Available groundwater resources in fresh/salt water transition zones of Lithuania

Algirdas Klimas, Marius Gregorauskas

Abstract: European Union Directives 2000/60/EC and 2006/118/EC oblige member states to assess groundwater quantitative and chemical status on the territory of their countries. Groundwater resources in Lithuania are much larger than present or future drinking water demands. Therefore all drinking water supply in the country is and will be based exceptionally on groundwater.

The favourable hydrogeological and economic situation assures relatively good groundwater chemical status, only locally and slightly affected by pollution. Considerably more serious is the problem of salt water encroachment into fresh groundwater bodies. Some wellfields, located in fresh/salt water transition zones demonstrate significant and sustained upward trends of chlorides and sulphates concentrations, sometimes exceeding drinking water standards. Simulation results show that even more serious changes of groundwater chemical status of this kind are possible in the future. Therefore we suggest that those changes are taken into account when assessing available groundwater resources in fresh/salt water transition zones.

Keywords: Lithuania, groundwater, available resource, groundwater quality

Algirdas KLIMAS ✉
Vilnius University & Vilnius Hydrogeology Ltd
J. Basanaviciaus 37-1
03109 Vilnius, Lithuania
Tel: +370 5 265 01 56
vh@zmail.lt

Marius GREGORAUSKAS
Vilnius Hydrogeology Ltd
J. Basanaviciaus 37-1
03109 Vilnius, Lithuania
Tel: +370 5 265 01 68
vh@zmail.lt

Received: 5 october 2010 / Accepted: 22 november 2010
Published online: 31 december 2010

Riassunto: *Le direttive EU 2000/60/EC e 2006/118/EC obbligano gli Stati Membri a accertare la quantità delle acque sotterranee e il loro chimismo nell'ambito del loro territorio.*

Tali risorse in Lituania non sono maggiori delle domanda presente e futura di acqua potabile. Tuttavia la disponibilità di acqua da bere nel nostro paese è e sarà basata essenzialmente sulle acque sotterranee.

Condizioni favorevoli da un punto di vista idrogeologico e economico garantiscono uno stato chimico relativamente buono delle acque sotterranee, solo poco e localmente inquinate.

Considerevolmente più serio è il problema dell' acqua salata che si intrude nei corpi di acqua dolce.

Alcuni campi pozzi, ubicati in zone di transizione tra acque dolci e acque salate mostrano tendenze significative e durature all'aumento delle concentrazioni di clorati e solfati, talvolta che superano i limiti per ritenere un'acqua potabile. I risultati di simulazioni mostrano, che perfino i più seri cambiamenti dello stato chimico delle acque sotterranee sono possibili nel futuro.

Tuttavia noi suggeriamo di considerare questi cambiamenti quando viene valutata la disponibilità delle risorse delle acque sotterranee nelle zone di transizione acqua dolce/acqua salata.

In Litauania infatti tutte le acque potabili sono fornite dagli acqueri sotterranei – non vengono usate acque di superficie per usi potabili (Klimas, 2003). La ragione di ciò e dovuta alle abbondanti precipitazioni (ca. 700 mm in media) e alle favorevoli condizioni geologiche/idrogeologiche, noi abbiamo considerevoli quantitativi di acque sotterranee potabili di buona qualità.

In Lituania sono stati trovati più di 20 acquiferi sotterranei di acque potabili, che fanno parte del Bacino Artesiano Baltico, che sono localizzati in rocce che vanno dal Cambriano nella Litania dell'est fino alle sabbie Oloceniche nei depositi di spiaggia sul Mar Baltico. Solo gli acquiferi poco profondi di questo bacino sono vulnerabili all'inquinamento. Quelli a maggiore profondità generalmente hanno acqua potabile di buona qualità.

Tuttavia acquiferi con acqua dolce, potabile costituiscono la parte superiore idrodinamica del bacino artesiano, lo spessore del quale varai da alcuni metri a centinaia di metri. A maggiore profondità si trovano acquiferi mineralizzati non idonei al consumo. Diversi acquiferi contengono acqua potabile solo in aree di ricarica, mentre in quelle di deflusso l'acqua è spesso salina. Lo sfruttamento della falda induce intrusione di acqua salata negli acquiferi di acqua dolce. Tuttavia le risorse di acque sotterranee potabili nelle zone di transizione acqua dolce /acqua salata sono limitate e dovrebbero essere correttamente valutate.

DOI 10.4409/Am-019-10-0020

Introduction

In Lithuania, all potable water is supplied by aquifers – no surface water is used for drinking (Klimas, 2003). The reason is that, due to relatively abundant precipitation (ca. 700 mm in average) and favourable geological/hydrogeological conditions, we have considerable fresh groundwater resources of good quality. More than 20 fresh groundwater aquifers, belonging to Baltic Artesian Basin (Fig.1), are found in Lithuania occurring in rocks ranging from Cambrian age in East Lithuania to water table aquifers in sandy Holocene deposits on the Baltic Sea shore. Only shallow, uppermost aquifers of this basin are vulnerable to pollution (Juodkazis et al., 2003). Deeper ones usually contains fresh water of good quality.

