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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 Unfortunately, the results of that work are out-of-date for Estonia at present.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

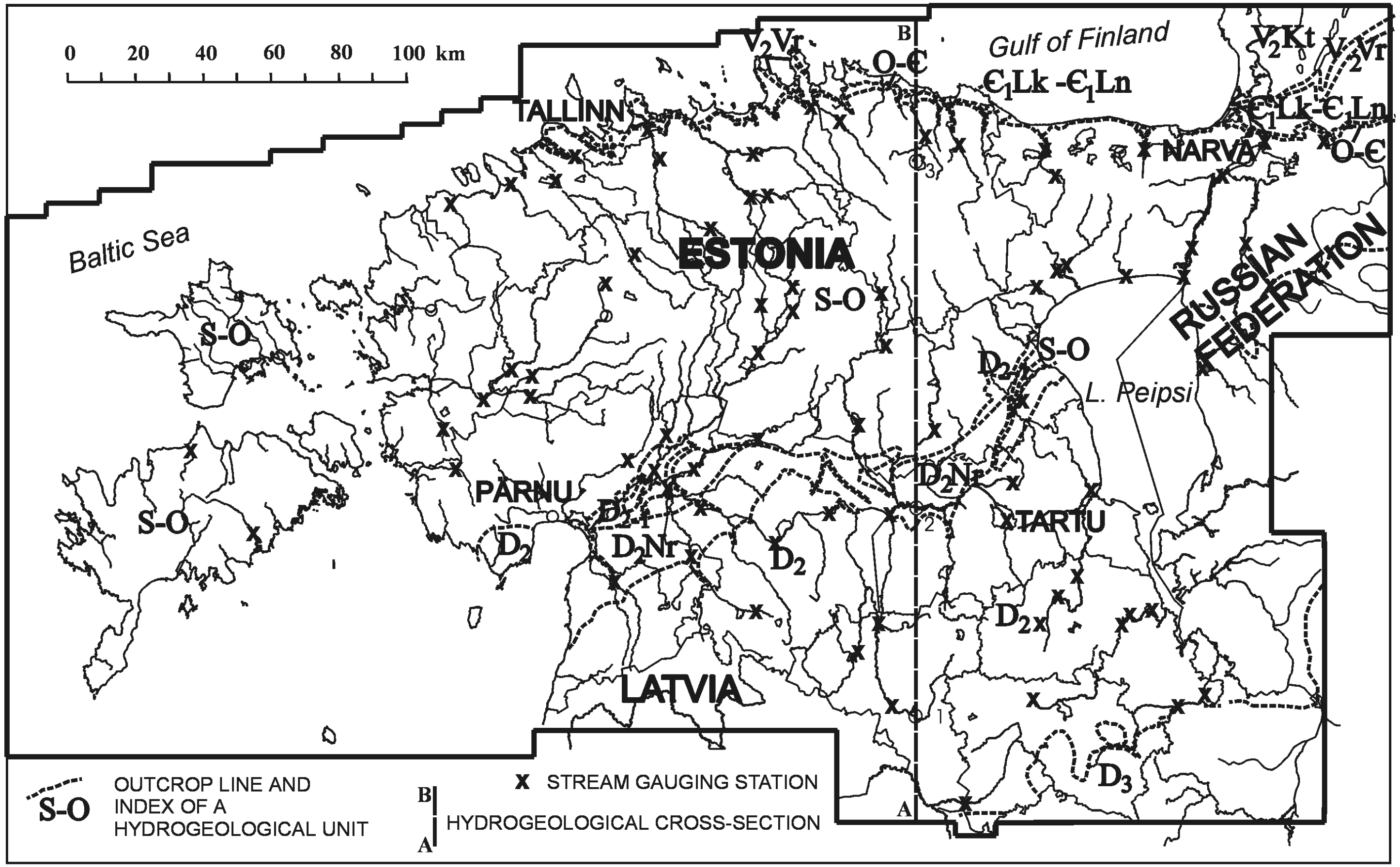

Fig. 1. Area of modelling (in bold frame). For explanation of abbreviations used in Figs. 1 and 2 see p. 180.

