waterloo hydrogeologic
SOFTWARE · CONSULTING · TRAINING

WHI E-News
Waterloo Hydrogeologic Inc.

2004 July Edition

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Waterloo Hydrogeologic, Inc. is a recognized leader in the development and application of environmental software and services.

We want your articles! Please send your groundwater related article to us today!

Product News

NEW Temperature, Level, and Conductivity Meter!

WHI is pleased to announce the addition of the **Model 107 TLC Meter** to our line-up of quality field equipment. For use in wells, open water, and for salt-water intrusion investigations, the new TLC Meter uses an intelligent conductivity sensor with platinum electrodes. The sensor is attached to flat-tape, accurately marked in millimeter and 1/100 ft. gradations The tape is available in lengths up to 300 ft./100 m. Click HERE for more information, or to order today Click HERE.

The NEW TLC Meter is perfectly partnered with WHI's AquaChem software package. AquaChem v.4.0 is the most widely-used software package developed for graphical and numerical analysis, modeling, and reporting of aqueous geochemical and water quality data. Save your temperature, level, and conductivity measurements in AquaChem for further analysis, modeling, and reporting. Once you start using AquaChem, you will discover that it is truly one of the most powerful tools available for interpretation, analysis, and modeling of simple or complex water quality data sets. ***Contact us TODAY for more details!***

Educational Software Bundles!

Summer is here and the Educational Software specials are HOTTER than EVER!! Let WHI help you prepare for the coming 2004-2005 school year and SAVE on specially selected software bundles of groundwater and environmental software products. Included in these bundles is our popular time-saving 5-pack of Visual MODFLOW Educational Tutorials to make your lesson plan preparations easier than ever!

Choose from these Software Bundles and Save...

***5-User Bundle of AquiferTest + 5-User Bundle of Visual MODFLOW with 5-Pack of Tutorials**
Use AquiferTest to calculate aquifer properties such as hydraulic conductivity (K); K is assigned in Visual MODFLOW models.
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***5-User Bundle of WHI UnSat Suite + 5-User Bundle of Visual MODFLOW with 5-Pack of Tutorials**
Use the WHI UnSat Suite to estimate contaminant concentrations in the vadose zone; import concentrations at the water table as contaminant loading rates in Visual MODFLOW.
ONLY US$1812

***5-User Bundle of Visual HELP + 5-User Bundle of Visual MODFLOW with 5-Pack of Tutorials**
Use Visual HELP to predict unsaturated flow (groundwater recharge); import groundwater recharge rates as initial recharge conditions into Visual MODFLOW.

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AquaChem v.4.0
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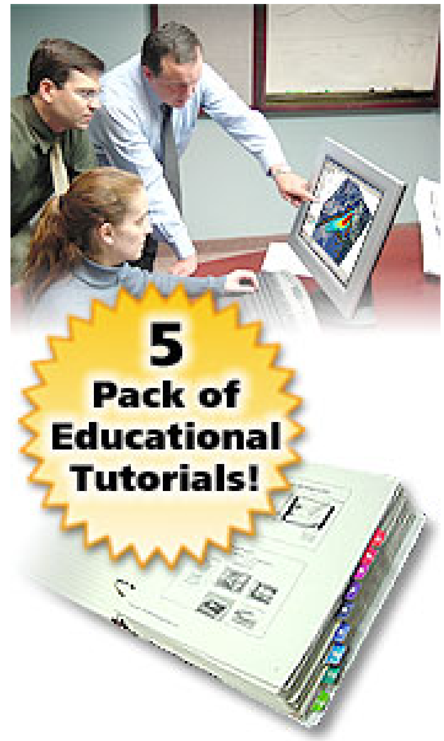
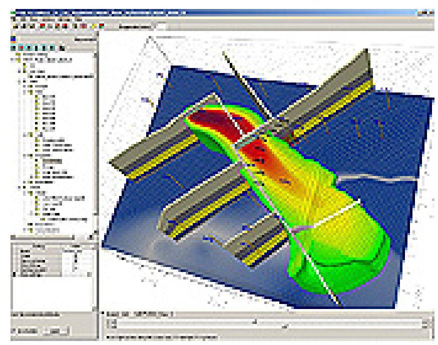
ONLY US$1887

* Please note that these bundles are only available to Educational Institutions.





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About the Educational Tutorials

Learn More

For more information about our software, please visit our website or contact us today:
Website: http://www.waterloohydrogeologic.com/software/software_main.htm
Email: sales@waterloohydrogeologic.com
Phone: (519) 746-1798

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Consulting News

Regional Groundwater Modeling in Southwestern Ontario

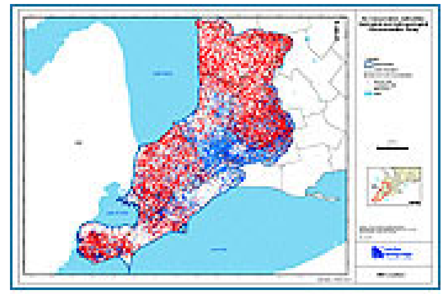
Waterloo Hydrogeologic, Inc. was recently awarded an Ontario Geological Survey funded contract to develop a three-dimensional geological model and regional groundwater flow model for six Conservation Authorities (CAs) in southwestern Ontario, including:

- Upper Thames River CA
- Lower Thames River CA
- Ausable Bayfield CA
- Maitland Valley CA
- Essex Region CA
- St. Clair Region CA

Study Area

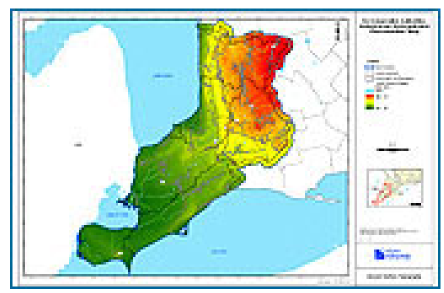
The purpose of the study is to improve the understanding of groundwater flow, including links between deep regional bedrock aquifers and the shallow groundwater system. Recently completed studies indicate that groundwater in the deep system flows through multiple watersheds and conservation authority jurisdictions, necessitating the regional approach adopted for this study.

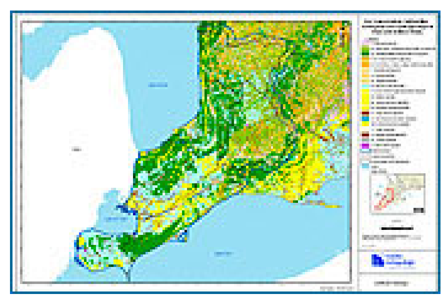
The study area is shown in the adjacent figure (see Fig. 1), and is approximately the same size as the state of New Jersey (20,000 km2).


Well Locations

The geological analyses and groundwater modeling completed during this project will help the six CAs prepare for forthcoming source water protection initiatives, and allow the following:

- **Assessment of regional groundwater flow pathways**. This will be completed using particle tracking, or reverse contaminant transport simulations, to identify flow paths that span multiple CAs, and to estimate the total groundwater flow rate in relation to other flows throughout the watershed.
- **Evaluation of groundwater travel times to specific regional aquifers**. The results of this assessment may be used to select current monitoring wells that are good candidates to identify areas most susceptible to droughts and surface contamination. This physical-based analysis approach can be used to complement other vulnerability and susceptibility mapping completed throughout the study area
- **Determination of recharge areas for specific streams and rivers.** This will be completed using reverse particle tracking, by releasing particles along streams and rivers in a groundwater model. The analysis would provide an assessment of the groundwater area contributing discharge to the stream, and provide information regarding the length of time for water to travel from the water table to a stream.


Ground Surface Elevation


Surficial Geology

In addition to the above scenarios, a regional groundwater budget that describes the quantity of groundwater that flows across watershed boundaries, discharges to streams, and is removed by pumping wells, will be completed.

For more information about this project, please contact:
Alge Merry, M.A.Sc., P.Eng.
Groundwater Modeling Group Leader
Email: amerry@waterloohydrogeologic.com

For more information related to this topic, or if you would like more information about WHI's Consulting activities and capabilities, please visit our website or contact us today:
Website: www.waterloohydrogeologic.com/consulting/consulting_services.htm
Email: consulting@waterloohydrogeologic.com
Phone: (519) 746-1798

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Training News

WHI Now Offering a New Line-Up of Environmental & Groundwater Modeling Courses!

