Thermal Use of Shallow Groundwater

Thermal Use of Shallow Groundwater

Fritz Stauffer, Peter Bayer, Philipp Blum,
Nelson Molina-Giraldo, and Wolfgang Kinzelbach

CRC Press
Taylor & Francis Group
Boca Raton London New York

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

MATLAB® is a trademark of The MathWorks, Inc. and is used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB® software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB® software.

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

Version Date: 20131025

International Standard Book Number-13: 978-1-4665-6020-8 (eBook - PDF)

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

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

Contents

Preface *xi*
Acknowledgments *xiii*
Authors *xv*
Symbols *xix*

1 Introduction 1

1.1 Motivation for the thermal use of underground or groundwater systems 2
1.2 Importance of the local conditions 4
1.2.1 Thermal regime 4
1.2.2 Hydrological and hydrogeological conditions 9
1.3 Technical systems 10
1.3.1 Heat pumps 10
1.3.2 Closed- and open-loop systems 12
1.4 Energy demand and energy production 16
1.5 Management of underground resources 19
1.5.1 Seasonal operation of technical installations 19
1.5.2 Water supply and thermal use 20
1.6 Impact on groundwater quality and ecology 20
1.7 Geotechnical issues 21
1.8 Regulatory issues 24
1.8.1 Swiss regulation 25
1.8.2 Austrian regulation 29
1.8.3 British regulation 29
1.8.4 German regulation 30
1.9 Challenges related to design and management 31
1.10 Scope of the book 32
References 32

2 Fundamentals 37

2.1 Theory of water flow and heat transport in the subsurface 37
2.1.1 Modeling hydraulic processes in porous media 37
2.1.1.1 Flow in saturated and unsaturated porous media, Darcy's law 37
2.1.1.2 Water mass balance, volume balance, flow equation 44
2.1.1.3 Initial and boundary conditions 49
2.1.1.4 Two-dimensional flow models for saturated regional water flow 50
2.1.2 Modeling thermal processes in porous media 52
2.1.2.1 Heat storage, heat capacity, and advective heat transport 53
2.1.2.2 Heat conduction 54
2.1.2.3 Dispersive and macrodispersive heat transport 61
2.1.2.4 Heat transport equation 68
2.1.2.5 Initial and boundary conditions 72
2.1.2.6 Concepts for BHEs 75
2.1.2.7 Coupling thermal transport with hydraulic models 79
2.1.2.8 Two-dimensional heat transport models 80
2.1.3 Integral water and energy balance equations for aquifers 81
2.1.3.1 Rough estimation of the potential of an unconfined shallow aquifer for thermal use 85
2.2 Thermal property values 87
2.2.1 Heat capacity and thermal conductivity values 87
References 93

3 Analytical solutions 101

3.1 Closed systems 105
3.1.1 Instantaneous point source—three-dimensional conduction 105
3.1.2 Moving point source—three-dimensional conduction and advection 105

3.1.3 ILS—two-dimensional conduction 106
3.1.4 Infinite cylindrical source—two-dimensional conduction 109
3.1.5 FLS—three-dimensional conduction 114
3.1.6 Finite cylindrical source—three-dimensional conduction 118
3.1.7 Moving ILS—two-dimensional conduction and advection 119
3.1.8 Moving FLS—three-dimensional conduction and advection 126
3.1.9 Infinite plane source—one-dimensional conduction 130
3.1.10 Moving infinite plane source—one-dimensional conduction and advection 132
3.1.11 Steady-state injection into an aquifer with thermally leaky top layer 134
3.1.12 Harmonic temperature boundary condition for one-dimensional conductive–advective heat transport 135
3.1.12.1 One-dimensional vertical conductive heat transport 135
3.1.12.2 One-dimensional horizontal conductive/dispersive–advective transport 136
3.1.12.3 Horizontal layer embedded in conductive bottom and top layer 138
3.2 Open systems 140
3.2.1 Analytical solution for steady-state flow in multiple well systems 142
3.2.1.1 Double well system in uniform flow field 145
3.2.2 Linear flow 152
3.2.3 Radial flow, infinite disk source 155
3.2.4 Natural background groundwater flow 156
References 158

