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Surface- and Groundwater Quality Changes in Periods of Water Scarcity

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Miloš Gregor

Surface- and Groundwater Quality Changes in Periods of Water Scarcity

Doctoral Thesis accepted by
the Comenius University, Bratislava, Slovakia

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New hydrological software is accessible from a page http://hydrooffice.org

Supervisor's Foreword

Groundwater is the primary source of drinking water supply in many countries and this is protected by acts in the state legislation for water. Natural amounts of groundwater and their quality are dependent on recharge, which can come from infiltrating precipitation or from surface streams. Groundwater quantity and quality are sensitive not only to extreme climatic situations, such as meteorological drought, but also to human influences. Discussion on climate change effects in hydrological balance elements on the Slovak territory has continued among specialists in climatology, hydrology and water-economy for more than 30 years; however the common research on both, quantitative and qualitative aspects of surface and groundwater drought occurrence was missing.

The work comprises a summary of present knowledge on drought propagation through the hydrological cycle, description of the statistical and graphical HydroOffice package developed by the author of the thesis and evaluation of surface and groundwater drought generally in Slovakia and especially in the upper part of the Nitra River Basin. The influence of drought occurrence on surface and groundwater quality during the drought periods was extensively studied.

The work is based on an extensive dataset of meteorological and hydrological data covering 75 gauging profiles in Slovakia. Results are utilized as comparative dataset for evaluation of surface and groundwater drought in the upper part of the Nitra River basin, where hydrological time series at 26 discharge gauging profiles, 19 groundwater monitoring wells and 27 springs were assessed representing different types of rock environment from crystalline through Mesozoic, Palaeogene and Neogene up to Quaternary sediments. Almost 3,000 chemical analyses of surface and groundwater from the hydrological monitoring network in the basin were processed, analyzed and evaluated with special respect on drought periods occurrence.

The results reflect the wide variety of methods used for data analysis and results presentation in the form of spatial–temporal plots of drought occurrence and changes in physical properties and chemical composition of surface and groundwater.

I hope that the methods proposed and used in the thesis might stimulate further research of drought impacts on quality of water—the inevitable natural resource of the Earth.

May 2012 Prof. Miriam Fendeková

Preface

Assessment of the hydrological drought and impact analysis of this phenomenon on water quality are an important and interesting area of hydrogeological research. The main reason is that a sufficient amount of quality drinking water limits the possibilities of society development. Therefore, it is important to deal with this issue more widely and in greater depth.

The presented thesis represents a comprehensive overview of the results obtained in the described field during 4 years of doctoral study. The thesis is quite extensive and is supplemented by 75 tables, 122 illustrations and eight appendices. Overall, the work can be divided into several individual parts.

In the first part, the author deals with theoretical analysis of the problem and the current state of its completion in home and foreign literature. The next section briefly describes new programs that were developed for the purpose of input data processing. These programs are available for a download on a separate website and are currently used in over 50 countries.

The next chapter is devoted to the evaluation of hydrological drought in various components of the hydrological cycle of water in the catchment. At first, the drought in surface water is assessed in a regional scale for the area of Slovakia. Then the assessment of drought in surface- and groundwater, and the assessment of meteorological drought in the area of selected upper part of the Nitra river catchment are processed. Finally, the individual parameters of drought in the hydrological cycle are compared with each other.

Another extensive chapter is the evaluation of the quality of surface- and groundwater at selected quantitative states of river discharges and groundwater levels. At the end of the chapter, the individual results are summarized and compared. The last two chapters present the summation of all the results obtained in the work, and a short description of the opportunities for further research.

The work results have been published in individual articles and presented at several conferences. Some results are going to be published after their completion in other articles. An individual and extensive result of the work is software HydroOffice, which is still being developed.

Acknowledgments

First of all, I want to thank my supervisor, Prof. Miriam Fendeková Ph.D., for her willingness to help, valuable advice and comments. I am also grateful for the opportunity to work on projects, through which I could attend some of the world hydrogeological and hydrological conferences. Many thanks belong to other people who helped me by their advice, methodology or comments. In particular, Assoc. Prof. Zlatica Ženišová, Ph.D., Dr. Peter Malík, Assoc. Prof. Marian Fendek, Ph.D., Dr. Zoltán Németh and Dr. Andrej Machlica. I would like to thank the dozens of anonymous contributors on programming forums, without who the developed software created in this work would lose its quality and some of problems would not be solved. Great inspiration and help were provided to me by the staff of Department of Hydrogeology and Geothermal Energy in the State Geological Institute of Dionyz Stur in Bratislava.

