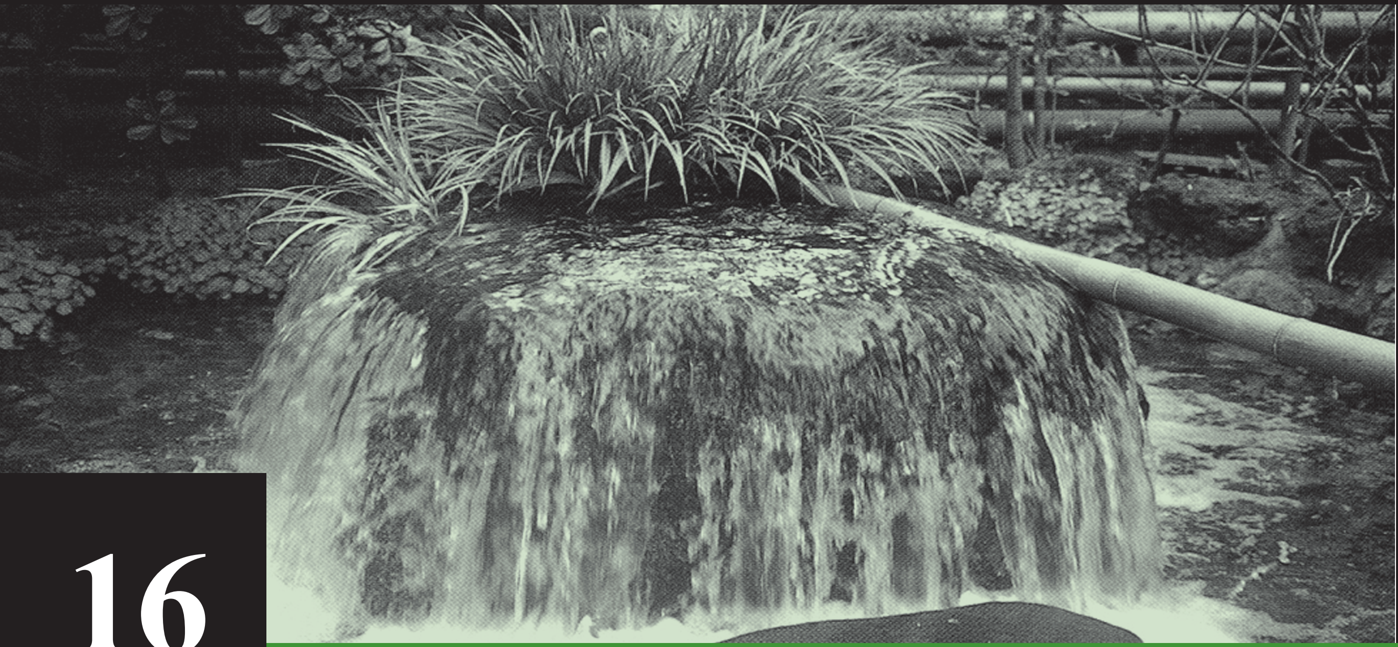
INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS SELECTED PAPERS



16

Groundwater Response to Changing Climate

Editors: Makoto Taniguchi
Ian P. Holman

CRC Press
Taylor & Francis Group
A BALKEMA BOOK

GROUNDWATER RESPONSE TO CHANGING CLIMATE

SELECTED PAPERS ON HYDROGEOLOGY

16

Series Editor: Dr. Nick S. Robins
Editor-in-Chief IAH Book Series
British Geological Survey
Wallingford, UK

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS

Groundwater Response to Changing Climate

Editors

Makoto Taniguchi
Research Institute for Humanity and Nature (RIHN), Motoyama Kyoto, Japan

Ian P. Holman
Department of Natural Resources, Cranfield University, UK

CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A BALKEMA BOOK

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20140602

International Standard Book Number-13: 978-0-203-85283-5 (eBook - PDF)

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Table of contents

Preface

Groundwater is the world's largest, accessible store of freshwater. It is the primary source of drinking water to nearly half of the world's population; a vital source of irrigation water to contribute to global food security and helps to maintain the delivery of vital ecosystem services from rivers, wetlands and lakes.

Effective groundwater management requires an understanding of the effects of natural climate variability on groundwater levels, fluxes and quality, particularly in the context of increasing climate uncertainty associated with global climate change. Although the potential impacts of climate change on groundwater resources have long been recognised, the Inter-governmental Panel on Climate Change (IPCC) has noted in its Second, Third and Fourth Assessment Reports that there has been comparatively little research relating to groundwater.

In partial response to this, two important initiatives were started in the early part of this century—the UNESCO Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) programme and the International Association of Hydrogeologists' (IAH) Commission on Groundwater and Climate Change.

This book focuses on integrating our knowledge of the relationships between climate change/variability and sea level rise and groundwater storage, recharge, discharge, and groundwater quality, based on case studies reported from around the world including Egypt (Barrocu & Dahab), Czech Republic (Novicky et al.), Japan (e.g. Hu et al.), Morocco (Ouysse et al.) and Indonesia (Abidin et al.). The knowledge from contemporary field investigations (Abidin et al.), water balance assessments (Hasegawa et al., Hu et al.), numerical simulations (Yoshimatsu et al.), satellite data (Ouysse et al.), paleohydrology (Teramoto et al., Iwatsuki et al., Hasegawa et al.), stable and radioactive isotope analyses (Kobayshi et al., Hasegawa et al., Machida et al., Yabusaki et al.) and monitoring studies (Taniguchi et al.) are reported. This book also examines the assessment of uncertainty in hydrological models that are driven by climate data (Novicky et al.).

Most of the papers were presented at the 36th IAH congress, which was held in Toyama, Japan on October 26th to November 1st, 2008. The papers were presented in Session S21 "Response of groundwater system from climate change, S22 "Impact of sea level rise on groundwater systems, S23 "Knowledge from paleo-hydrology, and Special Sessions 01" UNESCO-GRAPHIC" and 02 "Alluvial fans".