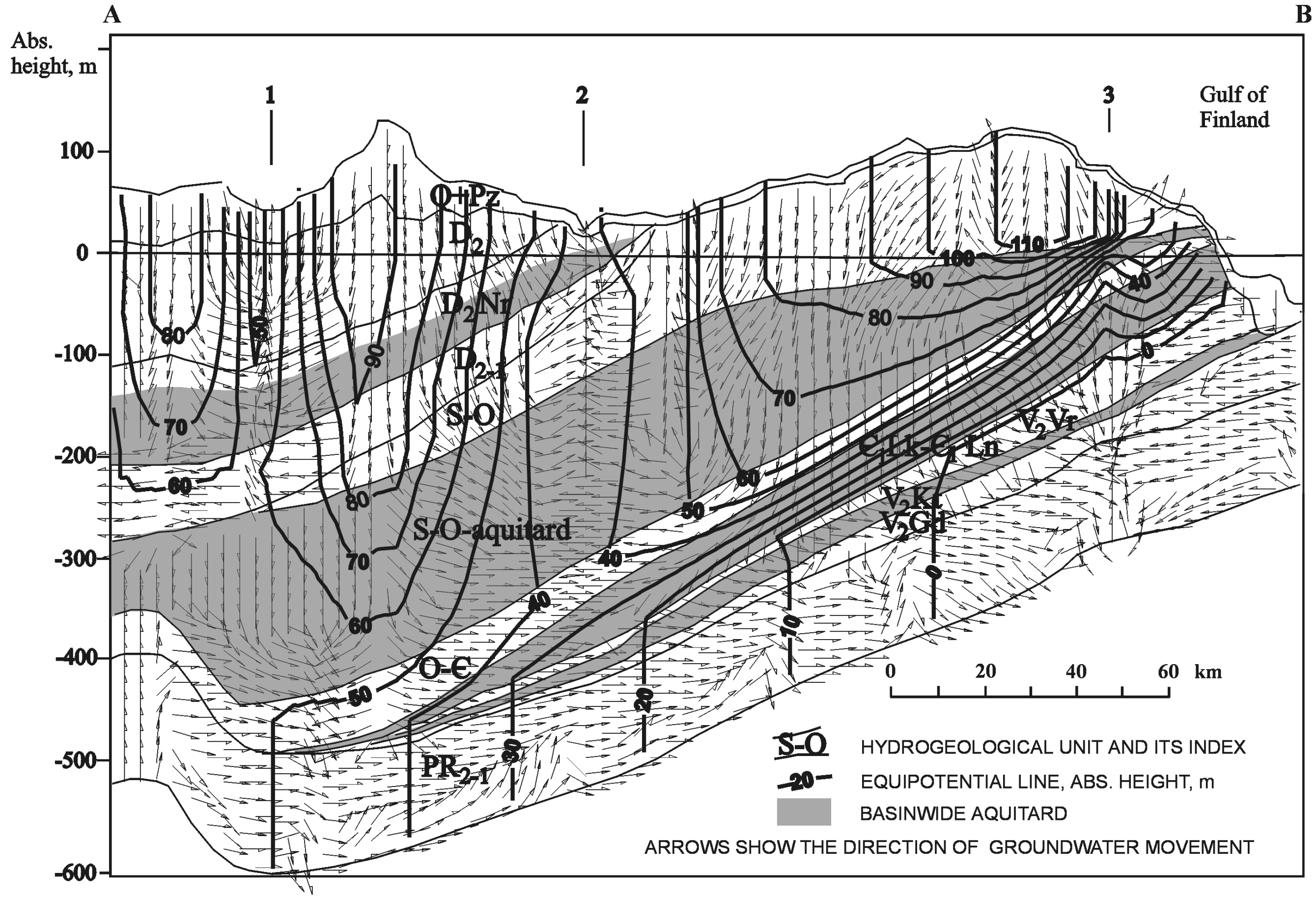

Fig. 2. Groundwater head and direction of movement in 1976.