Last, but not least I am exceedingly grateful to my Katka. Its space tolerance, royal care and all the help was signed in this result more that the reader might think.

Contents

Acronyms and Symbols

AMN	Annual minimal N-daily discharge
APHA	American Public Health Association
BFI	Baseflow index
C	Recession coefficient
CIS	Commonwealth of Independent States
CMI	Index of fertile moisture
CRED	Centre for Research on Environmental Decisions
D_f	Precipitation factor by Lang
d_i	Drought duration (days)
DIN	Deutches Institut für Normung
EC	European Commission
EDMI	Economic drought index
EP	Effective precipitations (mm)
EPA	US Environmental Protection Agency
FAO	Food and Agriculture Organization
FC_i	Fixed price
FDC	Flow duration curves
Fm.	Geological formation
FPW	Field water capacity
GIS	Geographical information system
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
H	Groundwater level in well (m; m a.s.l.)
IFAD	International Fund for Agricultural Development
K	Percentual anomaly in precipitations (%)
k	Recession coefficient
K_{HT}	Seljanin's coefficient of agronomical drought
m	Recession coefficient
MAM_n	Mean average annual minimal N-daily discharge (m^3 s^{-1})
m_{max}	Maximum deficit intensity
n	Recession coefficient
NDVI	Normalized differential vegetation index

OFDA	Office of U.S. Foreign Disaster Assistance
PDFs	Probabilistic density functions
PSDI	Palmer's index of drought intensity
Q	Discharge (m^3 s^{-1})
q_i	Water amount/supply (m^3)
Q_{min}	Minimal discharge in drought period (m^3 s^{-1})
Q_N	Discharge at percentile N (m^3 s^{-1}), initial discharge in recession curve (m^3 s^{-1})
RAP	Point of reduced availability
SPA	Sequent peak algorithm
SPI	Standard precipitation index
SWSI	Surface water supply index
T, t	Average air temperature (°C)/time/length of dry period (days)
TI/KI	Hydrothermal index
TLM	Threshold level method
UNESCO	United Nations Educational, Scientific and Cultural Organization
V_{area}	Area affected by drought (m^2)
VC_i	Variable cost
v_i	Water deficit volumes (m^3)
WHO	World Health Organization
WMO	World Meteorological Organization
WP	Wilting point
X_i	Binary constant
Z index	Palmer's index of anomaly humidity
Z,S,P	Precipitations (mm)
α	Recession coefficient/average consumptive water confidence
β	Recession coefficient
γ	Recession coefficients
λm	Weight of precipitation
φ	Recession coefficient
Θ_i	Average soil moisture of active root zone in day i of balanced period (m^3 m^{-3})
Θ_v	Wilting point of the active root zone (m^3 m^{-3})
Θ_{PK}	Field water capacity of the active root zone (m^3 m^{-3})

Chapter 1
Introduction

The drought as an extreme phenomenon occurs in the hydrological cycle with different intensity all the time. In the human history we have documented the amount of catastrophic events that have been linked with the occurrence of extreme dry periods. The hydrological drought has many direct but also indirect symptoms and consequences. The consequences of drought can be divided into environmental, economic and social. Some catastrophic droughts caused considerable damage which price reached billions of dollars in the extreme cases. The hydrological drought study has therefore not only scientific but also economic consequence. Thanks the risk assessment of the hydrological drought occurrence and the frequency analysis there is possible to determine the probability and intensity of catastrophic drought in the defined time and space, which allows the society to do the priority measures to be prepared for these events and thereby significantly reduces the damage of all kinds.

Among the hydrological drought consequences there belong the quality changes of the surface and ground waters. The water quality assessment is important, because water represents an essential precondition for the development life and society. Its importance, whether past or present, is supported by the high settlement of the territory in the vicinity of large rivers worldwide. On the other hand, the increased concentration of population in the vicinity of rivers significantly determines the river water quality. Human impact on water quality is considerable and at the time it has growing trend from the global perspective. In hydrological extremes (floods and droughts), the hydrological regime of surface and the groundwater are partially or completely changed and these changes affect the quantity and quality of the water in catchments.

The title of presented thesis is "Surface- and Groundwater Quality Changes in Periods of the Water Scarcity". The work was determined Prof. Miriam Fendeková, PhD, at the Department of Hydrogeology, Comenius University in Bratislava on 1. 9. 2007. The objective of this thesis was to evaluate the quality of the surface- and groundwater in the time of drought periods in selected catchment. At first the Topla

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and Torysa catchments were selected, but later due to lack of input data the locality has been changed to upper part of the Nitra river catchment (Slovakia).