The 2004 Waterloo Hydrogeologic Open Enrollment schedule has been set. In response to comments from groundwater professionals who have taken our Groundwater Modeling Courses in the past, and those who would like to attend courses in the future, WHI has combined the strengths of our previous Groundwater Modeling, Advanced Groundwater Modeling, and Model Calibration courses into one Applied Groundwater Flow & Contaminant Transport Modeling course. This course will include updated lecture material, as well as new hands-on laboratories to support the new course material. WHI has also created a new short course entitled GIS Data Management for Groundwater Modelers, which teaches the theory and hands-on application of GIS data integration and interpolation to support groundwater modeling efforts, as well as 3-dimensional visualization of modeling results in both the Visual MODFLOW and GIS environments.

Click on the titles below and see which courses are appropriate for you!

» Applied Groundwater Flow & Contaminant Transport Modeling **- NEW**
» Groundwater Contamination & Remediation **- UPDATED**
» Finite Element Groundwater Modeling **- UPDATED**
» Aquifer Test Analysis **- NEW**
» Unsaturated Zone Modeling and Evaluation of Landfill Impacts **- UPDATED**
» The Human Health Risk Assessment Course **- NEW**
» Water Quality Data Management & Modeling **- UPDATED**
» Regulatory Review of Hydrogeology Studies **- UPDATED**
» GIS Data Management for Groundwater Modelers **- NEW**

Who Can Benefit?

» Experienced hydrogeologists with no prior groundwater modeling experience;
» Regulators who review modeling reports;
» Managers who want to understand what the modelers are doing;
» Experienced modelers who want to enhance their skills;
» Students who want to acquire new skills;
» Lawyers who want to understand some of the technical issues; and
» Industry professionals who want to understand more about what their consultants are telling them.

For further details on any of these courses, please visit our website, or contact Miln Harvey, WHI Training Manager, at (519)

746-1798 x233.

Can't make one of our Open Enrollment Courses? Call us about our On-Site Custom courses designed to suit your specific needs!

Course Title	Dates/Locations
APPLIED GROUNDWATER FLOW & CONTAMINANT TRANSPORT MODELING **Theory and Hands-on Applications using MODFLOW-2000, MODPATH, MT3D & WinPEST** Simple to complex applications of groundwater flow and contaminant transport models are covered in this 4-day hands-on course. Groundwater resource topics include model development and calibration to groundwater heads and flows, new well development, capture zone delineation, well interference, and stream impact investigations. Contaminant transport topics include model development and calibration to contaminant concentration, source area design, concentration boundary choice, solver comparison, and 3D visualization of flow and transport results. This course is ideally suited for hydrogeologists and modelers with some field investigation and modeling experience who wish to advance their modeling knowledge, and whose responsibilities include model development, review, planning and project management. **Course Objectives and Benefits** » Apply Visual MODFLOW Pro to 3D groundwater flow and contaminant transport projects » Use MODFLOW-2000 to develop several groundwater flow models » Calibrate your groundwater models to observed field data » Use MODPATH particle tracking features to determine preferential flow paths and delineate capture zones » Use ZoneBudget to assess subregional water budgets within your groundwater model » Simulate 3D contaminant transport using RT3D, MT3DMS & MT3D99 » Use WinPEST to improve model calibration and understand model uncertainty	Waterloo, Ontario Canada Sept 14 - 17, 2004 Kraków, Poland Oct 11 - 14, 2004 Braunfels, Germany Oct 26 - 29, 2004 Rome, Italy Oct 26 - 29, 2004 Sicily Nov 1 - 4, 2004 Adelaide, Australia Nov 23 - 26, 2004 Register Now

CONTAMINATED SITE RISK ASSESSMENT AND GROUNDWATER MODELING

Transport Processes, Natural Attenuation and Risk Assessment

This course provides a more complete understanding of groundwater contamination and remediation, and the use of fate and transport models and risk assessment software for analysis. Topics that will be covered include contaminant source area characterization, the risk assessment process, the fundamentals of natural attenuation, and risk-based corrective action. This course is suited for groundwater modelers and risk assessors who wish to develop a better understanding of groundwater contamination and remediation, the risk assessment process, and the use of groundwater models to assess risk-based site-specific standards and contaminant remediation.

Course Objectives and Benefits

» Define the Risk Assessment process and Risk-Based Corrective Action
» Enhance your understanding of contaminant transport and natural attenuation processes
» Detail how to quantify the potential risks of exposure to chemical contaminants
» Link fate and transport models to risk-based decision making models
» Quantitatively assess human health and ecological risk from environmental contaminants
» Define site-specific target levels (SSTLs) for site clean-up goals

Waterloo, Ontario Canada
August 10 - 13, 2004

Ostrava, Czech Republic
Sept 7 - 10, 2004

Gent, Belgium
Oct 26 - 29, 2004

Madrid, Spain
November 16 - 19, 2004

Register Now

FINITE ELEMENT GROUNDWATER MODELING

Advanced Applications for Saturated/Unsaturated Flow & Transport, Density-Dependent Flow, and Heat Transport

Advanced applications of groundwater flow and contaminant transport models using the Finite Element method are covered in this 4-day hands-on course. This course provides a more complete understanding of the use and applicability of finite elements in groundwater modeling, and includes such topics as groundwater flow and transport modeling, principles of unsaturated flow, fracture flow modeling, thermal transport, and density-dependent flow modeling. This course is ideally suited for groundwater modelers who wish to advance their modeling knowledge, and apply finite elements, using FEFLOW, to more complex modeling designs.

Course Objectives and Benefits

» Understand when to use finite-element vs. finite-difference modeling
» Apply FEFLOW to 3D groundwater flow and contaminant transport problems
» Simulate unsaturated zone flow using FEFLOW
» Simulate density-driven groundwater flow (e.g. saltwater intrusion) using FEFLOW
» Simulate fracture flow modeling using FEFLOW, and compare to a research case study
» Introduce the Interface Manager and the concept of model calibration to observed field data

Waterloo,Canada
Nov 2 - 5, 2004

Register Now

THE HUMAN HEALTH RISK ASSESSMENT COURSE

Practical Approaches to Estimating Risk & Developing Site-Specific Target Levels

An introduction to the use of RISC Workbench for completing human health risk assessments is covered in this 2-day course of lectures and hands-on exercises. Topics that will be covered include hazard identification, exposure assessment, dose-response assessment and risk characterization. Lectures and exercises will be presented in partnership with Lynn Spence, the developer of RISC Workbench. This course is suited for risk assessors who wish to develop a better understanding of the risk assessment process and the use of groundwater models and RISC Workbench software for completing a human-health risk assessment.

Course Benefits

» Learn the fundamentals of accepted risk assessment protocols
» Acquire lots of hands-on experience using the RISC Workbench software
» Understand the practical aspects of conducting a risk assessment
» Learn from an experienced risk assessment professional with worldwide experience

Cambridge, UK
Sept 28 - 29, 2004

Auckland,
New Zealand
Nov 18 - 19, 2004

Register Now

GIS DATA MANAGEMENT FOR GROUNDWATER MODELERS

Understanding Data Sources, Data Analysis and Visualization

This 3-day hands-on course presents an introduction to the management and analysis of groundwater data for Visual MODFLOW modelers. Topics include the data types used in groundwater models, the coordinate systems, datums and map projections in a GIS, the interpolation of data within the GIS (kriging, natural neighbor analysis, …), the development of model layers (cross-sectional analysis of site hydrogeology) and parameter fields for groundwater model construction, and the import and export of different types of data from the GIS system to the groundwater model and back to the GIS system. Other topics that will be covered include 2-D and 3-D visualization of model input and model output. This course is ideally suited for groundwater modelers who wish to develop a comprehensive understanding of the sources of data that are used in groundwater models, the interpolation of this data for modeling, and the interchange of information between the groundwater model and the GIS system.

Course Objectives and Benefits

» Understand the integration between the GIS system and Visual MODFLOW
» Assess the applicability of MapInfo, Surfer and HydroGeo Analyst for developing a GIS
» Use HydroGeo Analyst to develop model cross-sections and layer interfaces
» Use HydroGeo Analyst to interpolate layer elevations and export

Waterloo, Canada
Dec 14 - 16, 2004

Register Now

them to Visual MODFLOW
» Export Visual MODFLOW results to GIS and prepare report figures
» Develop animation files of Visual MODFLOW results and insert them into client presentations

AQUIFER TEST ANALYSIS

Principles of Pumping Test Design and Techniques for Data Analysis

A wide variety of techniques can be applied to analyzing aquifer tests. This course covers the theory behind the techniques and provides an opportunity to obtain hands-on experience in analyzing aquifer test data collected from a variety of conditions.

