recession curves analysis for the quantitative assessment of changes in water reserves and its transfer between seasons. It is also possible to separate the groundwater runoff from the structure for individual years and semesters by using the knowledge of recession curves or quantify the depletion of water sources, accumulated in hydrogeological structure from previous years.

According to some authors (Tallaksen 1995) the nature of recession curves affects mainly relief, geological conditions, vegetation cover, climate and weather situation. Flat recession curves are typical for the catchments, where dominates the groundwater component in total runoff. Conversely, steep recession curves are typical for the catchments with small reserves of groundwater and therefore with its minor effect on the shape of the recession curve.

In the recession curves analysis we try to emulate the recession sections of hydrograph using various mathematical equations. For these purposes several recession models were compiled. A linear recession model belongs among the most basic models. Except this model, there were gradually analyzed also other, more complicated models, eventually superposition of several recession models in one recession curve for analysis of a complex depletion situation. For example, for the recession curves analysis in the case of highly karstified rocks, the superposition of linear and exponential recession models is used. Table 2.10 describes the basic and most commonly used recession models for these analyses.

The results of the recession curves analysis are the discharges in time t_n (Q_n) and the recession coefficients ($k, n, m, \alpha, \beta, \gamma, \varphi$). Recession coefficients define the dip of the recession curve and so indicate the speed of water depletion in the catchment. Based on these analyses, the individual component from total discharge can be separated, as well as analysed the speed of runoff in the catchment to determine the risk of the occurrence of hydrological drought in assessed area.

Deficit Characteristics

In contrast to the low flow characteristics presented in previous chapter, the deficit characteristics are based on analysis of the time series values of measured parameter in the hydrological cycle, which are below a defined threshold level (Tallaksen and van Lannen 2004). Deficit characteristics of hydrological drought are based mainly on a duration analysis of the deficit period and a deficit volumes assessment (e.g. number of days with discharge below Q_{90} threshold level or

Table 2.10 The most commonly used recession models for analysis of recession curves

| Conceptual model | Recession function | Storage types/comments |
|---|---|--|
| Linear reservoir (Boussinesq 1877; Maillet 1905) | $Q = Q_0 e^{-kt}$ | General storage Linearized Deput-Boussinesq equation |
| Horton's double exponential model (Horton 1933) | $Q = Q_0 e^{-\alpha_2 t^m}$ | General storage Transformation of linear reservoir model |
| Coutagne's model (Coutagne 1948) | $Q = Q_0(1 + (n-1)\alpha_0 t)^{n(1-n)}$ | Karstic aquifers |
| Padilla model (Padilla et al. 1994) | $Q = (Q_0 - Q_c)(1 + (n-1)\alpha_0 t)^{n(1-n)}$ | Karstic aquifers Q_c is discharge from low-transmissivity components of karst |
| Chanel bank storage (Cooper and Rorabaugh 1963) | $Q = \alpha e^{-k \cdot t}$ | Channel banks Variant of linear reservoir. Also used to model losses by evapotranspiration |
| Exponential reservoir (Hall 1968) | $Q = Q_0 / (1 + \varphi Q_0 \cdot t)$ | Throughflow in soil Hydraulic conductivity assumed to exponentially decrease with depth |
| Power-law reservoir (Brutsaert and Nieber 1977) | $Q = Q_0 / (1 + \mu t)^p$ $p = \beta / (1 - \beta)$ $\mu = \alpha^{(1/\beta)} (\beta - 1) Q_0^{(\beta-1)\beta}$ | Springs and unconfined aquifers ($p = -2$), Soil moisture Recessions modeled using $p \approx 1.67$; (Wittenberg 1994) |
| Deput-Boussinesq aquifer storage (Boussinesq 1904) | $Q = Q_0(1 + \alpha_3 t)^{-2}$ | Shallow unconfined aquifer Special case of power-law reservoir for Deput-Boussinesq aquifer model |
| Depression storage Detention storage (Griffiths and Clausen 1997) | $Q = \alpha_1 / (1 + \alpha_2 t)^3$ | Surface depressions such as lakes and wetlands Variant of power law reservoir |
| Cavern (karst) storage (Griffiths and Clausen, 1997) | $Q = \alpha_1 - \alpha_2 t$ | Underground caverns in karst |
| Hyperbolic reservoir (Toebe and Strang 1964) | $Q = \alpha_1 t^{-\nu} + b$ | Ice melt, lakes |
| Constant reservoir (Toebe and Strang 1964) | $Q = \alpha$ | Permanent snow and ice pack, large groundwater storages Constant stream flow over time period |
| Turbulent model (Kullman 1990) | $Q = Q_0(1 - \beta t)$ | Karstic aquifers |
| Hyperbolic model (Kovacs 2003) | $Q = Q_0 / (1 + \alpha t)^n$ | Karstic aquifers |

Q—discharge

t—time since beginning of recession

 Q_0 —discharge for $t = 0$ k, n, m, α , β , γ , φ —recession coefficients determined by recession curves calibration

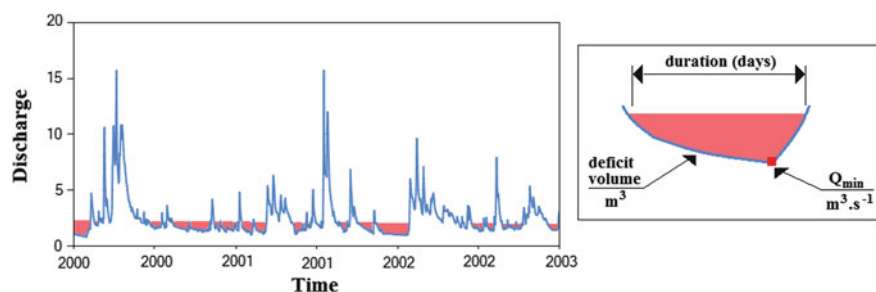


Fig. 2.10 Definition of hydrological drought deficit characteristics

deficient water volume in these days). The basic methods for determining the deficit characteristics include:

- Threshold level method (TLM)
- Sequent peak algorithm (SPA)

Threshold level method

Threshold level method is often used method for quantitative analysis of deficit characteristics of hydrological drought. The method is based on an assessment of the beginning and the end of the drought using definition of the threshold level in the time series of discharges. This threshold value—level (Q_0) divides values in time series on period with values below and above this limit. Periods having values below the defined threshold are defined as periods with the hydrological drought occurrence.

Figure 2.10 shows the methodology for evaluating the deficit characteristics of the hydrological drought. The analysis of hydrological drought deals with the following characteristics (Fleig 2004)—start time of drought (s), length of dry period (d_i), minimal discharge in dry period (Q_{\min}) and water deficit volumes (v_i).

Threshold level (Q_0) can be defined in various ways and methods according to the purpose of hydrological drought analysis and assessment (Tallaksen and van Lannen 2004). The threshold level is most often derived from the low flow indices. One of methods is to calculate it as a percentile of the flow duration curve. The most commonly used percentiles range from Q_{70} to Q_{90} . In the case of intermittent rivers and streams in arid areas, also the percentile values lower than Q_{70} are used. Woo and Tarhule (1994) tested and used in Nigerian intermittent streams the very low values (Q_5 , $Q_{7.5}$, Q_{10} , $Q_{12.5}$, Q_{15} , $Q_{17.5}$ and Q_{20}). At intermittent rivers, where the anhydrous periods lasting several months often occur, the flow duration curves are constructed only from the nonzero values of discharge and the threshold level is set as the Q_{70} value.