4 Numerical solutions 163

4.1 Two-dimensional horizontal numerical solutions 167
4.1.1 Analogy with solute transport models 170

4.1.2 Analysis of steady-state open system in rectangular aquifer 171
4.1.2.1 Scaled solution for open system in rectangular aquifer 173
4.2 Multidimensional numerical solutions 175
4.2.1 Principles of the finite difference method for heat transport 176
4.2.2 Principles of the finite element method for heat transport 181
4.2.3 Principles of the finite volume method for heat transport 183
4.2.4 Principles of the method of characteristics for heat transport 183
4.2.5 Principles of the random walk method for heat transport 184
4.3 Strategy for coupled flow and heat transport 185
4.4 Some available codes for thermal transport modeling in groundwater 186
References 190

5 Long-term operability and sustainability 197

5.1 Systems in low permeable media 197
5.2 Thermal evolution in aquifers 202
5.3 Further criteria of sustainability 204
References 207

6 Field methods 209

6.1 Hydrogeological field methods 209
6.2 Thermal response tests 210
6.2.1 Development of TRTs 210
6.2.2 Setup and application of TRTs 212
6.2.3 Evaluation of TRTs 213
6.2.3.1 Analytical models 214
6.2.3.2 Numerical models 218
6.3 Thermal tracer test 220
References 224

7 Case studies 229

7.1 Case study Altach (Austria) 232
7.2 Limmat Valley aquifer Zurich (Switzerland) 239
7.3 Bad Wurzach (Germany) 243
References 248

Index *251*

Preface

The thermal use of the shallow subsurface is increasingly promoted and implemented as one of many promising measures for saving energy. The energy extracted from such systems is referred to as shallow geothermal energy or low-enthalpy energy. Open and closed systems are distinguished usually consisting of boreholes combined with heat pumps. A series of questions arises with respect to the design, the management of underground and groundwater heat extraction systems, such as the sharing of the thermal resource, the long-term sustainability of the thermal use, and the assessment of its long-term potential. For the proper design of thermal systems, it is necessary to assess their impact on underground and groundwater temperatures.

The theoretical basis of heat transport in soil and groundwater systems is therefore introduced, and the essential thermal properties are discussed. In the planning and design of geothermal systems, hydrogeological and thermal site investigations have to be combined with modeling. Therefore, a series of mathematical tools and simulation models based on analytical and numerical solutions of the heat transport equation are presented. Finally, some case studies are introduced for illustration.

The book is directed toward MSc students in civil or environmental engineering, engineering geology, and hydrogeology and junior professionals. It provides a platform of principles and outlines the essential models and parameters to assess and design technical systems for the thermal use of the shallow underground.

MATLAB® is a registered trademark of The MathWorks, Inc. For product information, please contact:

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098 USA
Tel: 508-647-7000
Fax: 508-647-7001
E-mail: info@mathworks.com
Web: www.mathworks.com

Acknowledgments

We would like to thank everybody who supported us in our book project. In particular, we acknowledge the research of former members of the Hydrogeothermics Research Group: Gita Brandstetter, Stefanie Hähnlein, Joszef Hecht-Méndez, Karl Urban, Selçuk Erol, and Ke Zhu. Furthermore, we are grateful to Gabriele Moser, Gianni Pedrazzini, and Valentin Wagner, who have supported us in the editing of text and figures. Special thanks go to Signhild Gehlin and Markus Kübert for providing the photos and data of the thermal response tests. For the support, data, and excellent cooperation at the geothermal test site in Bad Wurzach, we would like to thank Gerhard Bisch, Jürgen Braun, Nobert Klaas, and Christoph Knepel. Moreover, we acknowledge the excellent work of the master students Niculin Cathomen, Esther Müller, and Daniel Ott in environmental engineering, which was utilized for the presentation of the regional case studies.