We acknowledge the organizing committee, executive committee, and scientific committee of the 36th IAH Congress, as well as the Japanese IAH sector. We wish to thank UNESCO-IHP and the Research Institute for Humanity and Nature (RIHN) for supporting the UNESCO-GRAPHIC session. We also acknowledge Yoko Horie (RIHN) and Janjaap Blom (CRC Press/Balkema–Taylor and Francis Group) for helping this publication.

Editors
Makoto Taniguchi
Research Institute for Humanity and Nature (RIHN) and Chairman of the GRAPHIC programme

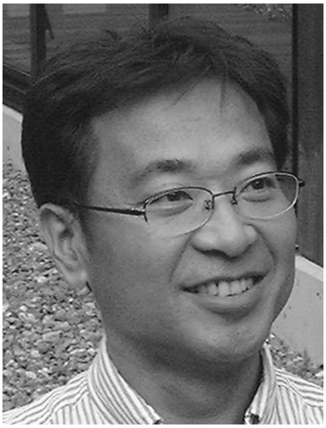
Ian Holman
Cranfield University and Co-Chairman of the IAH Commission on Groundwater and Climate Change

REFEREES

The Editors are grateful to the following people for their assistance with the reviewing of papers submitted to this publication:

Jason Gurdak, *U.S. Geological Survey*
Ian Holman, *Cranfield University*
Shiho Yabusakai, *Rissho University*
Tetsuya Hiyama, *Nagoya University*
Yoichi Fukuda, *Kyoto University*
Tsutomu Yamanaka, *University of Tsukuba*
Isao Machida, *Geological Survey of Japan*
Masako Teramoto, *NIPPON KOEI Co., Ltd.*
Michael Valk, *IHP & HWRP*
Bret Bruce, *U.S. Geological Survey*
Teruki Iwatsuki, *Japan Atomic Energy Agency*
Jun Yasumoto, *Ryukyu University*
Yossi Yiechieli, *Geological Survey of Israel*
Makoto Taniguchi, *Research Institute for Humanity and Nature*
Satoshi Nakada, *Research Institute for Humanity and Nature*
Takeo Oonishi, *Research Institute for Humanity and Nature*
Takashi Kume, *Research Institute for Humanity and Nature*

About the editors



Dr. Makoto Taniguchi is a Professor of hydrology and a project leader of "Human impacts on urban subsurface environment" in RIHN. He is also a leader of UNESCO-GRAPHIC Project "Groundwater Resources Assessment under the Pressures of Humanity and Climate Change", and a vice president of the International Committee of Groundwater of IAHS/IUGG. He has published several books and many papers in international journals of hydrology, geophysics and environmental sciences.

Dr. Ian Holman is a Senior Lecturer and head of the Integrated Land and Water Group within the Natural Resources Department of Cranfield University, UK. As a hydrogeologist and climate impacts modeller, his principal research interest has been the holistic assessment of climate change impacts on hydrogeological and water resource systems. He led the UK's first regional integrated assessment of the impacts of climate and socio-economic change on agriculture, water resources, flooding and biodiversity, and presently serves as Co-Chairman of the International Association of Hydrogeologists' (IAH) Commission on Groundwater and Climate Change.

CHAPTER 1

Vulnerability of groundwater resources in different hydrogeological conditions to climate change

Oldrich Novicky & Ladislav Kasparek
T.G. Masaryk Water Research Institute, Czech Republic

Jan Uhlik
PROGEO s.r.o., Czech Republic

ABSTRACT: During recent years, T.G. Masaryk Water Research Institute in Prague has carried out a number of studies which were focused on the possible impacts of climate change on groundwater resources. For these studies, the Bilan water balance model was used to simulate the water cycle components (including groundwater recharge and base flow), both for conditions unaffected by climate change and also for those modified according to climate change scenarios. The initial studies have shown that groundwater resources in unfavourable hydrogeological settings (e.g. those in crystalline geological formations) are highly sensitive to climate change and can rapidly be exhausted. Subsequent applications of the Bilan model in combination with MODFLOW (modular three-dimensional finite-difference groundwater flow model developed by the United States Geological Survey) however showed that climate change could have dramatic consequences, particularly in basins with good hydrogeological settings (such as those in cretaceous geological formations), mainly with respect to groundwater depletions that will greatly affect the availability of water supply.

Keywords: Bilan, MODFLOW, groundwater, climate change

1 INTRODUCTION

For studies of possible impacts of climate change on water resources, the T.G. Masaryk Water Research Institute, p.r.i., uses the Bilan hydrological model, which was developed by staff of the Institute. The Bilan model is described in detail by Tallaksen and Lannen (2004). The executable version is available with example data sets on the CD that is attached to the textbook. The primary input data for the Bilan model include time series of monthly precipitation, temperature and relative air humidity. The lumped model simulates the water budget at three vertical levels: on the land surface, in the soil layer and in the groundwater aquifer. Three water balance algorithms are applied for winter conditions, snow melting and summer conditions. The surface water balance depends on actual evapotranspiration, which is determined from water availability and potential evapotranspiration calculated from meteorological conditions. For calculation of the potential evapotranspiration, empirical values that were derived in Gidrometeoizdat (1976) for different climate zones are used. Excess water (precipitation minus evapotranspiration) forms direct runoff or infiltrates to the deeper zone, where it is divided into interflow and groundwater recharge.

The outputs of the model include monthly series of water storage in the snow pack, soil and aquifer. Furthermore, surface runoff, interflow, and base flow (groundwater discharge) are calculated at the outlet of the catchment. The eight free parameters of the Bilan model are calibrated by minimising the differences between simulated and observed outflow from the basin.

In 1998, T.G. Masaryk Water Research Institute completed a study (Kašpárek, 1998) that used the Bilan model for the analysis of the possible impacts of climate change in the Czech part of Elbe River basin. Kašpárek (1998) divided the basin into 18 sub-basins and concluded that the least vulnerable sub-catchments are mountain basins in North Bohemia and in the Šumava Mountains. Basins that have a low precipitation rate and small retention capacity (both natural in groundwater bodies and artificial in reservoirs) would be most affected by climate warming.