Some authors also use several types of the threshold levels (Stahl 2001). In addition to a fixed level throughout the year, there are also used seasonal, monthly and N-daily types of threshold levels (Fig. 2.11). When there is used some of defined threshold level type, the percentiles are calculated from selected annual period for a longer time. Peters et al. (2003) set threshold level by another

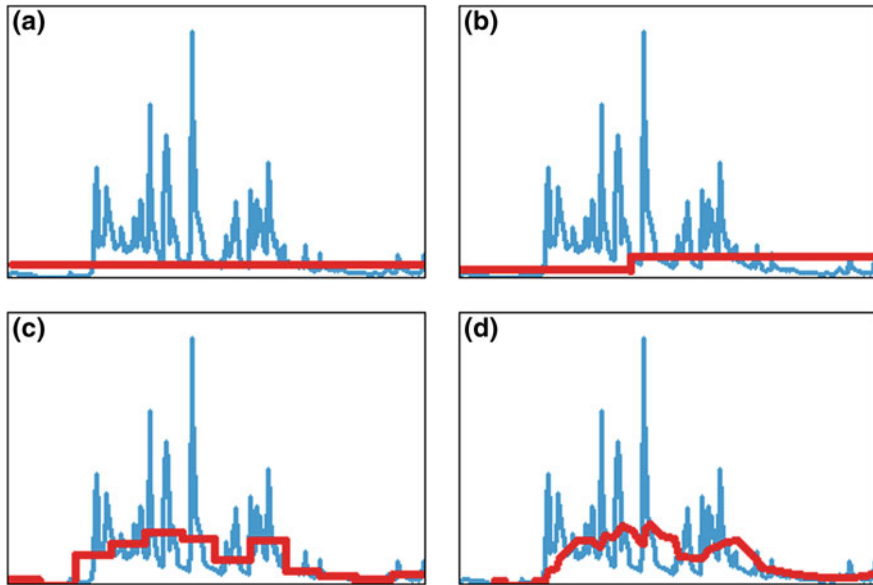


Fig. 2.11 Graphical representation of different types of threshold level (a—fixed annual; b—seasonal; c—monthly; d—daily threshold level type) according Stahl (2001) modified

approach. This method is based on an assessment of the relationship between the deficits characteristics below threshold level (ϕ_0) and below the level set as the average discharge value (\bar{x}). For this comparison there is used an Eq. (2.7):

$$\sum_{t=1}^N [(\Phi_0(b) - x_t)_+ \Delta t] = b \sum_{t=1}^N [(\bar{x} - x_t)_+ \Delta t] \quad (2.7)$$

where $x_+ = \begin{cases} x & \text{if } x \geq 0 \\ 0 & \text{if } x < 0 \end{cases}$ and

N length of time series

b drought criterion that determines the ratio between the deficit below threshold level and below level of average value (b ranges from 0 to 1)

x_t value of discharge in time series

For the selection and analysis of hydrological drought based on the threshold level method there was created a software tool, named Nizowka (Jakubowski and Radczuk in Tallaksen and van Lannen 2004). The program enables quantitative analysis of the deficit characteristics of hydrological drought.

Sequent peak algorithm

The SPA method was developed for engineering purposes to calculate the required volumes of reserves in the water reservoirs. From the discharge time series, SPA derives the maximum deficit volume during dry periods as the

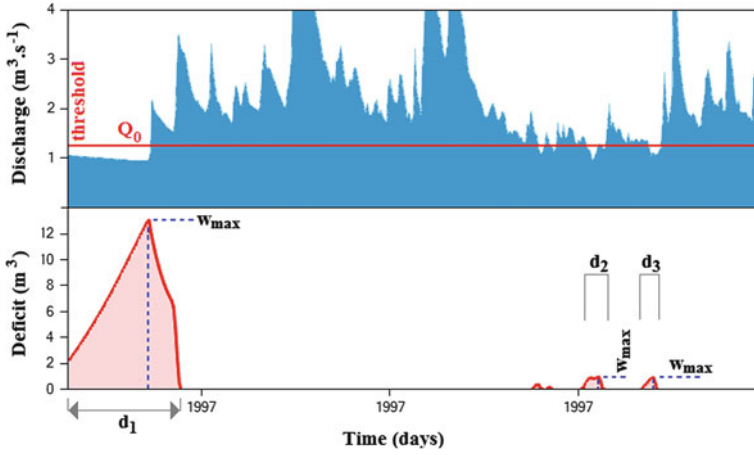


Fig. 2.12 Graphical presentation of the results of deficit SPA method (according Fleig 2004, modified)

maximum amount of the water that would be necessary for maintaining of a constant discharge on the threshold level (Q_0). Deficit volumes time series (w_t) are calculated from the discharge by following algorithm (2.8).

$$w_t = \begin{cases} w_{t-1} + Q_0 - Q_t & \text{if } w_{t-1} + Q_0 - Q_t > 0 \\ 0 & \text{if } w_{t-1} + Q_0 - Q_t \leq 0 \end{cases} \quad (2.8)$$

where

w_t is needed reverse

Q_0 discharge at the threshold level

Q_t daily discharge value in time

Figure 2.12 shows an example of the deficit characteristic analysis. For the calculation, this method uses the previously defined method—threshold level method. Example uses a constant annual threshold level (90-percentile), derived from the daily discharges. At statistical processing of the deficit period characteristics there is evaluated the length of drought period (d_i) in days and maximum deficit volume in one period (w_{maxi}) in cubic meters.

Frequency and Probabilistic Analysis

For the water resources management and planning there is equally important to evaluate not only the impact of the drought periods on the environment, but also the probability of the extreme hydrological phenomena occurrence in the future. Most often there is assessed the probability of hydrological extremes occurrence in 10, 50, 100 and 1,000 years. The assessed probability of occurrence of the extreme

hydrological events can be obtained from the analysis of discharge time series by evaluation of historical events or by mathematical simulation of discharge time series and a subsequent frequency analysis. Frequency analysis is common statistical methods used in hydrology. This method includes:

- The definition of hydrological extreme event and their characteristics
- Selection of extreme periods from the time series and analysis of probabilistic distribution
- Assessment of probability distribution parameters
- Estimation of extreme events and their verification.

Besides the frequency analysis of hydrological time series of the point character we are also interested in the frequency of extreme hydrological phenomena in the space. The spatial frequency analysis is commonly used in meteorology. In a minor extent the frequency analysis is used for evaluating of the drought event of surface water and groundwater (Tallaksen and van Lannen 2004). For frequency analysis there can be used many statistical methods. For the frequency analysis of hydrological drought the minimum annual N-daily discharges (or springs yields and groundwater level values) are often used as input data.