Course Objectives and Benefits

» Planning a pumping test
» Principles of aquifer test analysis
» Porous and fractured media
» Isotropic/anisotropic conditions
» Confined, leaky, and unconfined aquifers

Waterloo, Canada
August 17 - 18, 2004

Register Now

REGULATORY REVIEW OF HYDROGEOLOGY STUDIES

Approaches and Insights for Reviewing Modeling Reports

The overall objective of this course is to give regulators a greater understanding of how models work, and what to look for when reviewing a modeling report. Specifically, the objectives are as follows:

» To understand the uses and applications of numerical models;
» To understand the uses and applications of the analytical WHPA model;
» To have a practical basis for reviewing models;
» To identify the points of focus for reviewing a modeling study;
» To recognize when review by a specialist is required.

The content of this course will be applicable to the following areas:

» Alternatives for landfill or septic system design;
» Prediction of contaminant movement and impact from landfills, septic systems, and contaminated sites;
» Selection of remediation alternatives;
» Delineation of well capture zones and groundwater protection areas;
» Assessment of impacts from large groundwater extractions, and pit and quarry development in the context of the Permit To Take Water Program (PTTW) and groundwater interference investigations.

These applications could include review of modeling studies submitted by consultants, evaluation of workplans submitted by owners/proponents, and specification of modeling requirements for tendering hydrogeological studies.

Waterloo, Canada
Sept 21 - 24, 2004

Orlando, Florida
Sept 28 - Oct 1, 2004

Register Now

UNSATURATED ZONE MODELING AND EVALUATION OF LANDFILL IMPACTS

Calculating Recharge Rates, Contaminant Loading, and Impacts to Groundwater

Practical Applications for Landfill Design & Hydrologic Optimization by:

» Simulating multiple landfill profiles to find the most suitable design
» Evaluating leachate mounding or leakage problems with current landfill designs
» Determining the effectiveness of landfill caps to reduce leachate mounding
» Designing and optimizing leachate collection systems

Course Benefits

» Receive hands-on learning using standard vadose zone software tools recognized by environmental professionals
» Gain real-world experience in designing, implementing, and reviewing vadose zone models
» Learn in-depth knowledge/theory of the relationships between the saturated and unsaturated zones
» Develop fundamental skills necessary for optimizing landfill hydrology and design

Waterloo, Canada
Aug 3 - 5, 2004

Register Now

For our full 2004 training schedule, click here!

To request your free 2004 Training Course Schedule Catalog, click here!

For more information about our course offerings, visit our website or contact us today:
Website: www.waterloohydrogeologic.com/training/training.htm
Email: training@waterloohydrogeologic.com
Phone: (519) 746-1798

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Tips & Tricks

Understanding GIS Integration with Visual MODFLOW: Part IV

This month's tips and tricks article continues in the series on data entry and export in Visual MODFLOW. This month we will focus on new GIS integration features available in Visual MODFLOW v.4.0.

Visual MODFLOW v.4.0, you can now Export:

- **Contour lines to ESRI Shape .SHP files**
- **Pathlines to ESRI Shape .SHP files**
- **Gridded model data to TecPlot.DAT, .TXT, or Surfer Grids (ASCII or Binary)**
- **Layer information (cell top elevations, bottom elevations, and/or thickness) to TecPlot .DAT, .TXT, or Surfer Grids**

With these new features, it can be hard to keep track of all the export formats that Visual MODFLOW 4.0 supports. The following table provides a summary of the various images, data, and vector maps that can be exported from both the input and output of a Visual MODFLOW project.

From the INPUT mode, you can EXPORT:

Item	Description	Supported Formats
Grids	Locations of Rows and Columns	Raster Images* AutoCAD (.DXF) Text (.TXT, .ASC) TecPlot (.DAT) Surfer Grid (ASCII or Binary)
	Layer Elevations (Cell Top, Cell Bottom) and Layer Thickness	Raster Images* AutoCAD (.DXF) Text (.TXT, .ASC) TecPlot (.DAT) Surfer Grid (ASCII or Binary)
Wells		
	Pumping Well locations	Raster Images* AutoCAD (.DXF)
	Head / Concentration Observation well locations and details (screens, observations, etc.)	Raster Images* AutoCAD (.DXF) Text (.TXT)
Properties		
	Conductivity, Storage, Initial Heads, Bulk Density, Species (Kd), Initial Concentration, and Dispersion	Raster Images* AutoCAD (.DXF) Text (.TXT, .ASC) Surfer (.GRD) (ASCII or Binary) TecPlot (.DAT)
Boundary Conditions		

	Locations	Raster Images* AutoCAD (.DXF)
Particles		
	Locations	Raster Images* AutoCAD (.DXF)
Zone Budget		
	Locations	Raster Images* AutoCAD (.DXF)

***Raster Images include:** (.BMP, .JPG, .TIF, .PNG, .GIF, .EMF)

From the OUTPUT mode, you can EXPORT:

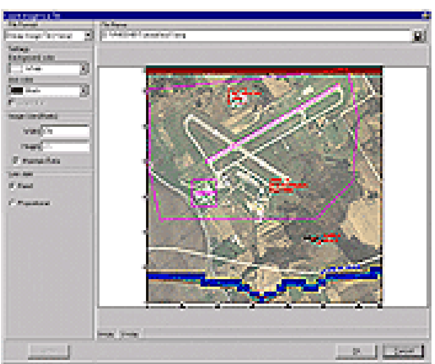
Item	Description	Supported Formats
Model Results - Contour Maps	Calculated Heads, Drawdown, Concentration, Water table elevation, Water table depth, Head difference, Flux between layers, Layer Elevations, Net Recharge	Raster Images* AutoCAD (.DXF) ESRI Shape (.SHP) Text (.TXT, .ASC) Surfer (.GRD) (ASCII or Binary) TecPlot (.DAT)
Calibration Residual Maps		
	Head and Concentration	Raster Images* AutoCAD (.DXF) ESRI Shape (.SHP) Text (.TXT, .ASC) Surfer (.GRD) (ASCII or Binary) TecPlot (.DAT)
Velocity Vectors		
	Locations and magnitude	Raster Images* AutoCAD (.DXF) Text (.TXT, .ASC) Surfer (.GRD) (ASCII or Binary) TecPlot (.DAT)
Pathlines		

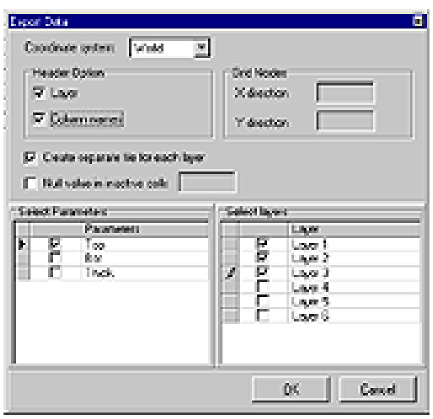
	Locations	Raster Images* AutoCAD (.DXF) ESRI Shape (.SHP)
Calibration Graphs		
	Head, Concentration, Time Series, Drawdown, Mass Balance (Flow or Transport), Zone Budget (Flow or Transport)	Raster Images* Text (.TXT, .ASC)
Zone Budget		
	Graphs	Raster Images* AutoCAD (.DXF)
	Zone Budget Report Mass Balance Report	Text (.TXT)

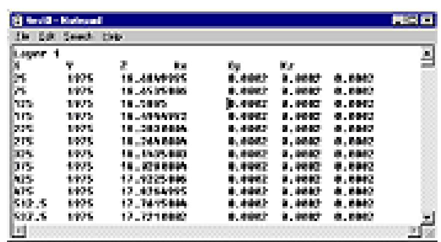
***Raster Images include:** (.BMP, .JPG, .TIF, .PNG, .GIF, .EMF)

When exporting gridded data to a file, you have the following options:

- Specify which layers to export (one, several, or all)
- Specify which parameters to export (e.g. all layer elevation information (cell top, bottom, thickness), or selected parameters only)
- Export to world or model co-ordinates, or IJK cell indexes
- Select the number of grid nodes to be output to the data file (for Surfer files)
- Separate files for each selected layer, or one file containing data for all layers
- Assign a null value for dry or inactive cells
- Exclude/Include column headings







Graphics file output, with image options	Data export, showing export options	Text file output of Conductivity data (cell by cell)

For more information about this tip, contact us at:
Email: techsupport@waterloohydrogeologic.com

For more information about **Visual MODFLOW Pro 4.0**, visit our website or contact us today:
Website: http://www.waterloohydrogeologic.com
Email: sales@waterloohydrogeologic.com
Phone: (519) 746-1798

Contributions from E-News Subscribers

Contribution from E-News subscriber - Leo Vallner

Waterloo Hydrogeologic, Inc. is always interested in hearing from our software users about their latest projects. Recently we were contacted by Leo Vallner from the Institute of Geology at Tallinn Technical University, Estonia, who provided us with a copy of his paper detailing his studies of groundwater flow and transport in Estonia. You can click on the link following the abstract and introduction for the complete paper.