The Bilan model was subsequently applied by Krátká and Kašpárek (2005) to data that were prepared for the period 1971–2002 by the Czech Hydrometeorological Institute for the basins of 50 water gauging stations from the whole territory of the Czech Republic. This study substantiated the above results in terms of the spatial distribution of the decrease in runoff, and concluded that decreases in minimum monthly flows were greater than decreases in mean monthly flows. For some basins and an unfavourable climate change scenario (assuming high CO_2 emissions and high climate sensitivity to CO_2 concentration), the minimum flow decreased by as much as 12% to 15% of the current flow. The percentage decrease in mean base flow was equal to or greater than the decrease in total runoff, which decreased from 6% to 43% depending on the climate change scenario and the physical conditions of the basin.

The results of a groundwater study by Kněžek and Krátká (2005) indicated that groundwater resources in unfavourable hydrogeological settings, such as those of a crystalline geological formation with shallow groundwater circulation, are highly sensitive to climate conditions or human influences. The groundwater resources in these systems can be rapidly exhausted under such climate change.

The attention in the subsequent studies was primarily aimed at examining possible impacts on groundwater resources in favourable hydrogeological settings, such as those in Cretaceous geological formations. This was initiated by the analyses of data from this type of basin which indicated that such groundwater resources could be also highly vulnerable. This can be illustrated for a selected study basin, whose groundwater storage did not drop below 94.8% of the mean value in the period 1976 to 1990, but decreased by 37% during the 2004 dry year (Kněžek and Krátká, 2005).

A combination of Bilan and MODFLOW (MODFLOW-2000, Harbaugh et al., 2000) was used to estimate the possible impacts of climate change on groundwater resources in the Metuje River basin (Novický et al., 2007), which is part of an important hydrogeological region (Cretaceous geological formation characterised by deep circulation of groundwater and high storage) in the Czech Republic. The results of a comparison of MODFLOW simulations using recharge series unaffected and affected by climate change showed that climate change could cause groundwater levels in the basin to decrease by as much as 10 metres. The base flow could drop to the levels of the existing groundwater abstractions in the basin (about 0.1 $m^3\ s^{-1}$) and therefore the Metuje River would be dry in the periods when it is normally almost exclusively fed from groundwater storage.

A subsequent study was focused on the possible impacts of climate change in the Budějovická basin (Uhlík, 2008). Selected results of this study are described in this paper.

2 METHODS

2.1 *Climate change scenarios*

The climate change scenarios are based on the results of simulations by the HIRHAM (Christensen and van Meijgaard, 1992; Christensen et al., 1996) and RCAO (Döscher et al., 2002) regional climate models (RCM). The HIRHAM RCM uses the boundary conditions from HadCM3 (Gordon et al., 2000) GCM simulations and the RCM RCAO uses ECHAM4 (Roeckner et al., 1996) and OPYC (Ocean and isoPYCnal coordinates) GCM boundary conditions. These simulations use ocean temperatures for 2071–2100 from the GCM outputs using SRES emission scenarios (A2 as pessimistic and B2 as optimistic alternative) developed by Nakicenovic et al. (2000). Low (2°C) and high (4.5°C) climate sensitivity to CO_2 concentration (climate sensitivity refers to the equilibrium change in global mean surface temperature following a doubling of the atmospheric CO_2 concentration) were used in the B2 and A2 scenarios, respectively.

The spatial resolution of the regional models is about 50 × 50 km (the area of the Czech Republic is covered by about 50 points). The simulations were performed for the period 2071–2100 (time horizon of 2085) with a reference period of 1960–1990. The climate change scenarios were prepared in the form of monthly time series of absolute changes (delta factor) in air temperature and dew-point temperature and relative changes (percentage change factor) in precipitation.

For the simulation of water cycle components for current conditions, the Bilan model used observed weather data (for the study, period 1942–2007 was available), which are subsequently modified by the monthly change factors for the climate change scenarios for the simulation of water cycle components affected by climate change.

2.2 *Linked application of Bilan and MODFLOW model*

For the purpose of the groundwater studies, the Bilan model was coupled with MODFLOW. In this application, the spatially uniform groundwater recharge series simulated for current and climate change conditions by the Bilan model were used as an input to MODFLOW. The parameters of the MODFLOW model were calibrated by minimising deviations between observed and simulated groundwater levels and also between simulated base flow (from the Bilan model) and base flow derived from streamflow hydrographs. Steady state simulation by the MODFLOW model was subsequently used to simulate the spatial distribution of groundwater levels and base flow in the study basin. This approach is described in more detail in Novický et al. (2007).

3 STUDY BASIN AND DATA

The Budějovická basin is located (Fig. 1) in the southern part of the Czech Republic. The total area of the basin is 484 km^2; 240 km^2 of which is one of the most important hydrogeological formations of groundwater resources in Southern Bohemia. The groundwater in the basin has accumulated in the upper Cretaceous and Tertiary sediments, which are located on crystalline bedrock whose upper surface is at between 50 m and 380 m above mean sea level (a.m.s.l). The elevation of the land surface ranges between 380 and 460 m a.m.s.l. Contour lines (isolines) of the bottom of the Cretaceous and Tertiary sediments are shown in Fig. 2 with the locations of groundwater observation sites and the main groundwater abstraction sites.

The mean annual air temperature is 7.9°C. The mean annual precipitation is 620 mm, of which 126.5 mm forms the total runoff (mean base flow is 35.4 mm). The groundwater storage is fed from recharge and partially from inflow from the surrounding crystalline rock formations.

Input data for the Bilan model (monthly series of basin precipitation, air temperature and relative air humidity) and flow series for calibration of the parameters of the model were available for the period 1942–2007. Observed groundwater levels in boreholes in the

Figure 1. Location of the study area (Budějovická basin).