The widely available statistical programs can be applied for the frequency analysis. In hydrology, the program NIZOWKA 2003 was developed for the frequency analysis of the deficit hydrologic characteristics, being based on methodology by Zelenhasić and Salvai (1987). In the program the dry periods are derived using the method of the threshold level and from them the cumulative distribution function is calculated. Program requires a time series of the daily river discharges measurements and an additional requirement is that the maximum length of the drought period must be less than one year. These periods can be analysed in the program, based on their duration or the deficit volumes. For the frequency analysis the following distribution models (Fleig 2004) can be used in the program:

- Poisson distribution
- Pascal distribution
- Gamma/Pearson type 3 distribution
- Weibull distribution
- Log-normal distribution
- Johnson distribution
- Double exponential/Gumbel or generalized Paterno distribution

Drought Characteristics in Groundwater

The groundwater hydrological drought in hydrological system is assessed very rarely. In the past, many of authors have considered that the sign of drought in the groundwater was caused by the excessive pumping of the water rather than a result of natural climate variability (Day and Roda 1978). In the evaluation of drought we are limited by the only available values of recharge and discharge in the

hydrogeological system and the groundwater level values. We can also use indirect analysis, such as base flow separation or a recession curves analysis. Recently there was created a lot of diverse works in this field. The groundwater hydrological drought is evaluated for different purposes, such as for the water resources (Robins et al. 1997; While et al. 1999), in connection with the storage properties of the rock environment (Price et al. 2000), for analysing of the nonlinearity relations between the groundwater collector and the surface rivers (Eltahir and Yeh 1999) and related climate change (Leonard 1999).

As in the case of surface water, in the groundwater there are often used the same methods of hydrology drought assessment, such as duration curves, average annual minimal N-daily values, or analysis of recession curves. As the input data for these analyses we use time series of the groundwater levels, piesometric pressure and springs yields. For the runoff evaluation from groundwater levels there is used the Eq. 2.9 (Tallaksen and van Lanen 2004).

$$H_t - H_b = (H_{t=0} - H_b) \exp\left(-\frac{t}{C}\right) \quad (2.9)$$

where

- H_t groundwater level at time t
- $H_{t=0}$ groundwater level at time 0
- H_b minimal observed groundwater level
- t time step
- C recession constant

In this type of evaluation the problem arises when using H_b value, because this value is taken as the lowest—zero level. This value depends on the length of the groundwater level observation and is practically impossible to determine it a priori. Similarly, in assessing of the hydrological groundwater drought there can also be used the methods of determining the deficit characteristics.

Given by the often slow groundwater response to changes in the climate and meteorology properties on the surface area, there are for this part of the hydrological cycle typical the long-term (in months or years) periods of drought. In the analysis of drought, due to the slow reactions, not only daily but also weekly time series of hydrological parameters observations are often used (Tallaksen and van Lanen 2004).

Complex Indicators of Hydrological Drought

Simple hydrological drought indicators are based on a single parameter, such as time series of river discharges or groundwater levels. In addition to these simple indicators, in practice were also implemented comprehensive indicators that are based on several variables, often including many elements of the hydrological cycle. In the frame of complex indicators, the meteorological parameters such as

precipitation or evapotranspiration measurements are often used as variables. Therefore, these indicators are often used at the same time for evaluation of hydrological and meteorological droughts. The most common complex indicators are included and described in the chapter—“*Methods for meteorological drought assessment*”. These indicators are often simply known as drought indicators.

Regional Drought Characteristics

The occurrence of hydrological drought often covers large areas over long periods and therefore it is important to assess the drought in the regional context. Regional drought characteristics are evaluated by different ways, namely by the spatial analysis of hydrological drought patterns, using historical time series of observed parameters (Hisdal et al. 2001) or by studying the spatial evolution of drought in real time (Zaidman et al. 2001) and by the study of regional drought characteristics, such as analysis of a total deficit for assessed area (Tase 1976).

For assessment of the regional hydrological drought characteristics, similar methods to those described in previous chapters are used (e.g. threshold level methods or deficit characteristics), or different index methods, such as surface water supply index (SWSI), which is calculated for defined regions and describes the regional aspect of hydrological drought. Precipitation and river discharge can be defined as temporally and spatially random process. Therefore, this process can be evaluated as multivariate stochastic process. Regional drought analysis includes three main steps (Rossi et al. 1992):

- Development of a mathematical model to describe the process
- Choice of regional hydrological drought characteristics
- Statistical properties analysis of hydrological drought characteristics

These analyses may be processed principally in three ways:

- Setting the probabilistic density functions (PDFs) of the drought characteristics from *observed time series*. This technique is bound to the existence of a sufficiently long time series of values with appropriate coverage of the evaluated area.
- Applying *analytical methods* to obtain the PDFs (or PDFs moment) hydrological drought indicators from statistical characteristics of the evaluated data files. To obtain analytical solution, a simplified assumption must be identified, which often does not correspond with reality and causes the main limitation of this method.
- Applying statistical *Monte Carlo method* to simulate long time series of hydrological characteristics in several places of the studied region and by the study of the statistical properties of regional characteristics from simulated time series.

$$A_{def} = \sum_{i=1}^n I_{(\Phi \leq \Phi_0)}(\Phi_i) \quad (2.10)$$

where $I_{(\Phi \leq \Phi_0)}(\Phi_i)$ is function indicator defined as:

$$I_{(\Phi \leq \Phi_0)}(\Phi_i) = \begin{cases} 1 & \text{if } \Phi_i \leq \Phi_0 \\ 0 & \text{if } \Phi_i > \Phi_0 \end{cases}$$

Total deficit area of hydrological drought calculated as the sum of the deficit volumes of affected cells in assessed area:

$$V_{area} = \sum_{i=1}^n (\Phi_0 - \Phi_i) I_{(\Phi \leq \Phi_0)}(\Phi_i) \quad (2.11)$$

Maximum deficit intensity is calculated as maximal deficit volume in one cell:

$$m_{\max} = \Phi_0 - \min\{\Phi_1, \Phi_2, \dots, \Phi_n, \Phi_{n+1}\} \quad (2.12)$$

In assessment of the hydrological drought in the regional scale, we are mainly concerned to the following variables (Tallaksen and van Lanen 2004):

- Regional drought duration (length of drought in region, while the size of drought affected area must be greater than the defined critical size).
- Overall regional deficit (total deficit volume in time interval of drought in affected area).
- Intensity, defined as the total regional surface deficit and duration of hydrological drought.

2.1.3.4 Evaluation Methods of Economic Consequences of Drought

In the assessment of the economic consequences of drought, different parameters enter into the equation in comparison with those at the evaluation of meteorological, agronomical or hydrological drought. This is due to the fact that into these methods there enters the primarily influence of various human activities and operations. Given by the diversity of human activities, the results of these drought effects evaluations encompass the financial loss or financial capacity needed to repair the damage that was caused by the drought. An example is presented in Table 2.2, showing the most extreme drought in the world since 1980 with their economic consequences.

There are many methods for the economic drought evaluation. One of them is calculating the cost of drought according to the Vesphal et al. (2007). The overall economic assessment of drought is calculated using Eq. 2.13.

$$MIN = \sum_i X_i FC_i + q_i VC + VC_i \sum_t q_{it} \quad (2.13)$$

where

- i decision index defined by the area of impact assessment
- t number of days in analysis
- X_i binary constant
- FC_i fixed price
- q_i water amount (supply)
- VC_i variable costs

The decision index depends on the water use. For example, the drinking water has greater economic importance than the water for industry. For entering the values of the individual variables in the equation the assistance tables were created. In these tables, the coefficients are sorted according to the alternatives of water resources management in periods of drought. Another method is to calculate the economic drought index—EDMI (Iglesias et al. 2001). Feng and Zhang (2005) quantitatively evaluated the degree and intensity of the drought disaster. For this purpose, they used Eq. 2.14 for the quantitative determination of drought.

$$N = \alpha \log KT + b \quad (2.14)$$

where

- K percentual anomaly in precipitations
- T length of dry period
- α, β uncertain parameters

Catastrophe intensity calculated according to Eq. 2.15. By this equation the direct economic damages are calculated. These are expressed as index (dimensionless), so the different types of economic drought can be compared. If the G index is greater than 8, then it is a great disaster. The smaller value of the index means the smaller economic consequences of the drought.

$$G = \alpha \log D + b \quad (2.15)$$

where

- D direct economic loss (financially quantified)
- α, β uncertain parameters

The assessment methods of the economic drought are numerous, but their description would go beyond this thesis.