Abstract.
The hydrogeological model constructed using the code Visual MODFLOW covers the whole territory of Estonia, the surrounding coastal sea, Lake Peipsi, and border districts of Russian Federation and Latvia, all together 88 032 km2. The 13 model layers include all main aquifers and aquitards from ground surface to as low as the impermeable part of the crystalline basement. Three-dimensional distribution of groundwater heads, flow directions, velocities, and rates as well as transport characteristics can be simulated by the model. Detailed basinwide or local groundwater budgets can be completed.

Introduction
The state of groundwater is complicated and causes anxiety in Estonia. Upper aquifers are suffering from industrial, agricultural, and former military pollution. In deeper aquifers a number of large depression cones have formed due to intensive withdrawals from wells, which induces intrusion of saline sea water towards coastal groundwater intakes (Vallner 1995, 1996; Vallner & Järvet 1998). The natural quality of groundwater is poor in several main aquifers.

In view of such a complex situation, a thorough basinwide modelling of groundwater flow and transport would be very useful for an optimum ground-water management. Heretofore the territory of Estonia as a whole has been hydrogeologically modelled only once, in 1976. Then it was considered as the northern portion of a large basinwide model that included Estonia, Latvia, Lithuania, and Kaliningrad district of Russia (Juodkazis 1980). Groundwater safe yields of main aquifers were calculated by an electrical analogue computer at modelling. Unfortunately, the results of that work are out-of-date for Estonia at present. However, the initial data used (values of hydraulic conductivity, measured groundwater heads, etc.) are still usable for hydrogeological research.

Proceeding from the above-stated reasons, the author of this paper has constructed a basinwide model suitable for a comprehensive treatment of hydro-geological problems of Estonia (Vallner 2002). The model was completed at the Geological Survey of Estonia in 1997–2002. The main characteristics of this model, its possible applications, and some modelling results are considered below...

Click here for the complete paper - The_paper_of_L._Vallner.pdf

If you have a project developed using WHI software that you would like to showcase in our E-News, please send your contact information and a brief outline of your project to techsupport@flowpath.com for consideration.

Article - Accessing Groundwater in Brazil

The following article is reprinted from the Canadian Department of Foreign Affairs and International Trade website (http://www.dfait-maeci.gc.ca/tna-nac/), as an excerpt from "Why Trade Matters, Stories of the Week - March 30, 2004".

Accessing Groundwater in Brazil

Waterloo Hydrogeologic, Inc. - Waterloo, Ontario

Waterloo Hydrogeologic, Inc. (WHI) is playing a key role in helping to improve the lives of the 25 million people of northeastern Brazil who subsist under the constant threat of drought. As a participant in the Northeastern Brazil Groundwater Project (PROASNE), WHI has carried out several projects aimed at augmenting sustainable access to safe drinking water.

The purpose of PROASNE, a Canada-Brazil joint venture funded by the Canadian International Development Agency and managed by Natural Resources Canada, is to transfer and adapt Canadian technologies that will improve the development and management of groundwater resources in semi-arid northeastern Brazil. This will, in turn, lead to a reduction in hunger, child mortality and extreme poverty.

Among WHI's contributions to the program is the development of the National Groundwater Information System known as SIAGAS, a one-of-a-kind ensemble of groundwater data management tools accessible through the Internet. "With SIAGAS, Brazil will be equipped with one of the most modern tools to manage its groundwater resources," says Daniel Gomes, WHI's International Division Manager. The technology's success in Brazil has generated a great deal of interest from other governments worldwide. "Already, WHI has been retained to develop similar systems for the Ontario Ministry of the Environment and for Lesotho in southern Africa," adds Gomes.

Elsewhere in Brazil, WHI specialists investigated the sustainability of a major aquifer system that supplies water to the western part of the state of Rio Grande do Norte. This work led to the identification of water resources that will support new economic development in the region. As in all PROASNE projects, the technologies employed here were transferred to Brazilian counterpart institutions. In the municipality of Cacapava/SP, the company's geographic information systems tools were used to generate maps of potential contaminant sources in the drinking water, which is supplied through a network of state-owned wells. WHI's clients in Brazil also include multinationals such as Daimler-Benz, Dow Corning, Esso, General Motors and Petrobras.

There are some 14,000 users of WHI's software in 85 countries around the world, where the Canadian Trade Commissioner Service (TCS) has been instrumental in the company's international success. "TCS staff have provided invaluable information on ways to expand our export markets," says Dr. Nilson Guiguer, President of WHI. "We always consult them, before going into a country, for different kinds of assistance, from establishing contacts before a trade show to obtaining advice on finalizing business contracts."

Headquartered in Waterloo, Ontario, WHI has offices in Tampa, Florida, and São Paulo, Brazil. A new office was recently opened in Recife in northeastern Brazil, which will be dedicated primarily to developing software for the Latin American water resources sector.

TOP

Thank you for reading this month's edition of WHI E-News! For more information about our products and services please use the links below!

Visit our Website - See what Waterloo Hydrogeologic Inc. has to offer!

Software Division - Check out our groundwater modeling software.

Consulting Division - Visit our Consulting Division on the web to see how we can help you.

Training Division - Visit our Training Division on the web to find a course in your area.

Equipment Division - WHI is now selling groundwater monitoring equipment.

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Hydrogeological model of Estonia and its applications

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Abstract. The hydrogeological model constructed using the code Visual MODFLOW covers the whole territory of Estonia, the surrounding coastal sea, Lake Peipsi, and border districts of Russian Federation and Latvia, all together 88 032 km^2. The 13 model layers include all main aquifers and aquitards from ground surface to as low as the impermeable part of the crystalline basement. Three-dimensional distribution of groundwater heads, flow directions, velocities, and rates as well as transport characteristics can be simulated by the model. Detailed basinwide or local groundwater budgets can be completed.

Key words: hydrogeological modelling, groundwater flow, base flow, net infiltration, predevelopment conditions, Cambrian–Vendian aquifer system, Estonia.

INTRODUCTION

The state of groundwater is complicated and causes anxiety in Estonia. Upper aquifers are suffering from industrial, agricultural, and former military pollution. In deeper aquifers a number of large depression cones have formed due to intensive withdrawals from wells, which induces intrusion of saline sea water towards coastal groundwater intakes (Vallner 1995, 1996; Vallner & Järvet 1998). The natural quality of groundwater is poor in several main aquifers.

In view of such a complex situation, a thorough basinwide modelling of groundwater flow and transport would be very useful for an optimum groundwater management. Heretofore the territory of Estonia as a whole has been hydrogeologically modelled only once, in 1976. Then it was considered as the northern portion of a large basinwide model that included Estonia, Latvia, Lithuania, and Kaliningrad district of Russia (Juodkazis 1980). Groundwater safe yields of main aquifers were calculated by an electrical analogue computer at modelling. Unfortunately, the results of that work are out-of-date for Estonia at present. However, the initial data used (values of hydraulic conductivity, measured groundwater heads, etc.) are still usable for hydrogeological research.

Proceeding from the above-stated reasons, the author of this paper has constructed a basinwide model suitable for a comprehensive treatment of hydrogeological problems of Estonia (Vallner 2002). The model was completed at the Geological Survey of Estonia in 1997–2002. The main characteristics of this model, its possible applications, and some modelling results are considered below.

HYDROGEOLOGICAL FRAMEWORK

The area modelled, all together 88 032 km^2, includes the territory of Estonia with the surrounding portions of the Baltic Sea and Gulf of Finland, Lake Peipsi, and border districts of Russian Federation and Latvia (Fig. 1). The latitudinal extent of the area is 420 km and meridional one – up to 252 km.