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

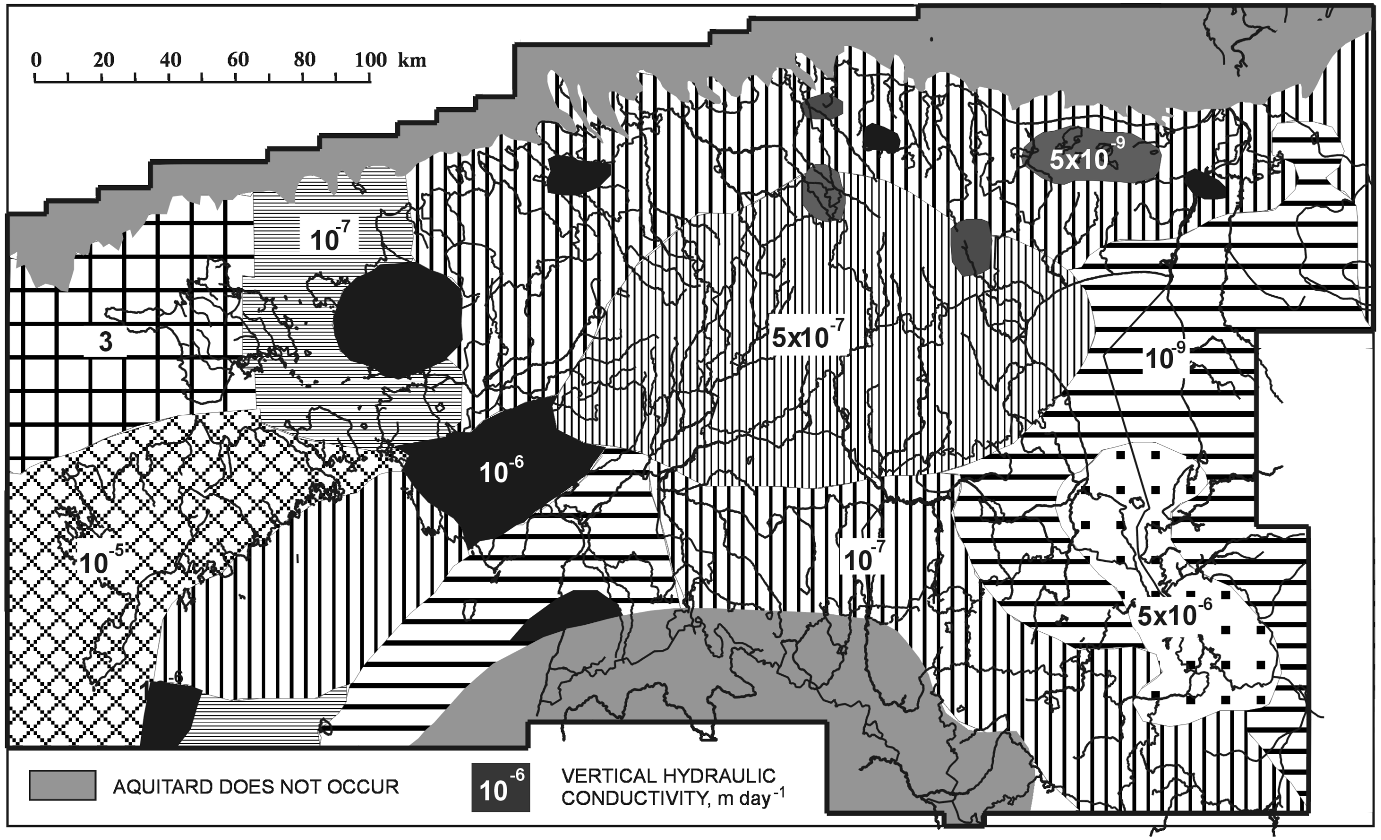

Fig. 3. Vertical hydraulic conductivity of the Lükati–Lontova aquitard estimated by calibration.