2.2 Theoretical Basis of the Water Quality Assessment

2.2.1 *Water Quality: Definition and Evaluation Methods*

Water quality assessment has a great importance for both—ecosystems and for humans, because the access to water, with enough amount and suitable quality, is a prerequisite for life and its development. Currently, the water quality is assessed mainly for its use as a drinking water, for needs of the economy, recreational purposes and for the life of organisms in aquatic ecosystems.

2.2.1.1 Definition of Water Quality

Due to factors complexity that affects water quality and the choice of parameters describing the qualitative status of water it is relatively difficult to provide a simple definition of water quality. Evaluation of the water quality began to be important, especially in the last century, which is related to a combination of two opposing factors, namely the increase of water consumption and increase of water pollution of all kinds.

In the water quality assessment two basic terms are common used, having different definitions (Chapman 1996):

- Water quality—defined as:
 - The concentration, speciation forms and physical properties of inorganic and organic substances in the water,
 - The composition and status of aquatic biota in the water,
 - The description of spatial and temporal variations in the water chemical composition, depending on the external and internal factors,
- Water pollution—causes by direct or indirect detrimental effects of chemicals or energy to water, documented for example by:
 - Damage to living organisms in water,
 - Risks to human health,
 - Human activities restriction (e.g. fisheries),
 - Deterioration of water quality depending on their use in agriculture, industry and other economic activities,
 - Reducing the values (economic, recreational, aesthetic, etc.).

The water quality can be described in several ways. The most commonly are used quantitative measurements (physical–chemical parameters), biochemical and biological tests (such as toxicity test) or quantitative–qualitative description (e.g. biotic index, visual aspect, smell and taste of water). In the water quality assessment two basic approaches are used (Bartram and Ballance 1996):

- Water quality assessment (including the evaluation process of the physical, chemical and biological parameters in relation to the natural water quality, effects on human health and development of aquatic ecosystems),
- Water quality monitoring (including the collection of information and data on water quality in time and space, when the most often result of this process consists of the spatial and temporal development of water quality in the monitored environment).

The water quality assessing mainly concerns of following issues (WHO 1991):

- Definition of water status
- Trends identification in water quality
- Sources identification of observed conditions and trends in water quality
- Identification of the water quality problems
- Overall assessment of the accumulated information and evaluations for other purposes, such as protection zones determination or land use planning.

2.2.1.2 Methods of Water Quality Evaluation

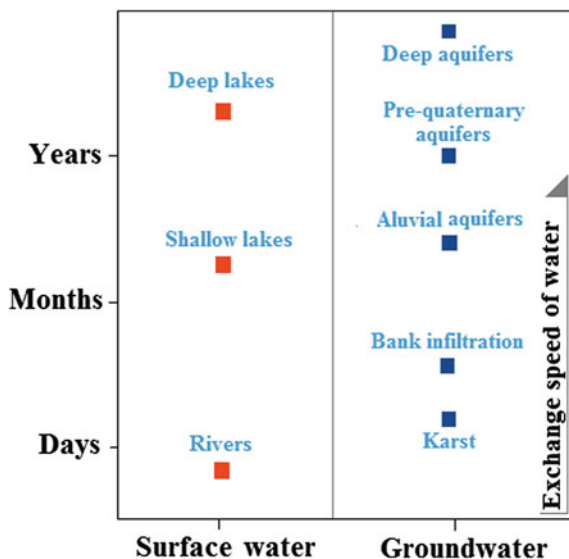
Water quality can be assessed in different ways. Choosing the assessment method is particularly dependent on the purpose for which the water quality is analyzed. The methodics are also differentiated according to the water occurrence in the hydrological cycle. The most basic classification of the water quality assessment methods is focused on the location of water in the hydrological system (Chapman 1996):

- Rivers and streams (group also includes artificially constructed stream channels, waste channels and drainage elements)
- Lakes (the group also includes marshes)
- Different types of reservoirs (mainly river dams)
- Groundwater

In addition to these basic types of water systems, in evaluation of water quality also other systems are allocated (such as estuaries, lagoons, sea, ocean systems, atmospheric water, thermal, mineral and coastal hydrogeological structures), but these are beyond this work.

Water quality is the result of a combination of several processes (e.g. organic pollution, eutrophication, acidification and contamination by toxic substances) which have an influence on the resulting water quality. The origin of these processes can be natural or influenced by human activity and to differentiate these two sources is not always easy. In many regions the human health is affected by diseases that are associated with chemical or microbiological contamination of drinking water. For example, in the world to 200 million people suffer from schistosomiasis, which is transmitted by drinking water. More information about

Fig. 2.13 Scheme of the water exchange speed in individual subsystems of the hydrological cycle (according Meybeck et al. 1989, modified)



diseases transmitted by drinking water can be obtained from WHO publications (1980, 1982 and 1983).

Basic work, often used in the world, dealing with the water quality monitoring is by Barcelona et al. (1985). From the global point of view, the water quality monitoring is addressed by WHO (1985) in the project GEMS/WATER. Publication (WHO 1992), resulting from this activity, deals in detail with all aspects of the water quality monitoring. For these purposes, the standardized methods and analyses are used, being managed by the International Organization for Standards (ISO). In addition, also organizations such as APHA (1989) in the U.S., DIN in Germany or the CIS (1987) in Russia, are dealing with these issues.

The water quality in the hydrological cycle can be characterized by three groups of parameters:

- Physical parameters
- Chemical parameters
- Biological parameters

In the hydrological cycle, all water on Earth is interconnected between atmosphere, land and sea. In the present work I deal with the water quality in the catchment, namely with the water in the surface water flows and the groundwater. Each of these sub-systems of hydrological cycle has the different hydrodynamic conditions and circulation, resulting in the difference in the chemical composition, quality and the evaluation methods. Rivers are characterized by one-way direct flow at an average speed ranging between 0.1 and 1 m.s^{-1} . Discharge in river is variable in time and depends on hydrological conditions in catchment and climatic situation. For the river the turbulent flow is typical with the intensive lateral water mixing in the profile. Conversely, the groundwater is characterized by rather

steady flow, which reaches an average values of speed in the range from 10^{-3} to 10^{-10} m.s⁻¹. Velocity of the groundwater flow depends on porosity and permeability of the rock environment in which the groundwater flows. From the flow velocity of the water in the environment there also depends the speed of water exchange between the various sub-systems of the hydrological cycle (Fig. 2.13).