Authors

Fritz Stauffer, Prof. Dr., is a retired professor at the Institute of Environmental Engineering at ETH Zurich, Switzerland. He was born in 1947 and is a citizen of Switzerland. He was a senior research officer and lecturer in groundwater and hydromechanics. He studied rural engineering at ETH Zurich, where he obtained his diploma in 1971 and his doctorate in 1977. The PhD thesis—under the supervision of Professor Dr. T. Dracos—was in the field of unsaturated flow in porous media. From 1981 to 2010, Fritz Stauffer taught courses in groundwater and organized a series of 20 international scientific short courses in groundwater management as well as several international symposia at ETH Zurich. In 1996, he was a visiting scholar at Stanford University. In 2001, he was awarded the title of professor by ETH Zurich. His research interests are in flow and contaminant transport in groundwater including the capillary zone.

Apart from using experimental techniques, he mainly focuses on mathematical modeling as well as geostatistics and stochastic modeling of flow and transport processes in highly heterogeneous aquifers. Main applications are the quantification of the uncertainty in the localization of groundwater protection zones, the interaction between rivers and aquifers, thermal processes in groundwater, the coupled flow and heat transport in porous media with phase change (as in the thawing permafrost of rock glaciers), the thermal use of groundwater, and two-phase flow processes in porous media. He retired from ETH in January 2012.

Peter Bayer, Dr., is a senior research associate at the Department of Earth Sciences at ETH Zurich, Switzerland. He was born in 1972 and is a German citizen. He graduated in 1999 from the Center for Applied Geosciences of the University of Tübingen (Germany) and earned his PhD from the same institution in 2003. From 2008 to 2010, Peter Bayer was a EU Intra-European Marie Curie Fellow at ETH Zurich hosted by the Institute of Environmental Engineering. His work was aimed at the development of algorithmic optimization procedures and their implementation to solve problems related to applied hydrogeology and geothermics.

Among his main scientific contributions in the area of thermal use of shallow aquifers are the development and application of life cycle–based concepts for analyzing environmental aspects of low-enthalpy geothermal systems. Together with coauthors P. Blum and N. Molina-Giraldo, he investigated the influence of groundwater flow on borehole heat exchangers by analytical and numerical simulation as well as through field studies. This work was accompanied by enhancements to thermal field investigation techniques in shallow aquifers, in particular, the application and interpretation of thermal response tests under conditions with significant groundwater flow velocity. Peter Bayer has been working on thermal processes in aquifers on the lab scale, the several meters field scale, as well as the large scale of urban subsurface temperature evolution. His research has been published in more than 75 scientific contributions, 50 of which are listed in the Web of Science.

Philipp Blum, Jun.-Prof. Dr., born in Ulm in 1972, is currently an assistant professor (junior professor) for engineering geology at the Karlsruhe Institute of Technology (KIT). From 1993 to 1996, he studied geology at the University of Heidelberg. In 1997, as part of the Erasmus programme, he joined the School of Earth Sciences at Cardiff University in Wales. From 1996 to 2000, he continued his studies in applied geology at the University of Karlsruhe, where he received his diploma in 2000. In 2003, as part of the international research project DECOVALEX, he received his PhD on hydromechanical processes in fractured rock at the School of Earth Sciences at the University of Birmingham (UK). From 2003 to 2005, he was working for URS Germany as a project manager and hydrogeologist. From 2006 to 2010, he was an assistant professor for hydrogeothermics at the University of Tübingen (Germany), where in 2010, he received his habilitation in applied geology on thermohydromechanical and chemical (THMC) processes in porous and fractured aquifers. He published more than 40 peer-reviewed publications, of which 36 are also listed in the Web of Science. His current research interests focus on contaminant hydrogeology, shallow geothermal energy, and engineering geology in porous and fractured rocks.

Nelson Molina-Giraldo, Dr., born in 1981 in Colombia, is a groundwater modeler at Matrix Solutions, Inc., Canada. He obtained his first degree in environmental engineering at the University of Antioquia, and then he moved to Germany and completed a master programme in applied environmental geosciences (AEG) at the University of Tübingen, Germany. He received his

PhD at the same university in 2011, where he conducted research into heat transport modeling in shallow aquifers. Currently, he has been working on analytical and numerical modeling to assess the feasibility of groundwater withdrawal forecasts for operational management and regulatory needs. He has been also implementing groundwater–surface water monitoring programs to attempt to measure changes in groundwater–surface water interaction based on temperature measurements.