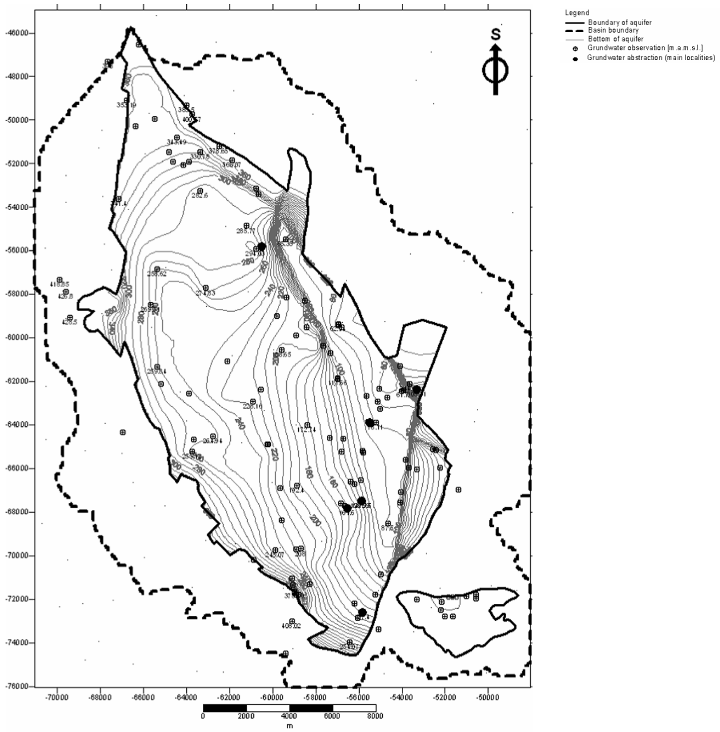


Figure 2. Contour lines (isolines) of the bottom of the cretaceous and tertiary sediments in the Budějovická basin and the locations of groundwater observation and groundwater abstraction sites.

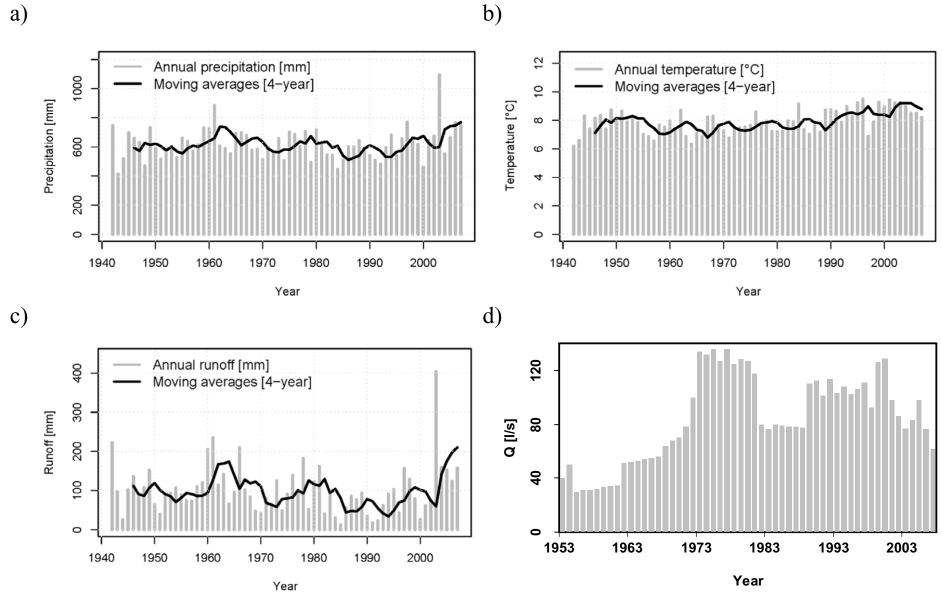


Figure 3. Results of hydrometeorological observations in České Budějovice (a—annual precipitation, b—annual air temperature, c—annual runoff from the Budějovická basin, d—annual groundwater abstractions (l/s) from Budějovická basin).

basin since 1974 were available for calibration of the MODFLOW model. Fig. 3 illustrates selected hydrometeorological observations and data on groundwater abstractions.

4 RESULTS

4.1 *Analysis of observed data*

During the last 20 years, mean annual air temperature increased by about 1°C (Fig. 3). Because of an increase in mean annual precipitation, the increase in mean annual air temperature was not reflected in a decrease in annual runoff. High annual runoff in 2002 is related to extreme flood conditions during the year. The increased temperature in combination with mean or low precipitation after 2000 (except for 2002) was probably reflected in a drop of groundwater levels. These results are consistent with results for other basins in the Czech Republic (Uhlík, 2006).

4.2 *Bilan model simulation*

The capability of the Bilan model to simulate the water cycle components in the basin is illustrated in Fig. 4, which shows the flow duration curves that were derived from the observed and simulated monthly flow series. The fit between the curves in the low flows is very good while high flows are moderately underestimated by the simulation. This is reflected in long-term mean annual runoff, which is 126.5 mm yr^{-1} when derived from the observed data and 112.8 mm yr^{-1} calculated from the simulation.

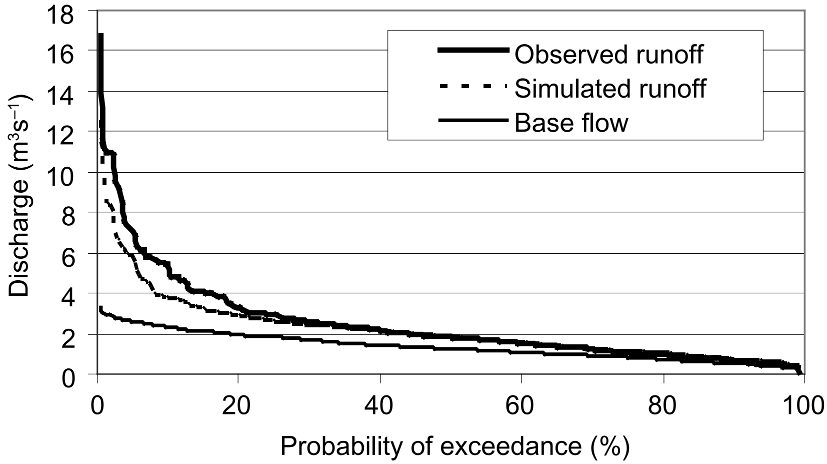


Figure 4. Flow duration curves derived from monthly observed and simulated data and base flow simulated by the Bilan model.