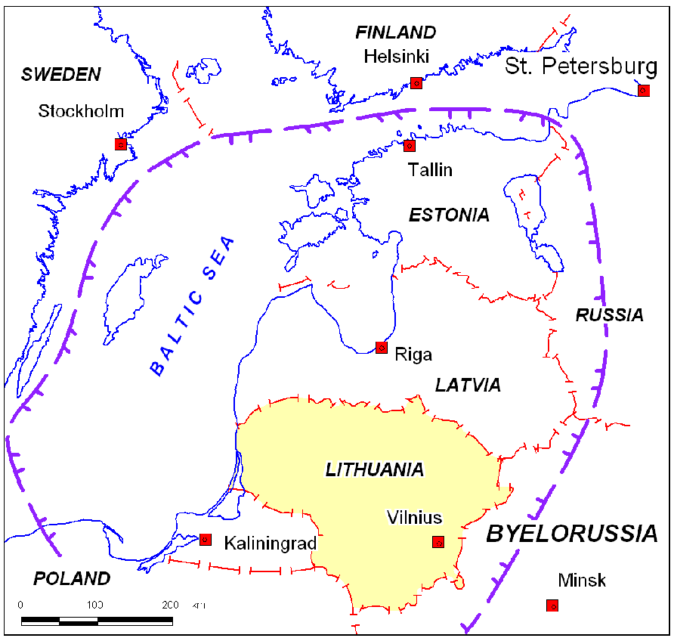

Fig. 1: *Location map (area of Baltic Artesian Basin is contoured)*

Nevertheless, fresh, drinking quality groundwater makes up only the upper hydrodynamic zone of the artesian basin, the depth of which ranges from several metres to several hundred metres. Deeper lies mineralised groundwater, unfit for consumption. Many aquifers contain potable groundwater only in recharge areas, while in discharge areas this water is often saline. Groundwater extraction activates salt water intrusion into fresh water zones. Therefore potable groundwater resources in fresh/salt water transition zones are limited and should be correctly assessed.

Groundwater Bodies at Risk

The groundwater resources of Lithuania (total area 65,300 km^2) have been well investigated (Juodkazis, 1980, 1988; Klimas, 2006): long-term annual average rate of groundwater flow (natural resources) is estimated to be 150,5 m^3/s; regional (exploitable) drinking groundwater resources at 37,6 m^3/s, and those surveyed in detail and prepared/used for extraction at 23,7 m^3/s. Drinking water supply, based on those resources, was 11,6 m^3/s in 1990 and 4,6 m^3/s in 2009.

Lithuania has been a member of the EU since 2004 and is obliged to enforce EU directives related to groundwater resources (Directive 2000/60/EC and Directive 2006/118/EC). Those Directives include some specific concepts, which should be considered when applying European groundwater policy, e.g., 'body of groundwater', 'available groundwater resource', 'groundwater status', 'threshold values', 'good and poor groundwater status', etc.

The cited Directives declare, that 'body of groundwater' means a distinct volume of groundwater within an aquifer or aquifers. Most hydrogeologists are sure that this definition is close to our traditional concept of groundwater systems (Freeze and Cherry, 1979). According to this concept, in the territory of Lithuania there are four large, separate and independent groundwater systems, which store fresh groundwater resources, assessed and named as 'regional exploitable' (Tab. 1).

We are sure that our concept of 'regional exploitable groundwater resource' is also very close to the Directive concept of 'available groundwater resource' (Gregorauskas et al., 2003). The main difference arises from the European concept of 'good/poor groundwater quality status': the Directives declare, that this status should be assessed by measuring concentrations of the most common and dangerous pollutants, nitrates and pesticides, which should not exceed threshold values (TV) of 50 mg/l for NO_3 and 0,1 µg/l for active substances in pesticides (Directive 2000/60/EC and Directive 2006/118/EC). Furthermore the groundwater chemical status provisions do not apply to high, naturally-occurring levels of substances or ions, which are not covered by the definition of pollution or are not regarded as intrusions (Directive 2006/118/EC, preamble-10). Nevertheless, Article 3 and Annex II of this last Directive recommend establishing 'threshold values' for some additional substances or ions, which may occur both naturally and/or as a result of human activities and includes on the list of such indicators, *inter alia*, chlorides, Cl and sulphates, SO_4.

Due to the favourable geological-hydrogeological and economic situation in Lithuania there are no large fresh groundwater bodies in the territory, whose chemical status can be defined as 'poor' due to the pollution (Klimas, 2006). But there are some places in Lithuania where groundwater resources of good, potable quality are complete-

Tab. 1: *Regional exploitable groundwater resources of Lithuania (Gregorauskas et al., 2008).*

Groundwater system/body	Regional exploitable resources		% of total
	thou. m^3/d	m^3/s	
Quaternary (Q)	1284	23,8	63,4
Cretaceous (K_2+K_1)	284	3,3	8,7
Upper Palaeozoic (P_2 +D_3zg+ D_3st)	288	3,3	8,7
Middle Palaeozoic (D_3sv+D_2up)	624	7,2	19,2
Total groundwater resources	3249	37,6	100

ly absent or limited due to the actual or potential intrusion of 'salt' water of Na-Cl or $Ca\text{-}SO_4$ composition, characterised by relatively high concentrations of Cl or SO_4, which are close to or even exceed MAC for drinking water (250 mg/l for both).