Wolfgang Kinzelbach, Prof. Dr., born in 1949 in Germany, is a full professor of hydromechanics and groundwater at ETH Zurich, Switzerland. He obtained his first degree in physics at Munich University and then turned to environmental engineering in Stanford, California. He earned his PhD at Karlsruhe University in 1978, with a thesis on managing waste heat emissions by power stations on the Rhine River. After professorships at Kassel University and Heidelberg University, he joined ETH in 1996. He has been working on groundwater themes including the modeling of pollutant transport, environmental tracers, design of remediation measures, and management of water resources for more than 20 years. His more recent work focuses on real-time modeling and control of well fields and sustainable management of water resources in arid environments. He is the author or a coauthor of more than 200 publications listed in the Web of Science. He was awarded the Henry Darcy Medal of the European Geophysical Union, the Prince Sultan International Prize for Water, and the Muelheim Water Award. He is a fellow of the American Geophysical Union.

Symbols

Bold symbols represent vectors and tensors, whereas italic symbols represent scalar quantities and variables.

$_{a}$: Subscript a: air
A: Area (m^2)
$_{b}$: Subscript b: borehole
B: Boundary
c: Solute concentration in water ($kg\ m^{-3}$)
C_m: Volumetric heat capacity of porous medium or aquifer ($J\ m^{-3}\ K^{-1}$) or ($W\ s\ m^{-3}\ K^{-1}$)
c_s: Specific heat capacity or specific thermal capacity, of solid material ($J\ kg^{-1}\ K^{-1}$)
C_s: Volumetric heat capacity of solid material ($J\ m^{-3}\ K^{-1}$) or ($W\ s\ m^{-3}\ K^{-1}$)
c_w: Specific heat capacity or specific thermal capacity of water ($J\ kg^{-1}\ K^{-1}$) or ($W\ s\ m^{-3}\ K^{-1}$)
C_w: Volumetric heat capacity of water ($J\ m^{-3}\ K^{-1}$)
D: Aquifer domain
$\mathbf{D}_h$: Hydrodynamic dispersion tensor for solute transport ($m^2\ s^{-1}$)
$\mathbf{D}_t$: Thermal diffusion tensor or thermal diffusivity tensor ($m^2\ s^{-1}$)
$D_{t,L}$: Longitudinal thermal diffusion coefficient ($m^2\ s^{-1}$)
$D_{t,T}$: Transversal thermal diffusion coefficient ($m^2\ s^{-1}$)
E: Energy (J) or (W s)
$_{f}$: Subscript f: fluid
f: Depth to groundwater (m)
Fo: Fourier number (–)
g: Gravitational acceleration constant (scalar) ($m\ s^{-2}$)
$\mathbf{g}$: Gravitational acceleration gradient ($m\ s^{-2}$)
H: Length of vertical borehole heat exchanger (m)
h_w: Piezometric head (m)
$_{i}$: Subscript i: ice
I: Recirculation rate between two wells ($m^3\ s^{-1}$)
I_{hor}: Horizontal flow gradient (–)

j: Specific heat flux (W m^{-2})
J: Heat flux (W) or (J s^{-1})
j_{disp}: Dispersive (specific) heat flux (W m^{-2})
k: Permeability of aquifer (tensor) (m^2)
$\mathbf{K}_w$: Hydraulic conductivity of aquifer (tensor) (m s^{-1})
L: Length scale (m)
L_f: Latent heat of melting/freezing (J kg^{-1}), 3.34 10^5 J kg^{-1} for water/ice
m: Aquifer thickness (m)
m_{VG}: van Genuchten parameter (–)
$\_{n}$: Subscript n: normal direction
n: Unit normal vector (m)
N: Recharge rate per unit surface area (m s^{-1})
n_{VG}: van Genuchten parameter (–)
$\_{p}$: Subscript p: pipe
p_b: Air entry pressure (Pa)
P_t: Heat production per unit volume (W m^{-3})
p_w: Water pressure (Pa)
q: Specific discharge vector, water discharge rate through unit area (gradient) ($m^3 m^{-2} s^{-1}$)
Q: Water discharge rate (m^3 s^{-1})
q_{tb}: Heat flow rate per unit length of the borehole (= J/H) (W m^{-1})
R: Dimensionless cylindrical radius (–)
R_c: Solute retardation factor (–)
R_{t_ret}: Thermal retardation factor (–)
R_{tb}: Thermal borehole resistance (K W^{-1} m^{-1})
R_{tw}: Thermal radius of influence (m)
R_w: Radius of influence of a well (m)
$\_{r}$: Subscript r: residual
r: Radius (m)
r_b: Borehole radius (m)
r_p: Pipe radius (m)
$\_{s}$: Subscript s: solid
s: Length (m)
S: Storativity of aquifer, specific yield of unconfined aquifer (–)
S_s: Specific storativity of aquifer (m^{-1})
S_w: Saturation degree of water (–)
$S_{w,r}$: Residual saturation degree of water (–)
$\_{t}$: Subscript t: thermal
t: Time (s)
T: Temperature (°C or K; 0°C = 273.15 K)
T_0: Initial or undisturbed temperature (°C)
T_{inj}: Injection temperature (°C)
u: Mean flow velocity (gradient) (m s^{-1})
$\mathbf{u}_t$: Thermal velocity (gradient) (m s^{-1})