All of the climate change scenarios predict large increases in the mean annual air temperature (of between 3.7°C and 5.2°C) and moderate decreases or increases in mean annual precipitation depending on the scenario (Table 1). The seasonal distribution of precipitation could significantly change, which would be unfavourable because a decrease is predicted for the summer season when drought periods frequently occur. The changes in climate variables would be reflected in substantial deterioration of hydrological conditions according to the results of the Bilan model simulations. The annual average total runoff would drop to between 28 and 58 mm/year, base flow to 5 to 10 mm/year and groundwater recharge (an important input to the MODFLOW model) would also dramatically drop from the current annual average value of 35 mm/year to 5 to 10 mm/year (14% to 28% of the current value) (Table 1).

4.3 *MODFLOW model simulation*

3D groundwater flow was simulated by dividing the Budějovická basin into four model layers in MODFLOW, with differing coefficients of hydraulic conductivity. The elevation of the bottom and top surfaces of the layers are shown in Fig. 5. Fig. 6 shows the distribution of the infiltrated precipitation (l/s) between the individual layers. Under current conditions, the average infiltration into the aquifer is 523.6 l/s, of which 367.4 l/s forms shallow water circulation in the upper part of the aquifer and 156.2 l/s percolates into the deeper aquifer parts. With climate change, the infiltration into layer 1would drop to between 73 and 145 l/s depending on the scenario. From 1990 the total groundwater abstraction decreased from 100 l/s to current 70 l/s. Budweiser bier abstracts constantly 20 l/s.

The original goal of the study was to simulate the impacts of the existing groundwater abstractions in combination with the scenarios of climate change. But predicted infiltration under climate change (73 l/s–145 l/s) will be almost equal to the current groundwater abstraction. Therefore, the original study goals were changed and the groundwater flow was simulated by MODFLOW alternatively for conditions involving groundwater abstraction

Table 1. Average annual climate parameters for current and future conditions and main hydrological results of the Bilan model simulations.

Model	SRES scenario	Precipitation [mm/year]	Temperature [°C]	Potential evapotranspiration [mm/year]	Runoff [mm/year]	Base flow [mm/year]	Recharge [mm/year]
RCAO	A2*	582.4	13.09	931	28	5.63	4.91
RCAO	B2*	634.5	11.66	815	48.3	8.5	7.82
HIRHAM	A2*	612.4	13.05	905	36.4	5.44	6.33
HIRHAM	B2*	658.3	11.63	803	57.66	10.41	9.77
Current conditions (1942–2007)		619.9	7.89	673	100.9	35.44	35.16

* Current weather (1942–2007) modified according to change factors for 2071–2100.

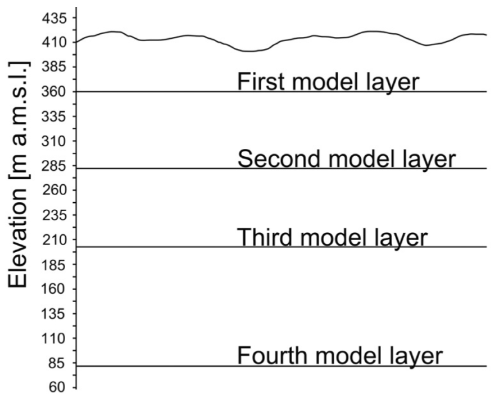


Figure 5. Elevation of the bottom and top surfaces of the MODFLOW model layers.

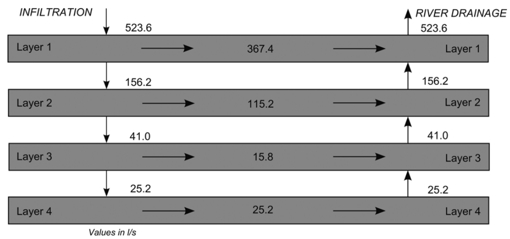


Figure 6. Distribution of the infiltrated water (l/s) between the individual aquifer layers under the current climate (1942–2007).

(but not climate change) and those reflecting climate change scenarios (but not groundwater abstraction).

Fig. 7a illustrates the results of the MODFLOW simulations for conditions of current groundwater abstractions, and indicates that groundwater level in the well screen depth dropped by as much as 10 m in the vicinity of the main groundwater-abstraction sites. These sites are located close to the centre of the basin and affect the groundwater conditions mainly in the model layer 3. The maximum decreases in groundwater levels caused by

a) b)

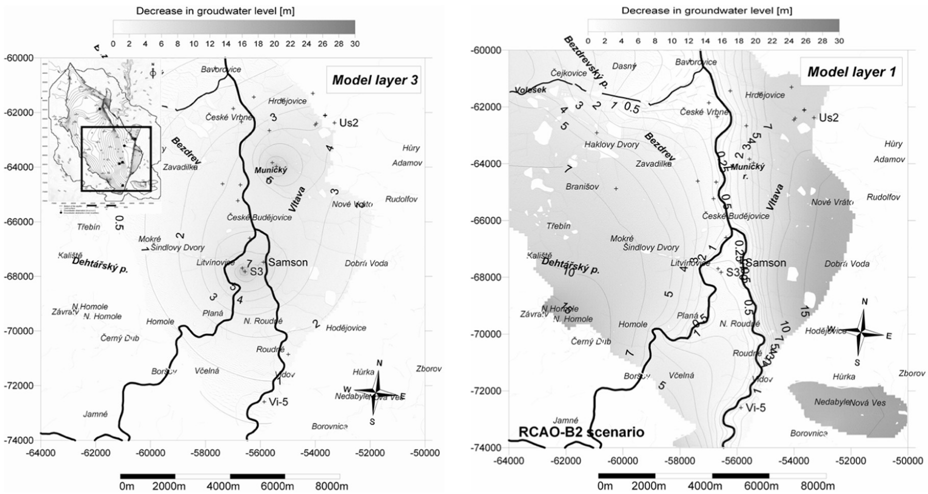


Figure 7. Decrease in groundwater levels caused by (a) groundwater abstraction under the current climate and (b) the B2 climate change scenario from the RCAO model (without abstraction).

climate change occur in the areas located close to the basin boundary. These decreases, which reach 15 and 25 m depending on the climate-change scenarios, affect mainly the groundwater conditions in model layer 1 (Fig. 7b).