This implies that water quality cannot be analysed and evaluated without knowledge of spatial and temporal variability of the hydrological regime. All waters have individual physical characteristics and chemical composition, which are dependent on climatic, geomorphological and geochemical conditions in the catchment and in rock environment. The development of biota (flora and fauna) in the waters is influenced by various environmental conditions. Primary production of organic matter in the water is bound mainly to lakes and reservoirs. In a limited amount the organic matter is also created in rivers and streams. Degradation of organic matter is bound to the bacterial production and may represent long-term process whose symptoms occur not only at the surface waters but also in the groundwater. In contrast to the physico-chemical quality of the water, which is determined by analytical methods, the biological water quality is usually determined by the combination of quantitative and qualitative characteristics. At biological assessment of the water quality there can be assessed the occurrence either of individual species, as well as the whole groups of organisms by the direct or indirect methods (Chapman 1996).

Water quality assessment includes mainly (Chapman 1996):

- Purpose-oriented monitoring of the water, which includes the quantitative and qualitative parameters of the surface water and groundwater with temporal and spatial analysis of urban contamination
- Statistical analysis of obtained data with determining the temporal and spatial patterns of the water quality development
- Compilation and verification of the water quality model in assessed area
- Overall assessment and analysis of the water quality with identification of the further progress in solved problem (e.g. as changes in monitoring methods, the change in the land use, determination of protection zones, the planning of future land use).

Human activities in the country significantly affect the water quality. The main types of human-induced water pollution in different sections of the hydrological cycle are shown in Table 2.11. From the table it is clear that given the diversity of hydrodynamic circulation and regime of the water in individual sub-systems of hydrological cycle, the various types of pollution occur with varying degrees of intensity. This table is prepared for a global scale. In the local scale the individual influences vary depending on the situation in the catchment. Spatial variability in water quality depends on several factors, but especially from the hydrodynamic characteristics of the environment. Water quality varies in all three dimensions and is influenced by the direction of flow, discharge and by time factor, therefore the water quality cannot be assessed only in one point, but the monitoring network

Table 2.11 Influence of water quality by impact of human activities on a global scale (according Chapman 1996)

| Influence type | Rivers | Lakes | Water reservoirs | Ground water |
|-------------------------------------|--------|-------|------------------|--------------|
| Pathogenic organisms | XXX | X | X | X |
| Suspended substances | XX | – | X | – |
| Degradable organic pollutants | XXX | X | XX | X |
| Eutrophication | X | XX | XXX | – |
| Pollution by nitrates | X | 0 | 0 | XXX |
| Salinization | X | 0 | X | XXX |
| Trace elements | XX | XX | XX | XX |
| Organic matter | XXX | XX | XX | XXX |
| Acidification | X | XX | XX | 0 |
| Modification of hydrological regime | XX | X | – | X |

XXX very significant impact on water quality
XX significant impact on water quality
X occasional impact on water quality
0 very occasional impact on water quality
– not rated parameter

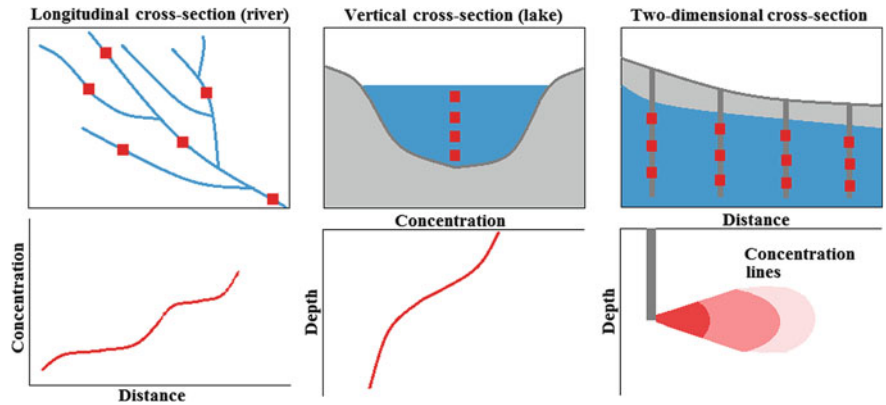


Fig. 2.14 Basic types of spatial design for water quality monitoring network (according Chapman 1996, adjusted)

must cover the entire area. Examples of spatial design of the water quality monitoring network are shown in Fig. 2.14.

Like as in the space, the water quality changes also over time. Therefore, it is also necessary to monitor the water quality in several time steps and the time step of measurements should be chosen appropriately depending on the choice of measured parameters and their properties. Due to the time step we can allocate several types of the water quality monitoring (Chapman 1996):

- Monitoring with the time step between hours and days (the results can be used to assess the impact of mixing of different water types, or the impact of weather conditions on water quality, for example the evaluation of changes in river at the storm events or increased discharges).
- Monitoring of daily variability (used to assess changes in water quality due to the daily biological cycles, solar cycles or cycles in the leakage of contaminants into the aquatic environment).
- Monitoring with daily or monthly step (applied in assessing the changes in water quality, depending on climatic factors).
- Monitoring for assessment of seasonal and longer biological cycles.
- Monitoring with an annual time step (used to assess long-term human impacts on water quality).

2.2.1.3 Strategies for Water Quality Assessment

Water quality monitoring is a complex issue, that uses a variety of data collection methods, statistical processing, modeling and results interpretation. The most significantly the need for the monitoring of the water quality increased since 1950. Since then many sophisticated methods have been developed that can be variably combined and complemented. In the world, several manuals for water quality monitoring were created (such as UNESCO/HWO 1978; Krenkel and Novotny 1980; Sanders et al. 1983; Barcelona et al. 1985; WMO 1988; Yasuno and Whitton 1988; WHO 1992), which are usually focused only to one type of monitored waters (e.g. monitoring of the water quality in rivers, lakes or groundwater) or one specialized area or monitoring (e.g. chemical or biological monitoring).

In assessing of the water quality three approaches are used (Chapman 1996):

- Monitoring—long-term, standardized measurements and observations of the aquatic environment for the definition of the status and trends in the water quality
- Research and mapping—a short-time intensive program focused on measuring and monitoring of the aquatic environment for any specific purpose
- Tracking—continuous, specific measurements and observation for the purposes of quality management and operational activities.

In the practice, the described approaches are often called monitoring, but their practical applications are different. Due to the purpose of the water quality assessment there are used two types of the water quality monitoring:

- Specialized monitoring—focused on local problems and purpose
- Multipurpose monitoring—focused on an overall assessment of temporal and spatial variability in the water quality.

Monitoring of the water quality includes not only the data about the water quality collection, but also an analysis and assessment of other factors such as the

geomorphological, climatic, hydrological, geological, hydrogeological, pedological conditions, water use in the evaluated area and the sources of water pollution. Next more comprehensive classification and monitoring for the water quality assessment is in Table 2.12. The overall process of the water quality assessment is different and depends on the purpose. The most common evaluation process consists of following steps (Chapman 1996):

- Determination of the assessment goal—the first step is aimed to determine the objectives of monitoring, assessment of the hydrological factors, water use, economical exploitation of assessed area, etc.
- Preliminary survey—short-term, limited activities to determine the initial variability in water quality, selection of methods and location of sampling sites for the long-term monitoring.
- Designing of the monitoring system—step involves the selection of types of contaminants for monitoring, sampling sites, sampling frequency and sampling equipments.
- Water sampling for analysis—the step comprising the water sampling in the area of interest with measuring the basic parameters.
- Hydrological monitoring—process including the measurement of discharge, groundwater levels, water temperature and measurements of meteorological parameters in relation to water quality.
- Quality control of measured data—a step concentrated to quality control of measured data used for assessment of the water quality.
- Database creating—after a control and selection of the measured values the complex databases are formed that are frequently linked with GIS programs. In this step the basic statistical data analyses are often processed, such as detecting trends in the data or multifactorial correlations.
- Data interpretation—step aimed to evaluate the results using statistical and graphical analyses, modeling, detecting the relationships between water quality and the environment (source of contamination, geological structure, etc.). The result of this step is often represented by the final report summarizing all results.
- Recommendations for the water quality management—the last step of monitoring and water quality assessment, which focuses on the land use designing for future or protection zones determining. In this there are also suggested changes in monitoring system and methodology for increased efficiency or reduce financial costs.