$\_{\text{v}}$: Subscript v: vapor
V: Volume (m^3)
vf: Volumetric fraction (–)
$\_{\text{w}}$: Subscript w: water
w: Water source/sink term, water volume per unit aquifer volume and unit time ($m^3\ m^{-3}s^{-1}$)
W: Source/sink term in two-dimensional flow equation ($m^3\ m^{-2}\ s^{-1}$)
x: x-coordinate (m)
$\mathbf{x}$: Location vector (m), with coordinates (x, y, z)
y: y-coordinate (m)
z: z-coordinate (m), positive upward
α: Angle (rad or °)
α_L: Longitudinal dispersivity for solute transport (m)
α_T: Transversal dispersivity for solute transport (m)
α_{VG}: Van Genuchten parameter (m)
β: Angle (rad or °)
β_L: Longitudinal thermal dispersivity of aquifer (m)
β_T: Transversal thermal dispersivity of aquifer (m)
γ: Euler's constant (–) = 0.5772…
Δ: Finite increment
θ: Dimensionless temperature (–)
θ_a: Volumetric air content ($m^{-3}\ m^{-3}$)
θ_i: Volumetric ice content ($m^{-3}\ m^{-3}$)
θ_w: Volumetric water content ($m^{-3}\ m^{-3}$)
λ_{BC}: Pore distribution index in the model of Brooks and Corey (–)
λ_{decay}: First-order decay coefficient for solute transport (s^{-1})
$\boldsymbol{\lambda}_{disp}$: Thermal dispersion tensor ($W\ m^{-1}\ K^{-1}$)
λ_{eff}: Effective thermal conductivity of subsurface ($W\ m^{-1}\ K^{-1}$)
λ_m: Thermal conductivity of porous medium or aquifer ($W\ m^{-1}\ K^{-1}$)
λ_s: Thermal conductivity of solid material ($W\ m^{-1}\ K^{-1}$)
λ_w: Thermal conductivity of water ($W\ m^{-1}\ K^{-1}$)
λ_{vert}: Thermal conductivity of the overburden ($W\ m^{-1}\ K^{-1}$)
μ: Dynamic viscosity (Pa s)
ρ: Dimensionless radius (m)
ρ_a: Density of air ($kg\ m^{-3}$)
ρ_i: Density of ice ($kg\ m^{-3}$)
ρ_s: Density of the solid phase of the aquifer ($kg\ m^{-3}$)
ρ_{rel}: Relative density (–)
ρ_w: Density of water ($kg\ m^{-3}$)
τ: Period (s)
φ: Flow potential ($m^2\ s^{-1}$)
φ_r: Angular coordinate (polar angle) (–)
ϕ: Porosity of aquifer, volumetric fraction of pores in aquifer ($m^{-3}\ m^{-3}$ or –)

χ: Scaled pumping rate (–)
ψ: Stream function (m^2 s^{-1})
ω: Angular frequency (s^{-1})
∇: Gradient operator, applied to scalar quantity f: $\nabla f = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right)$
∇·: Divergence operator, e.g., applied to vector **v**: $\nabla \cdot \mathbf{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}$