5 DISCUSSION AND CONCLUSIONS

The results of the study are consistent with findings from previous studies that groundwater resources in good hydrogeological settings are highly vulnerable to groundwater level declines, particularly when they are exposed to a combination of impacts from abstraction and climate change. Under likely climate-change scenarios for the Budějovická basin, it will probably not be possible to meet the existing requirements for groundwater abstraction and therefore other resources will have to be used to meet the water-supply demand. Thus, conjunctive use of groundwater and surface-water resources will be necessary in the future for successful water resource management because surface water resources will be also limited. In addition, water demands are likely to increase, particularly for some purposes such as irrigation of agricultural lands. The conclusions derived from the results of this and future studies and proposed measures must be incorporated into strategies aimed at reducing the impacts of climate change, particularly for water management planning. In the member countries of the European Union, these results can suitably be applied in the implementation of the Water Framework Directive and in meeting its requirements for the development of Programmes of Measures focused on protection of water resources and their sustainable use.

The results of the simulation of the impacts of climate change on groundwater resources are naturally affected by a number of uncertainties, which originate from inaccuracies in input hydrological and meteorological data, the time step used for the simulation, uncertainties in hydrological model simulations, and particularly those stemming from the climate model simulations. The main drawback of the existing climate models is their insufficient capability to simulate the spatial distribution of precipitation. Data on the simulated total runoff in Table 1 suggest that the key uncertainties originate from different assumptions concerning CO_2 emissions.

ACKNOWLEDGEMENT

This paper was prepared from the results of research projects sponsored by the Ministry of the Environment of the Czech Republic, particularly the project on Research and protection of hydrosphere—research of relationships and processes in water component of the environment focused on impacts of human pressures, the sustainable use and protection of the hydrosphere and legislative tools (project No. MZP0002071101) and the project on Refining of current estimates of impacts of climate change in sectors of water management, agriculture and forestry and proposals of adaptation measures (project No. SP/1a6/108/07).

REFERENCES

Christensen, J.H., van Meijgaard, E. (1992) On the construction of a regional climate model, Tech. Rep., 92–14, DMI, Copenhagen, 22 p.

Christensen, J.H., Christensen, O.B., Polez, P., van Meijgaard, E., Botzet, M. (1996) The HIRHAM4 regional atmospheric Climate model, Sci. Rep., 96-4, DMI, Copenhagen, 51 p.

Döscher, R., Willén, U., Jones, C., Rutgersson, A., Meier, H.E.M., Hansson, U., Graham L.P. (2002) The development of the coupled regional ocean-atmosphere model RCAO, Boreal Env. Res. Vol. 7: 183–192.

Gidrometeoizdat (1976) Rekomendatsii po roschotu ispareniia s poverhnosti suchi. Gidrometeoizdat St Peterburg.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B., Wood, R.A. (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, Climate Dynamics, Vol. 16: 147–168.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G. (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Kašpárek, L. (1998) Regional study on impact of climate change on hydrological conditions in the Czech Republic. Prague, VÚV T.G.M., 1998, ISBN 80-85900-22-X, 69 p.

Kněžek, M., Krátká, M. (2005) Quantification of groundwater regime during extreme hydrological situations. In: Hydrological days 2005, Slovak Hydrometeorological Institute and Slovak National Committee for hydrology, Bratislava, ISBN 80-88907-53-5 [in Czech].

Krátká, M., Kašpárek, L. (2005) Regional impacts of climate change on water regime in the CR. In: Hydrological days 2005, Slovak Hydrometeorological Institute and Slovak National Committee for hydrology, Bratislava, ISBN 80-88907-53-5 [in Czech].

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.I., Kram, T., Lebre La Rovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z. (2000) IPCC Special Report on Emissions Scenarios, Cambridge University Press, Cambridge, United Kingdom and New York, NY.

Novický, O., Kašpárek, L., Uhlík, J. (2007) Possible impacts of climate change on groundwater resources and groundwater flow in well developed water bearing aquifers. In: Proceedings from The third international conference on climate and water. Helsinki, Finland, 3–6 September 2007, ISBN 978-952-11-2790-8.

Roeckner, E., Oberhuber, J.M., Bacher, A., Christoph, M., Kirchner, I. (1996) ENSO variability and atmospheric response in a global coupled atmosphere-ocean GCM. Clim. Dyn. Vol. 12: 737–754.

Tallaksen, L., Lannen, H. (editors) 2004 Hydrological drought—processes and estimation methods for streamflow and groundwater. Developments in water science, 48, Elsevier B.V., Amsterdam.

Uhlík, J. (2006) Analysis of impacts of climate change in central part of Intra-Sudeten basin. PROGEO and T.G. Masaryk Water Research Institute, Prague. [in Czech].

Uhlík, J. (2008) Possible impacts of climate change on groundwater resources in Budějovická basin. PROGEO and T.G. Masaryk Water Research Institute, Prague. [in Czech].

CHAPTER 2

Changing climate and saltwater intrusion in the Nile Delta, Egypt

Giovanni Barrocu
Department of Land Engineering, University of Cagliari, Italy

Kamal Dahab
Geology Department, Faculty of Science, Menoufia University, Shebin El-Kom, Egypt

ABSTRACT: The Nile delta aquifer, consisting of sediments deposited by the most important river flowing into the Mediterranean, provides the main water supply for nine Governorates in the area. Groundwater is endangered by salt water encroachment due to lateral intrusion of present sea water and upconing of connate salt water trapped in paleodeltaic sediments. The interface between sea and groundwater with different salinity is very fragile, as a result of alternate sea level fluctuations due to climate changes over geological time. The natural water cycle and river sedimentation in the delta have been strongly affected by human actions, namely the construction of the Aswan High Dam, and pollution. Therefore, integrated surface water and groundwater resources of different salinity should be rationally managed in terms of quantity and quality for different uses to face the ever-growing demand of the increasing population in the Nile Delta, who make a living from intensive agriculture.