The topography of the modelled area is slightly dissected and low. The average absolute height of the area is about 50 m; only a few places in its southern part are 150–250 m above sea level. The Baltic Sea with the Gulf of Finland is the main drainage basin, Lake Peipsi with an elevation of 30 m above sea level being second largest. The climate is moderately cool and humid. Average annual precipitation is 500–750 mm. The total surface runoff from the territory is about 270 mm $year^{-1}$.

Quaternary deposits (Q) consisting predominantly of glacial till and glaciolacustrine sandy loam form the uppermost aquifer system (Perens & Vallner 1997). Their thickness ranges usually from 3 to 30 m, but occasionally reaches 100–150 m (Fig. 2). In the southern and eastern parts of the study area Quaternary deposits cover Devonian aquifer systems (D_3, D_2, D_{2-1}), which are represented chiefly by sandstone and siltstone. Between the D_2- and D_{2-1}-aquifer systems lies Narva aquitard (D_2Nr). In North and Central Estonia and on West Estonian islands the Quaternary deposits lie on the outcrop of the Silurian–Ordovician aquifer system (S–O) consisting of limestones and dolomites. The upper part of this formation is generally heavily karstified and cavernous. Deeper than 100 m from the bedrock surface the fissures are almost closed in carbonate strata which turn into the Silurian–Ordovician aquitard ($S–O_{aquitard}$) of regional extent.

Below come the Ordovician–Cambrian (O–Є) and Cambrian–Vendian (Є–V) aquifer systems consisting mostly of sandstone with siltstone interbeds. These aquifer systems are separated by the Lükati–Lontova aquitard ($Є_1Lk–Є_1Ln$). The Cambrian–Vendian aquifer system, including in the eastern part of the study area the upper, Voronka aquifer (V_2Vr), the lower, Gdov aquifer (V_2Gd), and the intermediate, Kotlin aquitard (V_2Kt), crops out along the northern coast of Estonia on the bottom of the Gulf of Finland. The Vendian strata are the most important source of drinking water for North Estonia. Cracks and pores of the up to 100 m thick upper portion of the crystalline basement (PR_{2-1}) contain a certain amount of water, which takes part in basinwide groundwater flow. The depth of

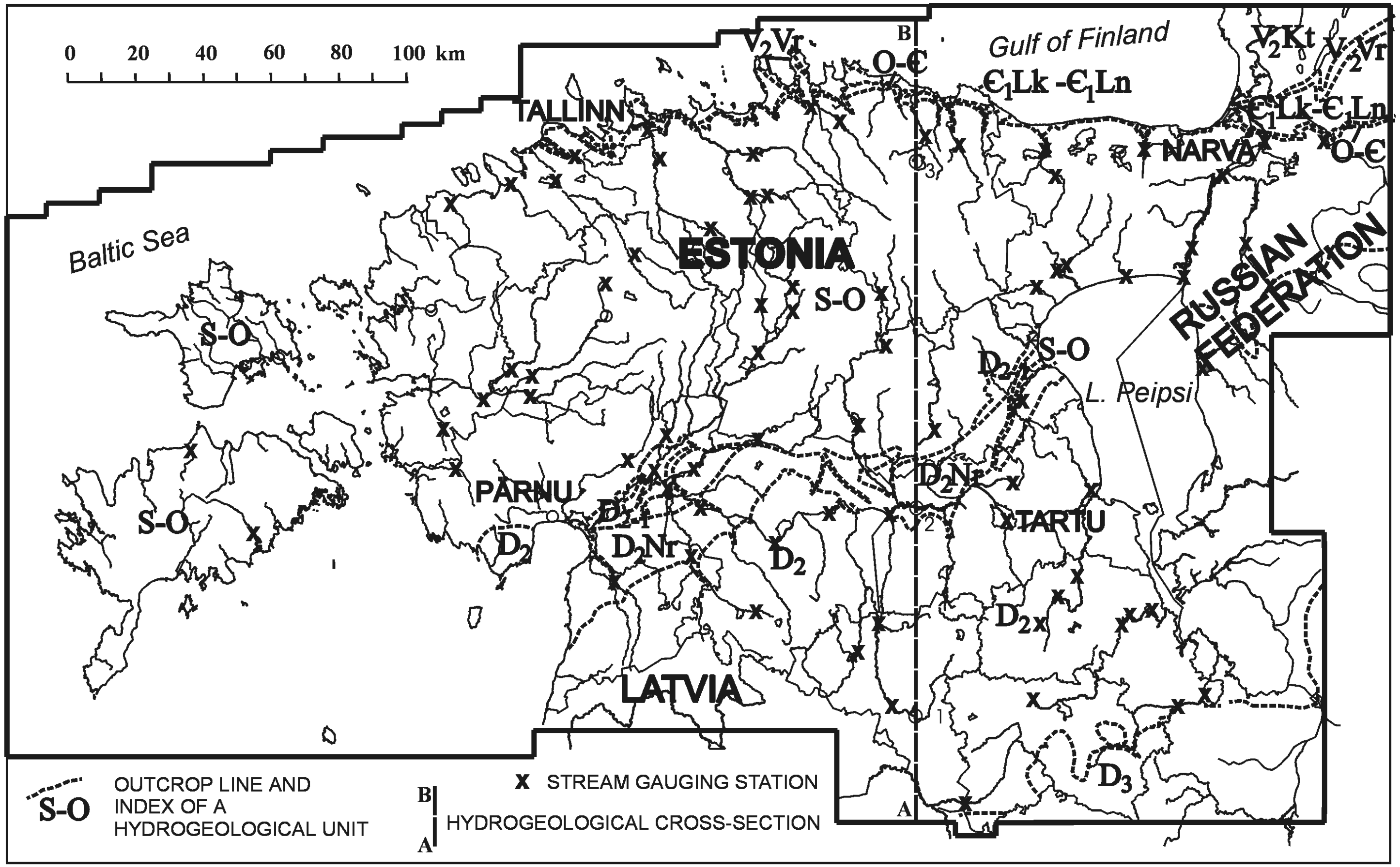

Fig. 1. Area of modelling (in bold frame). For explanation of abbreviations used in Figs. 1 and 2 see p. 180.