The length of the individual steps is variable and depends on many factors. The water quality assessment, except the actual water quality data, needs also a quantity of additional information, describing hydrological conditions in evaluated area. Table 2.13 defines the basic types of documentation needed for the evaluation of water quality in different types of environment.

Evaluation of water quality has a significant interdisciplinary character and there exist a relationship between individual types of environmental monitoring systems. This relationship is most visible between the meteorological monitoring system, monitoring systems of atmospheric pollution and water quality.

Table 2.12 Classification of monitoring and evaluation of water quality (according Chapman 1996)

| Type of water quality assessment | Main focus of water quality assessment |
|--|---|
| Common evaluations | |
| 1 Multipurpose monitoring | Basic spatial and temporal distribution of water quality |
| 2 Monitoring of trends | Long term evolution of pollution |
| 3 Basic research | Identification and localization of basic problems and their spatial distribution |
| 4 Operational monitoring | Water quality for specific uses |
| Specific evaluations | |
| 5 Background monitoring | Evaluation of background levels for the study of natural processes, used as reference concentrations for assessment of pollution and impacts |
| 6 Preliminary survey | Preliminary assessment of pollution and its temporal and spatial variability to design the final monitoring survey |
| 7 Emergency survey | Emergency research focused on the rapid evaluation and analysis of contamination in the situation after a catastrophic event |
| 8 Impact survey | Survey limited in time and space and focusing on a limited number of parameters near the source of contamination |
| 9 Survey for modeling | Intensive water quality assessment in defined time and space, concentrated on a small number of parameters (e.g. water eutrophication model or oxygen regime model) |
| 10 Monitoring for early warning purposes | Continuous sensitivity measurement focused on water quality before its usage (e.g. before the drinking water abstraction) |

Table 2.13 Hydrological information required for the water quality assessment (according Chapman 1996)

| Rivers | Lakes and water reservoirs | Groundwater |
|----------------------------------|---|---|
| Basic information | | |
| River network maps | Thermal regime | Type of hydrogeological structure |
| Seasonal regime | Bathymetric map | Hydrogeological map |
| Discharge statistics | Water balance | Hydrodynamic characteristics |
| Hydrological monitoring | | |
| Water level at sampling | Level at water sampling | Piesometric level |
| River discharge at sampling | Water level in lakes | Long term observation of groundwater levels |
| Continuous discharges monitoring | Continuous measurements of runoff from lakes and reservoirs | Knowledge of groundwater flow hydrodynamics |

2.2.1.4 The Legislative Frame for the Water Quality Assessment

Evaluation of the water quality depends mainly on the origin, occurrence and the use of water. According to Pitter (1999), from the viewpoint of its origin it can be divided into natural water and waste water. Waste water can be divided into sewage and industrial. According to the ways of occurrence of natural water, it is divided onto atmospheric water, surface water and the groundwater. According to the water use, it can be defined as drinking water, water for general use and the waste water. Depending on the use of the water, we can differentiate it such as water for irrigation, for fishing purposes, for construction, for cooling purposes, for steam boilers, etc. Due to the multiple types of the waters and their use, the assessment of the water quality is not uniform, but rather very diverse. Therefore there are many standards, laws and regulations governing different types of waters. These standards are not uniform in different countries even within one type of the water and in the course of time they are also gradually adjusted by the rise of knowledge. It is possible to say that, like in the analysis of hydrological drought, in the water quality assessing, the threshold level method is very important. In this method, the comparative value is firstly set and then the actual measured values of the quality parameters are compared with this value. The comparative threshold value is mostly determined by using:

- Values from standards, laws and regulations on water quality
- Statistically determined values (e.g. average or percentile values)
- Background concentration values (determined by various methods, which differ the substances concentration in the water, determined by the natural geogenic background and by anthropogenic influences).

In Slovakia, the water quality is assessed mainly by the following regulations, standards and laws:

- Council Directive 98/83/EC—on the quality of water intended for human consumption
- Council Directive 1/676/EEC of 12 December 1991—on the protection of waters against nitrates pollution from agricultural sources
- Directive 2000/60/EC of 23 October 2000—establishing a framework for action in the field of water policy
- Act. 364/2004 of 13 May 2004—on the waters and on the amendment of the Act 272/190 on offences (Water Act)
- Act. 354/2006 of 10 May 2006—about requirements of water for human consumption and control of the water quality intended for human consumption
- Government decree 354/2006 of 10 May 2006—about requirements for water intended for human consumption and control of the quality of water intended for human consumption
- Act. 355/2007 of 21 June 2007—on the protection, support and development of public health

- Decree 528/2007 from Ministry of Health of 16 August 2007—about details of the requirements for exposure restriction from natural radiation
- Act. 384/2009 of 8 September 2009—that amending Act. 364/2004 and Act. 372/1990 (Water Act) and 569/2007 on geological works (Geological Act) and Act. 515/2008
- Directive 2009/128/EC of 21 October 2009—establishing a framework for actions to achieve sustainable use of pesticides
- Government decree 269/2010 of 25 May 2010—about setting out the requirements for achieving good water status
- Government decree 270/2010 of 25 May 2010—on environmental quality standards in the field of water policy
- Government decree 282/2010 of 9 June 2010—establishing the thresholds values and the list of groundwater units
- Government decree 496/2010, which amends government decree 354/2006
- Decree 418/2010 of 14 October 2010—on the implementation of certain provisions of the Water Act

For analysis and evaluation of the water quality, the determination of background concentrations of the components dissolved in water is also used. Background value (geochemical background concentration) is the spatial and temporal characteristic extent of the substance concentration in one component of the natural environment, which does not include a positive or negative anthropogenic and contrast (anomalous) geogene effects (Slaninka et al. 2005). By the European Commission (EC DG Environment 2003), the background concentration of target elements represents in the aquatic ecosystem or in sub-unit of the surface water, the value corresponding to undisturbed conditions (none or a very low degree of anthropogenic influence). For example, U.S. EPA (1998 and 2000) defines the background conditions as the upper 75 percentile value of the sub-catchments data under consideration as the least degraded with no or low level of anthropogenic influence in defined area (undisturbed conditions). Haggard et al. (2003) modified this approach when determine the background concentration as median value (50 percentile) from all assessed data.

From the definitions above, it is clear that the calculation of background concentration is a complex task and this value cannot be determined mechanically. The overall difficulty of this determination increases also involving the time factor. In determining the background concentrations the geochemical and statistical methods are often used. From the geochemical methods, various standards are known (e.g. Clark numbers, average composition of the upper crust of the earth), as well as works referring the pre-civilization element accumulation from records of limnic and marine sediments, floods and river sediments, etc. Evaluation of such measurements is usually done through fixed values (median, mean) and requires a number of geochemical knowledge. On the other hand, geochemical methods usually do not take into account the natural variability of components concentration and can be subjective, which is very significant limitation at the results interpretation. From this perspective, if possible, it is better to define background

concentration using dispersion of values. For this purpose, the statistical methods of determination can be used, which are less subjective and produce numerically determined and defined results (Slaninka et al. 2005).