Keywords: Climate change, salt water, Nile Delta

1 INTRODUCTION

The Nile Delta ($\sim$22,000 km^2) constitutes a large leaky aquifer system, representing the most important groundwater resource for nine Governorates of Egypt. Its apex is located at about 20 km north of Cairo and 180 km from its base, stretching around 220 km along the Mediterranean seashore.

The closure of the Aswan High Dam disrupted the natural surface and groundwater flow and sediment discharge cycle, so that the northern part of the delta is endangered by erosion, saltwater intrusion, and pollution. These processes are inducing loss of both land and coastal lagoons, and a marked decline in agricultural productivity at a time when the population is expanding exponentially. In order to assess the impacts of the natural processes and human actions on groundwater and the extension and origin of salt water intrusion in the aquifers of the Nile Delta, a network of observation wells, irrigation and domestic pumping stations was developed and data on salinity and hydrochemistry collected by one of the co-authors in a study area between Longitude 30°30′ and 31°30′ E, and Latitude 31°00′ and 31°30′ N were reassessed (Fig. 1).

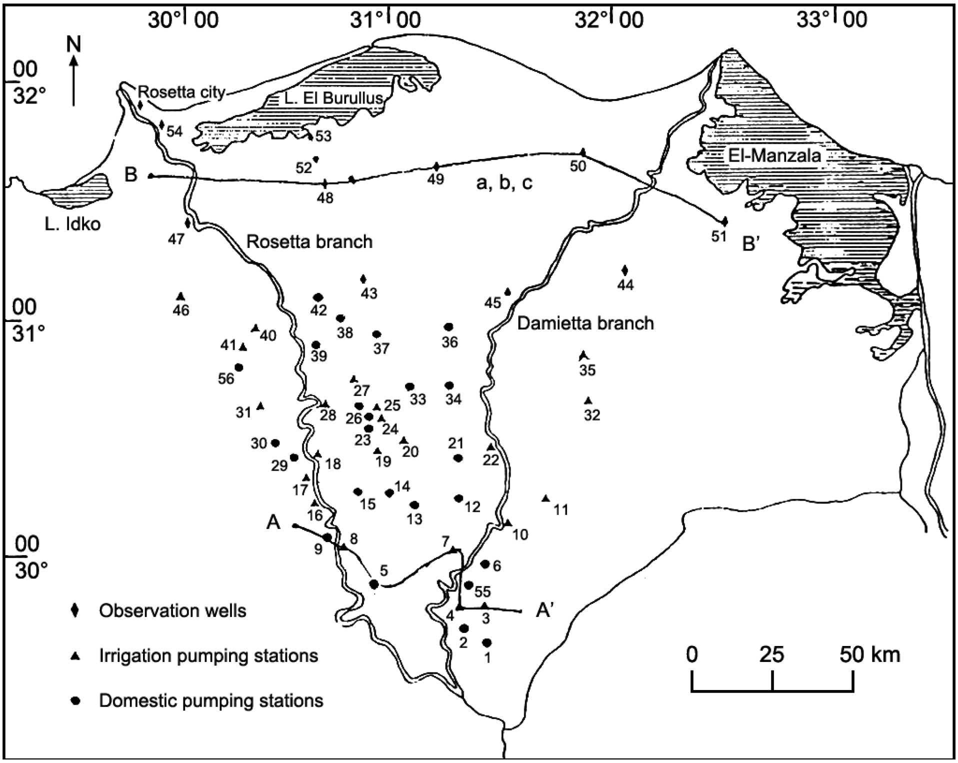


Figure 1. Observation well network in the Nile Delta.

2 GEOLOGICAL SETTING

The present day delta is the result of different sedimentation phases from the Late Pliocene to Present associated with alternating sea regressions and ingressions due to climate changes and tectonic movements, with down faulting development or rejuvenation of older faults, affecting the Mesozoic bedrock and overlaying sediments deposited by the Nile. Downslope mass movements, sediment slumping and basin bottom subsidence gave space to a highly developed deltaic front underlined by the prodelta formed by the deposits of the old Nile, with its tributaries from the Eastern and western deserts, and some local tributaries (Sestini, 1989).

The Plio-Quaternary aquifer system of the Nile Delta overlays the thick sequence of Pliocene, Messinian (El Wastani, Kafr El-Sheikh, Abu Madi) and older Tertiary and Cretaceous strata (Fig. 2). Stratigraphically, the system can be easily distinguished according to lithological characteristics into two rock units, from top to bottom:

a. *The Bilqas Formation*, belonging to the Holocene, is mainly composed of silt and sandy or clayey silt with few sand layers in the lower part. Also some calcareous inclusions are detectable at different depths.

   In the Nile delta coastal area, sediments are fine and attain thicknesses of up to about 50 m, so that they act as an aquiclude. Southwards, they become gradually thinner, their

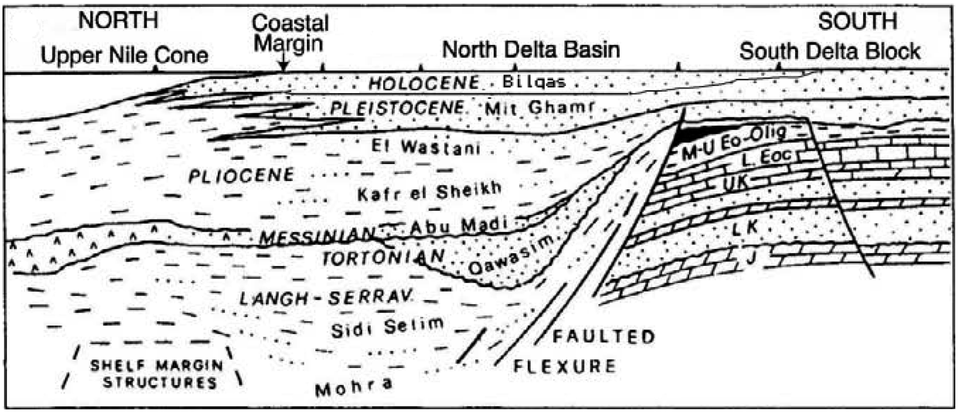


Figure 2. Cross-section from S-to-N showing Quaternary deposits above thick Tertiary and Mesozoic sequences (modified after Sestini, 1989).