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

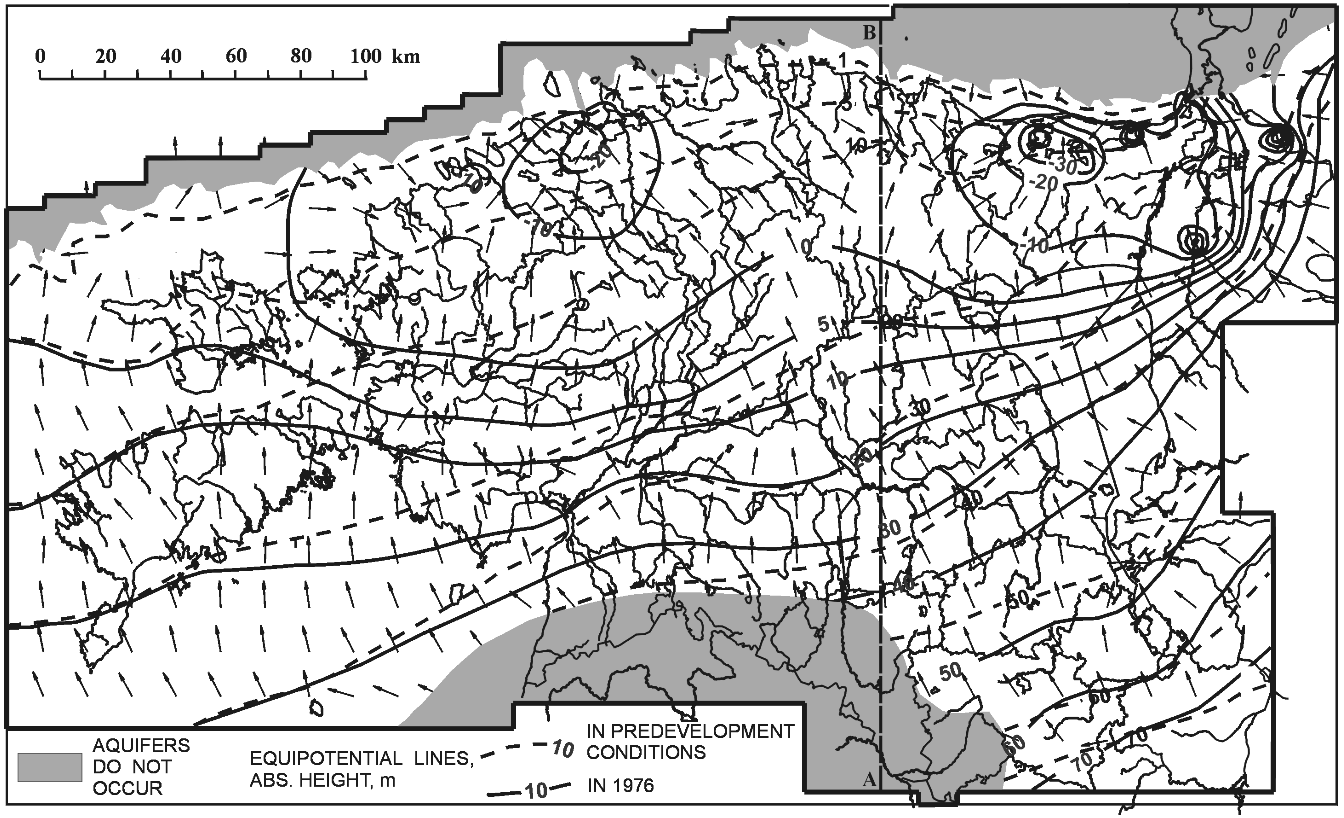

Fig. 4. Distribution of groundwater heads in the Cambrian–Vendian aquifer system. Arrows show the direction of groundwater movement in 1976.

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 groundwater 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.