First part of thesis deals with the theoretical approaches and the current exploration of the theory of drought and the water quality assessment. The second part focuses on the exploration and description of natural conditions of the selected locality from geological, geomorphological, hydrological and hydrogeological points of view. Third—shortened part of the work deals with a brief description of the software tools developed by the author. The fourth section describes the evaluation results and drought analysis in all runoff components of the hydrological cycle in the Horna Nitra catchment. In addition, the chapter includes a regional assessment of the nature and character of the hydrological drought in the Slovak rivers. The fifth chapter is devoted to describing of the quality of the surface- and groundwater in relation to different quantitative condition in the catchment. The last two chapters focus on assessment, summarizing and interpretation of obtained results and finally recommendations for further research.

Generally, the presented thesis summarizes results obtained during four years of author‘s doctoral study at the Department of Hydrogeology. Individual results were partially published in papers, conference abstracts and on the Internet (e.g. http://hydrooffice.org). The work was also supported by FP6 project WATCH (Water and Global Change), project APVV-0335-06 “Hydrological drought and its impact on the available quantities of groundwater” and VEGA grant no. 1/0783/08.

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.

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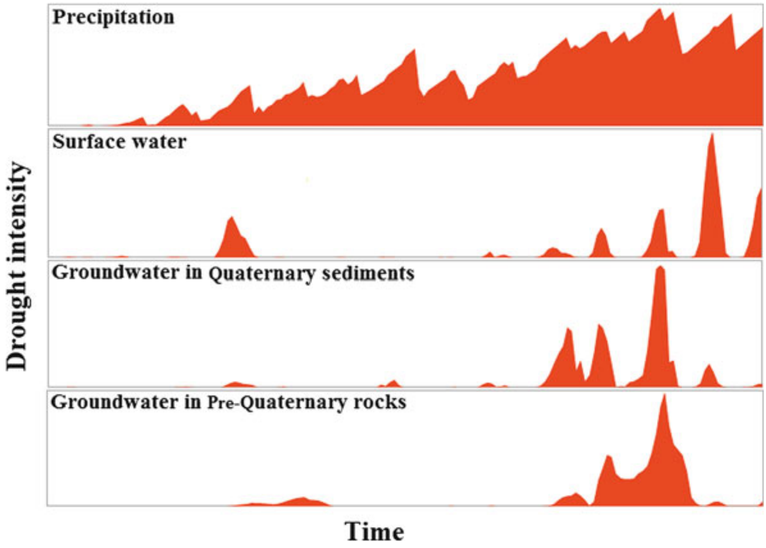

Fig. 2.1 Schematical illustration of drought occurrence in hydrological system

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

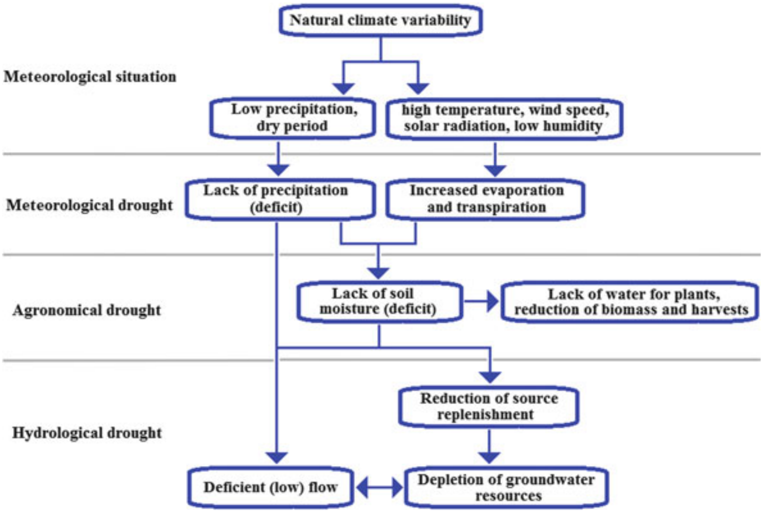

Fig. 2.2 Classification and mechanisms of drought formation (according Rassmuson et al. in Maidment 1993, adjusted)

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	• Soil moisture • Groundwater level • Runoff • Springs' yields • Surface runoff • Water level in lakes • Available (exploitable) amounts of drinking water	• Water quality • Biomass development • Biodiversity • Dust storms • Desertification • Forest fires
Economical	• Exploitation of surface water • Exploitation of groundwater • Diminishing of drinking water sources	• 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	• Drinking water	• 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 that 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 that 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)