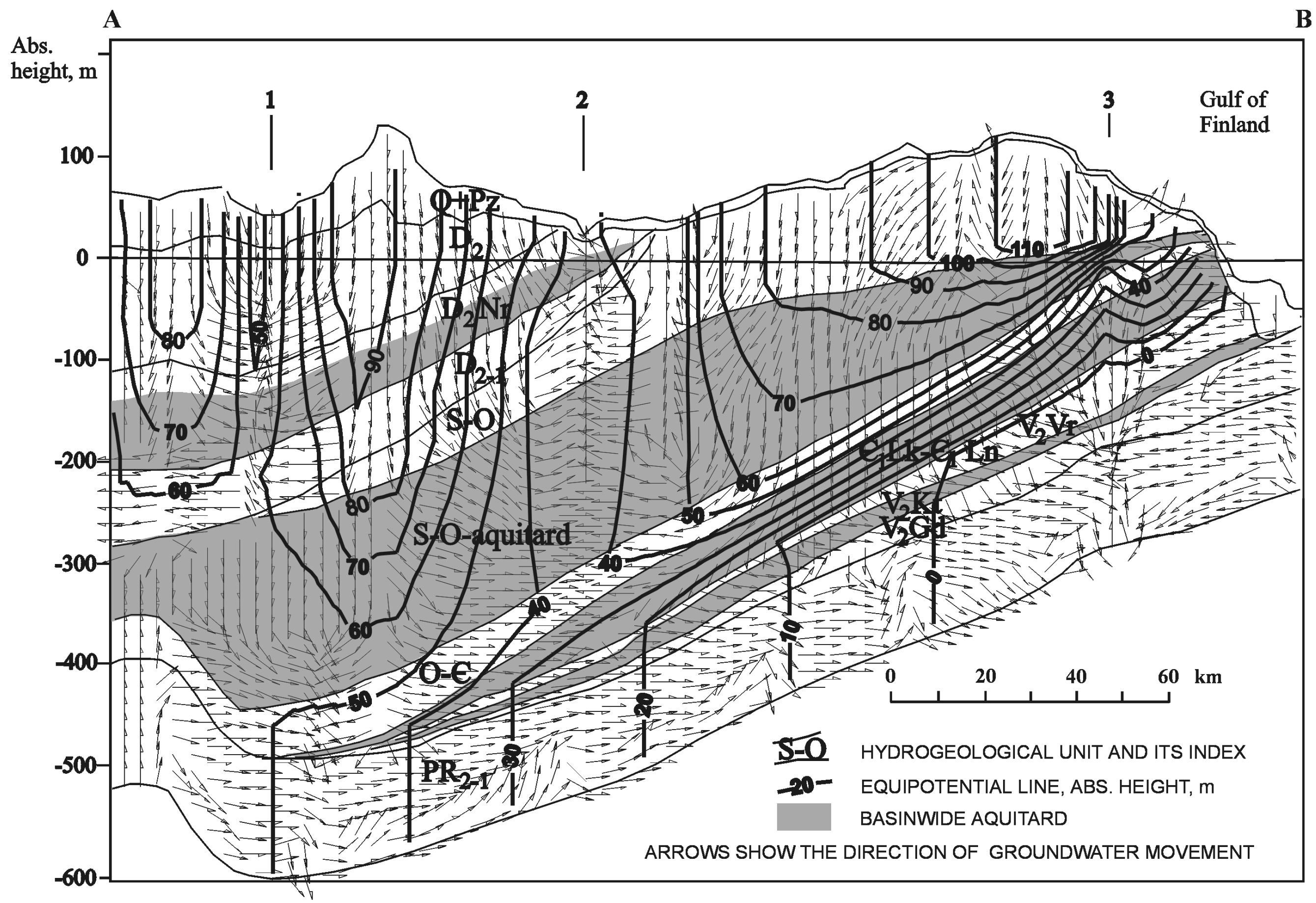

Fig. 2. Groundwater head and direction of movement in 1976.

the basement from the ground surface increases from 100–150 m on the shore of the Gulf of Finland to 500–800 m along the southern border of the study area.

The lateral hydraulic conductivity of sandstones, limestones, and dolomites is usually between 2 and 8 m day^{-1}, the storage coefficient ranges mostly from 10^{-5} to 10^{-3}. The lateral conductivity of karstified carbonate rocks can reach 50 m day^{-1} or even more. The vertical hydraulic conductivity of aquitards varies in an interval of 10^{-9}–10^{-2} m day^{-1}.

The strata described lying less than 200–300 m below sea level usually contain fresh water, but in deeper ones the TDS value increases southward up to 22 g l^{-1} (Vallner 1994). The content of fluoride exceeds the limit (1.5 mg l^{-1}) in places. Groundwater often contains too much iron and requires special treatment before using. Because of the misuse of manure and mineral fertilizers, the concentration of nitrogen has drastically increased in upper aquifers. Oil pollution occurs in many places, and especially in former Soviet military bases. Mining and processing of oil-shale carried out in the northeastern part of the study area has caused large-scale pollution of carbonate bedrock.

An intensive groundwater abstraction for water supply and mine dewatering with totals up to 600 000–800 000 m^3 day^{-1} have taken place in the study area during the past five decades (Vallner 1996, 1999; Vallner & Järvet 1998; Boldõreva & Perens 2003). As a result, basinwide head depressions have formed in several aquifers. The direction and velocity of filtration flows have changed radically, which threatens with intrusions of saline or polluted water.

THE MODEL AND ITS PARAMETER ESTIMATION

A three-dimensional flow and transport model of the area described was constructed using the code Visual MODFLOW v.2.10 (Guiguer & Franz 1996). This code is based on a finite-difference solution of the equation (McDonald & Harbaugh 1988)

$$(\partial/\partial x)(K_{xx}\partial h/\partial x) + (\partial/\partial y)(K_{yy}\partial h/\partial y) + (\partial/\partial z)(K_{zz}\partial h/\partial z) - W = S_s \partial h/\partial t .$$

Here K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes [LT^{-1}]; h is the potentiometric head [L]; W is the volumetric flux per unit volume and represents sources and/or sinks of water [T^{-1}]; S_s is the specific storage of the porous material [L^{-1}]; and t is time [T].

The model constructed involves all main aquifers, aquifer systems, and aquitards marked by hydrogeological indices in the previous section. These units are represented by 13 model-layers. The study area was covered with a rectangular grid at spacing from 1000 to 4000 m for finite-difference discretization. A database of the Geological Survey of Estonia containing characteristics of about 16 000 boreholes and water wells, managed by the Microsoft Access was used for modelling.

The top boundary of the model coincides with the ground surface or bottom of streams, lakes, and the sea. As a supposed impermeable bottom boundary of the model acts a surface lying at a depth of 100 m beneath the upper surface of the crystalline basement. The thickness of the whole water-bearing formation modelled varies from 100–150 m in north to 600–900 m along the southern border of the area (Fig. 2).

The recharge of groundwater on the top of the model was given as the net infiltration I (total groundwater recharge minus evaporation from the zone of saturation or capillary fringe). It has been calculated preliminarily from the budget equation comprising the main components of groundwater flow (Vallner 1980, 1997):

$$I = R + P + M - A \pm V \pm S,$$

where R is the groundwater discharge (base flow) to streams, P is the pumping from layers, M is the direct seepage of groundwater to the sea, A is the flux from streams into aquifers (induced recharge, mostly in the vicinity of mines), V is the subsurface exchange of groundwater between the study area and surrounding region, and S is the storage change.

The long-term groundwater discharge into streams R and flux A have been estimated on the basis of observations carried out during several decades at more than 100 hydrological gauging stations all over the area modelled (Fig. 1). Apart from the gauging stations, many irregular measurements of the low flow have been made approximately in 1000 stream cross-sections. The gained sporadic low flow data were modified to average base flow value by statistical methods using regular observations of gauging stations. A detailed map of the base flow at a scale of 1 : 200 000 for the study area was compiled by Vallner (1976). The pumping data P were obtained from state institutions checking the groundwater use. The subsurface fluxes to sea M and groundwater exchange with adjacent areas V were calculated by Darcy's formula.

To estimate the net infiltration I, the study area was divided into a number of calculation domains, which coincided mostly with catchment basins of main hydrogeological gauging stations. The I value was found by the above budget equation for every calculation domain and a corresponding map of net infiltration was completed (Vallner 1976, 1997). This map was used for the input of groundwater recharge data into the model.

Groundwater discharge to the channel network and the instrumentally checked pumping both make up about 90% of the sum of the right-hand-side in the above water budget equation. Therefore, the value of the net infiltration estimated by the budget equation is probably more authentic than that based on indirect data, such as the air temperature and atmospheric humidity, evapotranspiration, etc., which are often used for the calculation of net infiltration by empirical formulas.

The boundary conditions describing the relationship between the surface water bodies and groundwater system (Cauchy conditions) were incorporated into the model for the channel network, lakes, and sea. Thereat the streambed conductance C was calculated by the formula

$$C = R/(H - H_r),$$

where R is the groundwater discharge into the stream under consideration, H is the average value of the groundwater head beneath stream, and H_r is the mean stream stage elevation.

The values of the parameter R were got from the base flow map mentioned and the heads H were estimated on the basis of various boring data. In this way, an authentic calculation of the streambed conductance C was feasible. Determination of the streambed conductance C using the hydraulic conductivity K of the river bed material was impossible because not enough empirical data were available about this parameter. The sea and big lakes were modelled as streams. The conductance of the bed material was estimated for them as well as for real streams. Instead of the value of R the direct seepage of groundwater to the sea M was used in the last formula above. The value of M was calculated by the budget equation.

Boundary conditions of hydrogeological units along the borders of the area modelled, especially the constant heads (Dirichlet condition), were mostly given according to data of hydrogeological mappings. In some cases, where lower hydrogeological units extend to the sea, the general head (a modification of the Cauchy condition) was established along these borders. Numerous springs occurring in the study area were modelled by Visual MODFLOW drain condition (another modification of the Cauchy condition). All significant groundwater intakes with their abstraction rates were taken into account and incorporated into the model. The results of about 1000 time-drawdown and distance-drawdown pumping tests were used to characterize the hydraulic conductivity K, the specific storage S_s, and the specific yield S_y of aquifers.

CALIBRATION

The steady-state model was calibrated against two different sets of calibration targets – one set representing the measured elevation of the groundwater table and head in the study area in September 1976, and another set corresponding to measured rates of the base flow at stream gauging stations at the same time. The synchronous pumping data were also incorporated into the model for its calibration. This calibration term was fixed, because on the hydrogeological maps compiled by H. Vares and A. Viigand elevations of the groundwater table and head had been modified to September 1976 for every water-bearing unit modelled. The boreholes used for the construction of water table contours and equipotential lines on these maps served as calibration points at the modelling.