The most common statistical methods for determining background concentrations include (Matschullat et al. 2000):

- Lepeltier method
- Determination from the relative cumulative frequency curve
- Determination from normal range of analysis
- Regression techniques
- Mode analysis
- Testing 4σ —outliers
- An iterative 2σ technique
- Calculation of the distribution function

The actual statistical processing of data files by different ways is actually a reflection of methods power to eliminate outlying values at various procedure conditions. Such processing results in the concentration average value enlarged by the twice standard deviation value, corresponding to the average, respectively upper limit of the background value. Despite the efforts on the most comprehensive approach at setting the background concentrations, there remains a question of which procedure and which result represent best the value of geogenic background. It is also important to note that in establishing of the background values, the universal methodological approach does not exist and necessary is to process data on the case by case basis.

2.2.2 Water Quality Indicators

The selection of indicators for assessing the water quality depends on the purpose of quality evaluation. In assessing the water quality there are also used the time series values from observations of the hydrological characteristics of the environment, which are an important aspect of the assessment. Measurements of the runoff from the catchment serve to production of balance and runoff calculations and also represent the basis for the water quality modeling. The assessing of hydrological parameters is mainly concerned with the analysis of the flow velocity, runoff variability from the catchment, the groundwater levels and with the water transport of sediments. Velocity of water is particularly important for evaluating the options of contaminants transport. It allows predicting the mobility of chemical constituents in the water. Velocity is very diverse and depends primarily on the geological and geomorphological conditions of evaluated area. Measured is either directly, such as by the hydrometric flow meter, or indirectly by natural and artificial tracers. Assessment of the runoff is especially useful for determining the amount of removed dissolved and suspended solids. Their amount is determined by their concentration in the water and sum of drained water. Knowing the water level and

its change over time is important for determining the hydrological regime of lakes, reservoirs and the groundwater. The groundwater levels can be measured either directly or indirectly, e.g. by geophysical methods. Suspended solids in the water consist of material that is eroded from the catchment surface area. The importance of suspended solids assessment in the water lies in the possibility of their influencing the chemical composition of the water (Chapman 1996).

In assessing the water quality we are interested in the following information:

- Physical–chemical properties of water
- Inorganic chemicals in water
- Organic substances in water

In the following text the basic indicators of the water quality are defined. Not all, but only the most important components of the water quality are presented, being used in the later assessment of water quality in area of interest, because their range goes beyond this work. Similarly in the text, the organic dissolved substances in the water are not defined and described, because this thesis is focused on the evaluation of the water quality by analysing the concentrations of inorganic substances dissolved in the water.

2.2.2.1 Physical Indicators of Water Quality

Water temperature

The water temperature depends mostly on air temperature. Changes in the water temperature have usually seasonal character, in some cases there are changes with the 24 h periodicity, such as in rivers and streams. Lakes and reservoirs are typical with vertical temperature stratification in the water column. Knowing the temperature is important, because it affects the physical, chemical and biological processes in the water. Water temperature is essential parameter when calculating chemical equilibrium (e.g. in assessing the calcium-carbonate equilibrium, aggressivity of water, solubility of solids and gases in water, etc.), in determining the biochemical oxygen demand, in assessing the self-purifying processes in the surface waters. Water temperature as a parameter often occurs in several standards for the water use, such as standards for drinking water or for fish farming. Therefore, for each chemical analysis there is referred the water temperature, measured directly at the water sampling. If the temperature is not measurable directly at the source, such as in the deep geothermal waters, it can be estimated from chemical composition, as for example, by application of the Van't Hoff's reaction isobar (Pitter 1999).

Water electrolytic conductivity

The electrolytic conductivity is the concentration rate of ionizable organic and inorganic components in the water. In natural and industrial water with very low concentration of organic substances it is a measure of inorganic electrolytes (cations and anions). Components that are present in these waters mainly as nonelectrolytes (e.g. silicon or boron), do not participate on the conductivity.

Electrolytic conductivity of water depends on the concentration of ions, their mobility and temperature. The water conductivity is usually measured or converted to 25 °C. Measuring of conductivity is a normal part of the chemical water analysis. The advantage is that its value can be obtained relatively easily and quickly. It also allows getting an immediate conception of temporal changes in concentration of inorganic dissociated substances in the natural, used and waste waters, because the measurement can be made continuously (Pitter 1999).

Water pH and redox potential

The water pH and redox potential significantly affect the chemical and biochemical processes in the water and therefore their determination has a great importance. It enables to distinguish different forms of some elements in the waters, what is one aspect of the assessing the corrosive properties of the water and affects the efficiency of most chemical, physical–chemical and biochemical processes in the waters, such as coagulation, sorption, precipitation, oxidation, reduction, hydrolysis, nitrification, denitrification, aerobic and anaerobic biodegradation (Pitter 1999).

2.2.2.2 Chemical Indicators of Water Quality

The following subchapter describes the most important inorganic substances in the waters that were used in assessing the water quality, being specified by their relationship. The occurrence of individual elements forms in the water depends on the pH, redox potential and on complexing reactions. Individual elements may be present in the waters at the same time as cations, anions and nonelectrolytes. From a practical point of view, in the natural water there is generally assumed (Pitter 1999):

- Calcium, magnesium, sodium, potassium and ammonium nitrogen occur mostly as cations.
- Bicarbonates, sulfates, chlorides, nitrates, nitrites, fluorides and phosphates occur mostly as anions.
- Silicon and boron are present mostly in non-ionic form.

This division usually complies with the basic mass balance, electroneutrality equation and fundamental assessment of the water properties. However, for a detailed interpolation of the results and assessment of chemical and biological state, the more detailed analysis of speciation is necessary. The most important inorganic substances in the water are shown in Table 2.14.

Gases in water

The most important gases occurring in the waters are represented with oxygen, nitrogen, carbon dioxide, chlorine, chlorine dioxide, ozone, hydrogen sulfide, ammonia, nitrous oxide, carbon monoxide, radon, deuterium, tritium, methane and hydrogen. Gases in the waters can be natural or of anthropogeneous origin and specifically of atmospheric, chemical (or radiochemical) and biochemical origin. Some gases react with the water, or react only in a limited extent, and occur in the