thickness ranging between 20–25 m in the southern and middle parts, whereas their grain size becomes coarser, so that they act as an aquitard.

b. *The Mit Ghamr Formation*, assumed to be of Late Pliocene—Early Pleistocene age, consists of sands and gravels interbedded by thin clay layers and lenses. Locally, the grain size of the sediments change so that they predominantly consist of clay and silt with sand intercalations. The funnel-shaped depositional basin of the formation covers most of the study area and its fringes, its long stem extending southwards into the Nile valley. Clays are more frequent in the north, whereas coarser sediments dominate in the southern part and are occasional in the eastern and western sides. The series of alternating clays and sands with gravel, present especially in the northern and north-eastern parts, reflects the progradation cyclicity sequence of the Delta. The formation, over 900 m thick in the northern part of the Nile Delta, 500–600 in the middle part, and 100–400 m in the southern part, constitutes the main aquifer of the region.

Sedimentological research carried out on a number of core samples from lagoon/marsh, delta front and prodelta facies in the northeast sector of the region clearly shows that the deltaic deposits mainly consist of detritus and weathering products from the Trap Series Basalts covering the 75% of the Ethiopian Highlands (Siegel et al., 1995).

In Fig. 3, the Nile Delta development phases due to sea level variations caused by climate changes from late Pliocene to the beginning of the Holocene are outlined over the image of the present delta.

During the very strong pluvial periods at the end of the Pliocene, the Nile deposited enormous quantities of sediment in the pre-existing sea gulf. During the Early and Middle Pleistocene, the main bulk of the Nile Delta was built under fluviomarine conditions, and nearly all porosities were saturated with salt water. The thickness of fresh water-saturated sediments was very limited and existed only in the earliest delta lobes to the southeast and southwest. By the end of the Middle Pleistocene, the Mediterranean Sea had reached a level similar to the present one or even lower. Such progressive sea level lowering determined the leaching of the old Pleistocene aquifers through the dilution of the inherited salt water by the infiltrated rain water discharging into the effluent channel (Dahab, 1994).

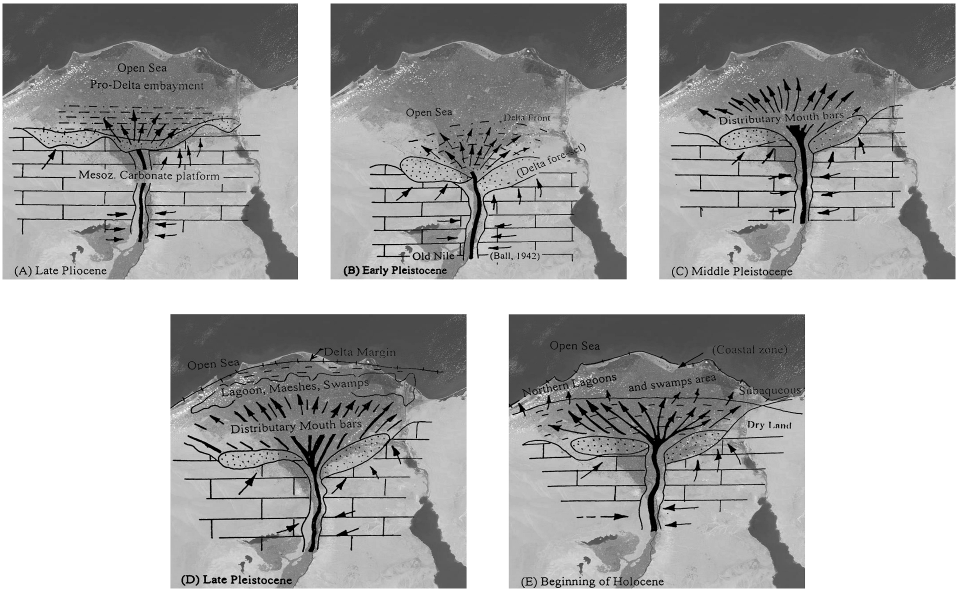


Figure 3. The Nile Delta development due to climate changes from late Pliocene to Holocene outlined over present delta satellite images. A) Late Pliocene: 2.6-1.8 My. B) Early Pleistocene: 1.8-0.78 My. C) Middle Pleistocene: 0.78-0.12 My. D) Late Pleistocene: 0.12-0.0017 My. E) Beginning of Holocene: 0.0017 My.

The most drastic changes in the Nile Delta aquifer system took place during the late Pleistocene (nearly 180,000 years Before Present (B.P.)), owing to severe changes in sea level and climatic conditions. At least eight stages are of certain importance for groundwater quality evolution:

i. Interglacial episodes separating the Middle and Late Pleistocene (Mindel-Riss interglacial) caused a sea level rise above its present day level by about 8 m (Fairbridge, 1961). This caused coastline regression on the subaerial delta plain with a corresponding aggradation in the distributaries and on the low lands. Deterioration of groundwater occurred but, on the other hand, the channels in the Nile valley and the southern parts of the Nile Delta became influent and recharged the adjacent older sediments with fresh water, which leached out their inherited salinity.
ii. Geological and archaeological investigations indicate that the Nile Delta margin has been affected by submergence due to eustatic sea-level rise (∼1 mm/year) since the late Holocene, and land subsidence at variable rates, confirmed by the submergence and burial of the base of most archaeological sites along the delta (Sestini, 1989; Stanley and Warne, 1998; Stanley, 2005). The interval between 180,000 and 125,000 yr B.P. was the time of the Riss glacial stage, associated with a notable drop in sea level, below the present one. This favoured the degradation of the main river courses and the effluent channels caused another cycle of leaching in the Early and Middle Pleistocene aquifers in the southern parts.
iii. In the time interval between 125,000 and 110,000 yr B.P., there was a maximum transgression, when the sea level rose up to 9–15 m above the present one, so that