The total groundwater abstraction reaching 603 000 m^3 day^{-1} in the study area in 1976 was close to the mean abstraction during the last four decades. This made it possible to prevent eventual unfavourable impact of extreme abstractions on the results of calibration.

Calibration was carried out using the trial-and-error adjustment mostly of hydraulic conductivity and net infiltration values for achieving the optimum match between simulated parameters and calibration targets. Simulated elevations of the groundwater table and heads were rechecked against field data until the difference between computed and measured values was ≤3.5 m. The maximum difference allowed between the measured and model-calculated rates of the base flow was ±20%.

Corrections of hydrogeological parameters introduced by model calibration remained within acceptable ranges. The trial-and-error adjustment of hydrogeological parameters at the calibration gave a unique possibility of determining the vertical conductivity of aquitards (Fig. 3).

All groundwater intakes were deactivated in the calibrated steady-state model and a corresponding distribution of the heads $h(x, y, z)$ was simulated. The latter was considered as a mathematically correct description of the initial condition for a transient model of the study area. After that, pumping schedules were incorporated into groundwater intakes for transient simulations. Mean annual elevations of the groundwater table and heads estimated for 1976, 1990, and 1998 in the observation network were used as targets for transient calibration. Using the fully calibrated model, the mean annual equipotential isolines of every hydrogeological unit have been simulated for both predevelopment conditions and for 1976 (Vallner 2002).

The model calibrated is suitable for the simulation of variable three-dimensional groundwater flow and particle tracking problems. A simulation of advection, dispersion, and chemical reactions of contaminants will also be possible in the future using the MT3D code included in the Visual MODFLOW. To this end, definition of transport boundary geometry and an additional input of groundwater ingredients concentration, layers dispersivity, and chemical reaction parameters are necessary. The model data prepared by the Visual MODFLOW are also transferred in the codes Visual MODFLOW v.3.1 (Anonymous 2003) and Groundwater Modeling System (GMS) v.2.1 (Anonymous 1996).

PERSPECTIVE APPLICATIONS

The model completed is an indispensable tool for the investigation of basin-wide problems above all. It can provide a scientifically well-founded picture about large-scale hydrogeological processes in their mutual relationship. Modelling enables calculation of the three-dimensional distribution of drawdowns caused by groundwater abstraction from dissimilar layers and in different places. Flows

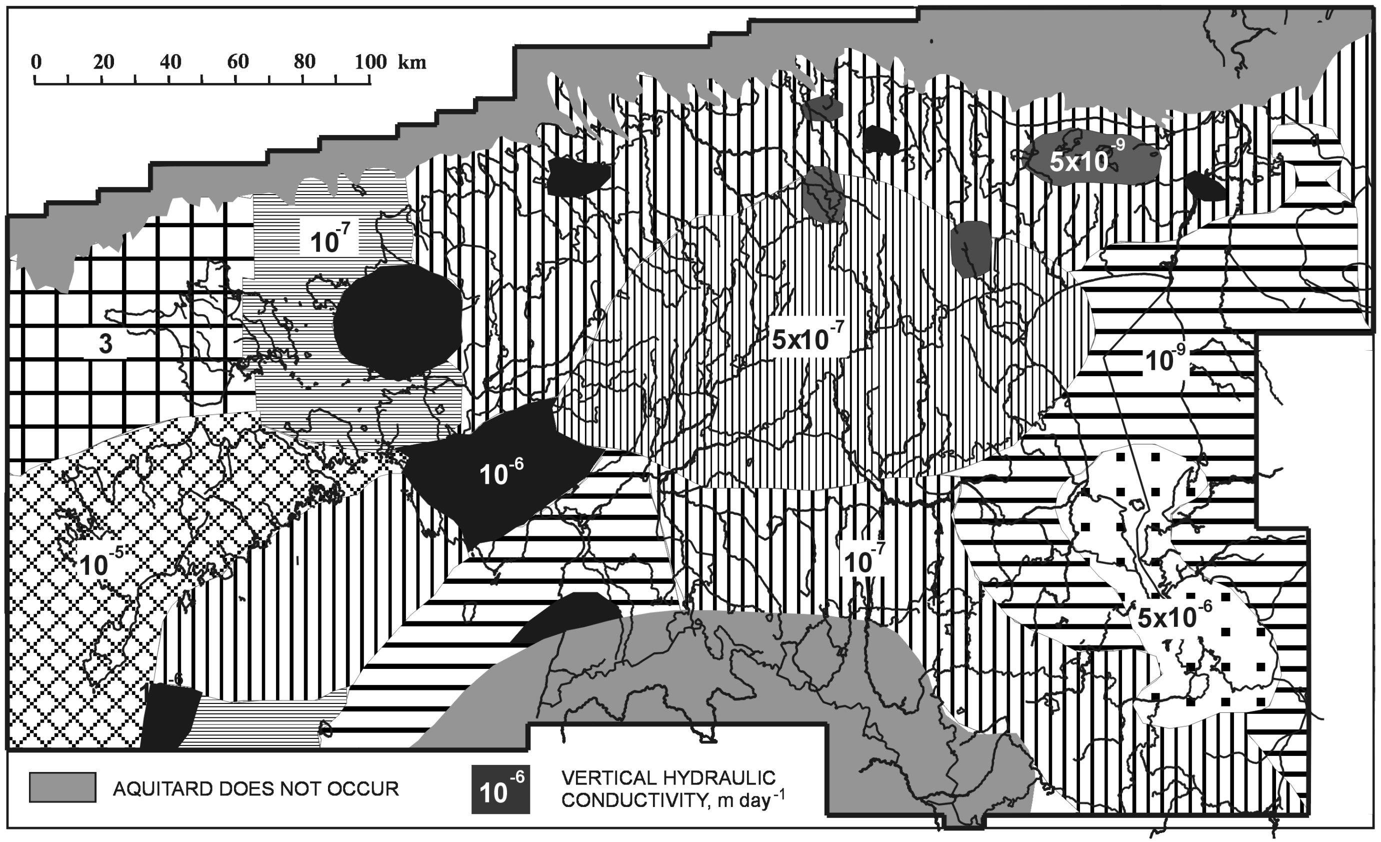

Fig. 3. Vertical hydraulic conductivity of the Lükati–Lontova aquitard estimated by calibration.

between adjacent layers, aquifers, and surface water bodies, as well as changes in the groundwater quality, can be determined both in natural and man-made conditions. So, an estimation of the influence of many groundwater intakes, mine dewatering, and pollution sources on the groundwater state is possible. It renders feasible compilation of a long-term plan of the optimum groundwater management and protection for the study area.

A principle reappraisal of the whole groundwater management policy in Estonia is indispensable because of the European Community (EC) requirements (Anonymous 2000). The long-term annual average rate of abstraction must not exceed the available groundwater resource. Alteration to groundwater flow direction must not cause saline water or other intrusion into a groundwater body. Concentration of pollutants must not exceed the EC quality standards. To meet all these very strict requirements, a holistic assessment of groundwater flow and transport conditions and their risk factors is necessary in the study area. Apparently, the model completed could serve as an effective instrument for solving these problems.

The basinwide hydrogeological model can be very useful in the investigation of many local problems, too. For that purpose, the data of the "big" model checked by calibration already should be used for a new local model. The flow lines simulated by the basinwide model should serve as the boundaries of the local model, with the Cauchy non-flow condition along them. The local model can contain fewer layers than the basinwide one, but in this case initial conditions of the local model should be calculated by basinwide modelling. All these methods facilitate completing the local model and enhance its authenticity.

On the other hand, the basinwide model can be used for a local modelling also directly. In that case, it is required to refine the model grid, and sometimes model layers have to be split into thinner ones. An input of additional data to specify the local hydrogeological situation and a new model calibration are necessary.

In spite of the applied problems described, the study area provides interesting opportunities for scientific research. For instance, the isotope composition and radiocarbon concentration indicate that the Cambrian–Vendian aquifer system has been recharged in glacial or periglacial conditions (Vaikmäe et al. 2001). However, the time and mechanism of such a recharge are still disputable, as well as the extent of the palaeogroundwater in layers. A possible recent saline sea water intrusion into the Cambrian–Vendian aquifer system has also been under discussion. All these problems can be thoroughly investigated using the model completed.