Table 2.14 Inorganic substances in water (according to Pitter 1999, adjusted)

| Substance | Forms of occurrence | Importance of substance |
|----------------|--|---|
| Lithium (Li) | Li^+ | <ul style="list-style-type: none"> – positively affects the human nervous system – accumulates in plants and may inhibit their growth |
| Sodium (Na) | Na^+ , K^+ , $[\text{NaSO}_4]^-$, $[\text{KSO}_4]^-$, $[\text{NaHCO}_3]^0$, $[\text{NaHCO}_3]^-$ | <ul style="list-style-type: none"> – two elements (from the four main cations) of natural and industrial waters |
| Potassium (K) | | <ul style="list-style-type: none"> – play an important role in the water chemical classification, in determining groundwater genesis and in the control of results of water chemical analysis – important role in assessing the effects of water corrosive impact |
| Calcium (Ca) | Ca^{2+} , Mg^{2+} , $[\text{CaCO}_3(\text{aq})]^0$, $[\text{CaHCO}_3]^+$, $[\text{CaSO}_4(\text{aq})]^0$, $[\text{CaOH}]^+$ | <ul style="list-style-type: none"> – important role in assessing the corrosive or contaminating effects assessment |
| Magnesium (Mg) | $[\text{MgCO}_3(\text{aq})]^0$, $[\text{MgHCO}_3]^+$, $[\text{MgSO}_4(\text{aq})]^0$, $[\text{MgOH}]^+$ | <ul style="list-style-type: none"> – positive effects on the organoleptic properties of water – high concentration of magnesium in the water causes aggressive effects of water |
| Iron (Fe) | Fe^{2+} , Fe^{3+} , complexes | <ul style="list-style-type: none"> – iron is present in water mainly due to technical failures, because stains the materials to yellow to brown – from a hygienic point of view affects the organoleptic properties of water (color, taste and opacity) |
| Manganese (Mn) | Mn^{2+} , Mn^{3+} , Mn^{4+} | <ul style="list-style-type: none"> – significantly affects the organoleptic properties of water |
| Arsenic (As) | As^{III} , As^{V} | <ul style="list-style-type: none"> – highly toxic, long term consumption of water with small As concentrations causes of chronic disease – one of biochemical oxidation inhibitors, its carcinogenic effects were documented, represents neural poison with cumulative character |
| Silicon (Si) | $\text{Si}(\text{OH})_4$ | <ul style="list-style-type: none"> – usually undesirable for technological use of water, |
| Fluorine (F) | F^- , fluoroaluminates, fluoroirones, fluorosilicates | <ul style="list-style-type: none"> – one of the essential elements |
| Chlorine (Cl) | Cl^- , ClO^- , HClO , Cl_2 | <ul style="list-style-type: none"> – chlorides are hygienically safe, at higher concentrations, however, influence taste of the water |
| Sulfur (S) | H_2S , HS^- , S^{2-} , SCN^- , S^0 , $\text{S}_2\text{O}_3^{2-}$, SO_3^{2-} , SO_4^{2-} | <ul style="list-style-type: none"> – sulfates, in common concentrations, have no hygiene importance, but at high concentrations affect taste of water, and together with higher concentrations of Mg and Na cause laxative effects on water – have importance in assessing the aggressive properties of water |

(continued)

Table 2.14 (continued)

| Substance | Forms of occurrence | Importance of substance |
|-------------------|---|---|
| Phosphorus (P) | PO_4^{3-} , HPO_4^{2-} , $[\text{CaHPO}_4]^0$, $[\text{MgHPO}_4]^0$, $[\text{FeHPO}_4]^0$, $[\text{CaPO}_4]^-$ | <ul style="list-style-type: none"> – phosphorus compounds play an important role in the natural cycle of matter and are necessary for the organisms – also have a key role in the eutrophication of surface waters – hygienic importance of phosphorus is low |
| Nitrogen (N) | NO_3^- , N_2 , NH_4^+ , NH_3 , CNO^- , CN^- , N_2O , NO_2^- | <ul style="list-style-type: none"> – ammonium nitrogen in water significantly increases the corrosion of copper and other alloys and is toxic to fish – is an indicator of fecal contamination – nitrates are important because they cause alimentary methemoglobinaemia |

water in a relatively stable molecular form (oxygen, nitrogen, ozone, chlorine dioxide, nitrous oxide, radon, methane, hydrogen and helium), others react with the water, partly depending on the pH and redox potential values and form chemical equilibrium (CO_2 , H_2S , NH_3 , Cl_3). Properties of some gases have been mentioned in the previous subchapter. The most important gases in the water are shown in Table 2.15 (Pitter 1999).

Radioactive substances in water

Determination of radioactivity is one of the important indicators of pollution in natural, used and waste waters. Considerable importance has the differentiation between natural and artificial radioactivity. Determination of the entire spectrum of radionuclides in waters is time consuming and expensive process. Usually, the total volume alpha activity, total volume beta activity and from individual radionuclides ^{226}Ra , ^{222}Rn , tritium and uranium are determined. In determination of the total volume beta activity, for precise interpretation of results, there is necessary the correction for the natural background, given by ^{40}K radionuclide (Pitter 1999).

2.2.2.3 Processing and Presentation of the Water Quality Assessment

After collecting the water quality data, processing and storing them in the database, we can in principle analyse them in several steps. Basic methods of the data processing and presentation are shown in Table 2.16. The table shows that the water quality can be evaluated on several levels. In the first level, the basic statistical method is used to assess the overall water quality. In the second step, we focus on analysing the relationships between variables and trends evaluation. The result of the last step is to create models of the water quality, depending on the purpose of evaluation.

Table 2.15 Gases in the water (according to Pitter 1999, adjusted)

| Substance | Forms of occurrence | Importance of substance |
|------------|---|---|
| Carbon (C) | CO_2 , HCO_3^- , CO_3^{2-} | – Positively affects the taste of water, but increases aggressive properties of water |
| Oxygen (O) | O_2 | – Oxygen is necessary to ensure the aerobic conditions in the natural purification processes of surface water – Oxygen concentration represents an important water quality indicator – Affect the water taste |
| Ozone (O) | O_3 | – Significant oxidation and disinfection effect – Toxic properties |
| Methane | CH_4 | – Methane concentrations are used in oil prospection |

Table 2.16 In principle, the methods of the data presentation and water quality analysis (according Chapman 1996)

| Level of assessment | Rivers | Lakes and water reservoirs | Ground water |
|---------------------|---|--|--|
| A | Basic statistic of the time variability of quality in profile | Vertical variation in concentration, stratification analysis Trends in concentration | Temporal variability in the measured point |
| B | Relationship between the change in water quality and quantity Analysis of pollution contaminants Contaminants statistics Spatial mapping of water quality | Variability in quality characteristics of sediments Seasonal variation in water quality | Evaluation of trends in water quality Spatial mapping of water quality |
| C | General evaluation of trends in water quality after data adjustment for the cyclical component Evaluation of changes in water quality along the river flow Creating maps of water quality in profiles Creating models of water quality | Temporal and spatial mapping of water quality Development of water quality models (e.g. eutrophication) | Temporal and spatial mapping of water quality Development of water quality models (e.g. pollution dispersion) |

Several techniques and methods are used during the processing and presentation of the water quality:

- General statistics—answering questions about:
 - Water quality in the evaluated point, line or area
 - Trend of water quality changes

- Relationships between quality parameters
- Sources of the water quality changes
- Possibilities of the water quality assessment in the past
- Parametric and nonparametric statistics—collect statistical information about the distribution and probability of changes in the water quality
- Error statistics—helps us to detect errors in previous step of water quality assessment (e.g. problems with water sampling, suitability of sampling points)
- Hypothesis testing—for determining the probability and feasibility of the theoretical statistical hypotheses
- Graphical analysis—use for:
 - Time series (chronological records of defined values)
 - Graphical correlation between the number of parameters
 - Spatial and temporal relations of water quality parameters
- Modeling—which is especially important for:
 - Identification of important factors affecting water quality
 - Impact predictions for land use changes
 - Testing and analysis of strategies
- Geographical information systems (GIS)—especially for effective analysis of spatial data

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