Apart from other applications, the basinwide model could be used as an effective training aid for grounding students in hydrogeology, hydrology, or water management in universities of Estonia. The model gives a comprehensive view about spatial locality, properties, and mutual relations of water-bearing layers. Students could get a needful experience in using modern effective methods of hydrogeological research.

FLOW CONDITIONS IN THE CAMBRIAN–VENDIAN AQUIFER SYSTEM

A preliminary estimation of recharge and discharge conditions of the Cambrian–Vendian aquifer system has been carried out using the model completed. It can serve as an example of possibilities and methods of basinwide hydrogeological modelling.

As mentioned above, deactivation of all groundwater intakes and mine dewatering in the study area restored predevelopment conditions. A detailed water budget (Table 1) and a map of head contours (Fig. 4), compiled as a result of the corresponding simulation, showed that the natural recharge of the Cambrian–Vendian aquifer system was 76 000 m^3 day^{-1} in predevelopment conditions. About half of this was formed by a lateral inflow coming from south and southeast and another half came from above, leaking through the overlying Lükati–Lontova aquitard. The direct seepage of groundwater in the sea was about 50% and the flow up into the overlying aquitard was 30% of the total discharge. Water moved laterally mostly northwards at a prevailing speed of 1–0.5 m $year^{-1}$ in the Cambrian–Vendian aquifer system. It means that during the last 5000 years while the model lateral boundary conditions were close to the present ones, the front of deep connate groundwater could move laterally for 5–7 km on average.

Flow conditions changed drastically in the Cambrian–Vendian aquifer system because of intensive groundwater abstraction, which reached 156 400 m^3 day^{-1} in 1976 (Table 1, Fig. 4). Extensive cones of depression formed, with centres in Tallinn and Kohtla-Järve where drawdowns were respectively 25 and 35 m. Instead of prevailing discharge of Cambrian–Vendian water in the sea, an inverse direction of the groundwater flow came into being – from the Gulf of Finland to the coastal intakes in North Estonia. The amount of saline sea water intrusion was 95 000 m^3 day^{-1} or about 1.3 times as much as the predevelopment total

Table 1. Water budget of the Cambrian–Vendian aquifer system, m^3 day^{-1}

Flow direction	Flow	Predevelopment conditions	In 1976
Inflow	Through lateral boundaries	39 100	54 200
	From the sea	0	95 000
	From the overlying strata	31 900	39 100
	From the underlying crystalline basement	5 000	7 700
	Total inflow	76 000	196 000
Outflow	Through lateral boundaries	15 200	12 400
	In the sea	36 000	3 000
	Into the overlying strata	21 900	19 800
	Into the underlying crystalline basement	2 900	4 400
	Pumping from wells	0	156 400
	Total outflow	76 000	196 000

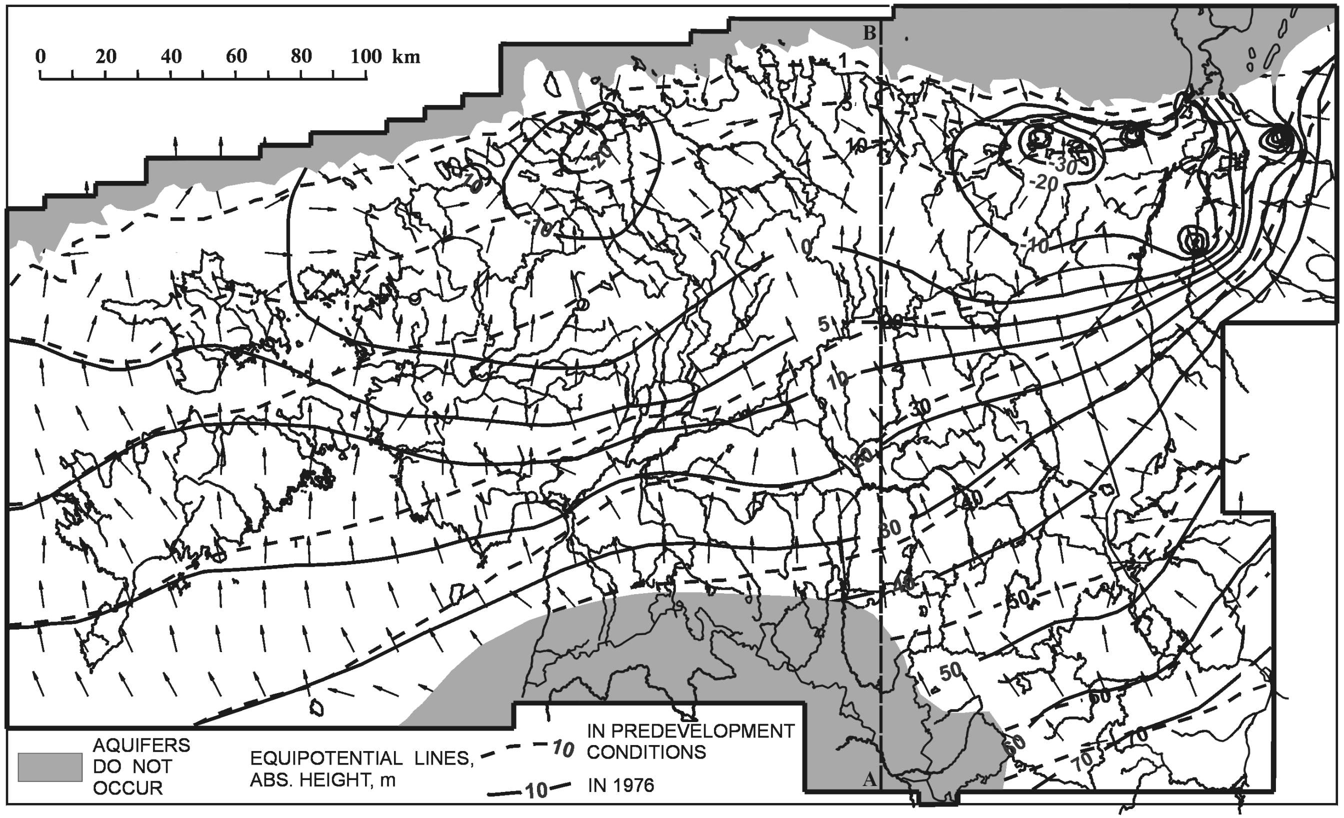

Fig. 4. Distribution of groundwater heads in the Cambrian–Vendian aquifer system. Arrows show the direction of groundwater movement in 1976.

recharge. As long as the potentiometric surface of this aquifer system is below sea level, the saline water intrusion continues and surely finally reaches the coastal intakes. The modelling showed that it would happen during the next 20 years if groundwater abstraction would continue in accordance with safe yields calculated.

In the same way the hydrodynamical state of the Cambrian–Vendian aquifer system for the glacial period could be reconstructed, but then the authenticity of results would mainly depend on the palaeohydrogeological adequacy of boundary conditions estimated by geological and palaeogeographical methods.

CONCLUSIONS

The hydrogeological model was constructed using the code Visual MODFLOW, covering the whole territory of Estonia, surrounding coastal sea, Lake Peipsi, and border districts of Russian Federation and Latvia. The 13 model layers include all main aquifers and aquitards from ground surface to the impermeable part of the crystalline basement. By the model three-dimensional distribution of groundwater heads, flow directions, velocities, and rates as well as transport characteristics can be simulated. Detailed basinwide or local ground-water budgets can be completed. The model should be considered as a mighty and feasible tool for advanced hydrogeological investigations.

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Eesti hüdrogeoloogiline mudel ja selle rakendused

Leo Vallner

Hüdrogeoloogiline digitaalmudel haarab Eesti maismaa ja territoriaalmere, terve Peipsi-Pihkva järve ja piiriäärsed Venemaa ning Läti alad, kokku 88 032 km^2. Mudeli 13 kihti hõlmavad kogu põhjaveekihtkonna, sh kristalse aluskorra ülemise 100 m paksuse vöö. Modelleerimiseks kasutati programmipaketti MODFLOW koos pre- ja postprotsessoriga Visual MODFLOW. Mudeli abil saab arvutada põhjaveekihtkonna mis tahes punkti jaoks mis tahes ajamomendiks põhjavee hüdraulilise rõhu, filtratsioonivoolu suuna, kiiruse ja hulga, samuti põhjavee ingredientide migratsioonikarakteristikud. Mudeliga võib koostada üksikasjalikke regionaalseid ja lokaalseid vee- ning ainebilansse.