Besides, here and further in this article 'salt water' means water characterized by concentrations of Cl or SO_4, >250 mg/l. Those concentrations in 'fresh water' should be <250 mg/l; 'salt' groundwater chemical status is considered as 'poor'and *vice versa*, 'fresh' means 'good' chemical status.

It was decided that groundwater bodies, where concentrations of Cl or SO_4 reaches or exceeds 250 mg/l, were should be declared 'at risk' (Fig. 2).

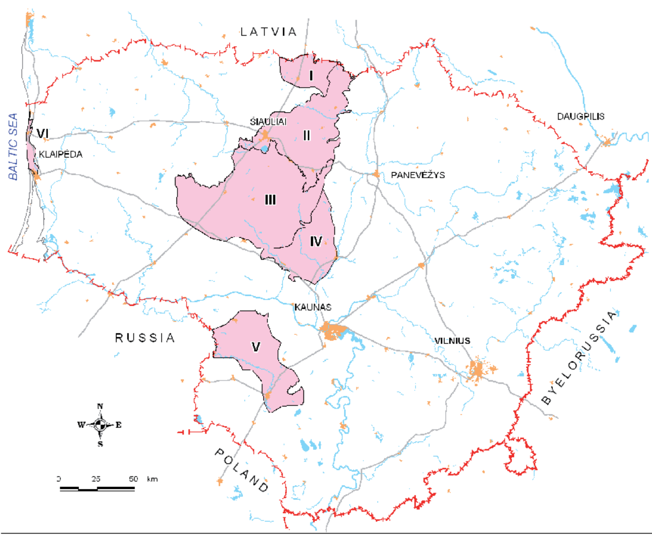

Fig. 2: *Location Groundwater bodies at risk (I–VI), where salt water intrusions are observed or possible (Satkunas ed., 2010)*

Figure 2 shows those bodies where groundwater quality deterioration due to salt water intrusion from pumped or adjacent aquifers (bodies I–V) or even from the Baltic Sea (North part of the body VI) is observed or considered possible (Gregorauskas et al., 1986).

As will be shown later, fresh/salt groundwater interfaces divide those bodies into three sectors: 1 – the salt water zone, where Cl or SO_4 concentrations are >250 mg/l. 2 – the fresh water zone, where Cl or SO_4 concentrations are and will always be <250 mg/l. 3 – the intermediate fresh/salt water transition zone (TV), where Cl or SO_4 concentrations are <250 mg/l, but due to groundwater extraction those concentrations can hazardously increase.

Figure 3 shows some of those transition zones, as well as those wellfields located near fresh/salt groundwater interfaces, which first and foremost are 'at risk'.

Groundwater bodies 'at risk', depicted in Figures 2 and 3 belong to various groundwater systems: Nos. I–IV are related to Upper and Middle Devonian formation (D_3,st, D_3sv+D_2up), No. V to Cretaceous formation (K_2+K_1), and No. VI to Upper Permian (P_2) aquifer.

Principles of fresh/salt groundwater transition zones delineation

Salt water intrusion, both vertical and horizontal, occurs in many aquifers in Lithuania (Juodkazis and Klimas, 1991; Klimas and Gregorauskas, 2002). Salt (brackish) water can encroach from below,

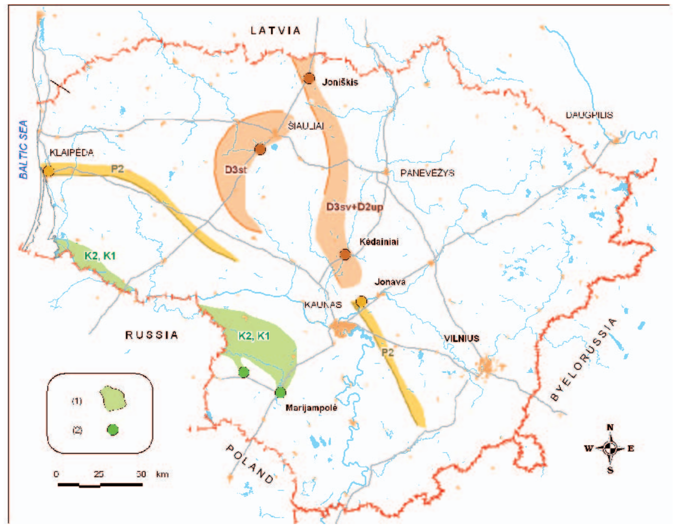

Fig. 3: *Fresh/salt groundwater transition zones (1) in various aquifers and wellfields (2), operating in those zones (Klimas, 2004).*

from the lower part of a pumped aquiferous system or from a deeper aquifer nearby. In northern Lithuania, salt water from gypsiferous Devonian rocks may leak downwards into fresh water aquifers. In extremely complex cases such water can enter pumped aquifers from all three directions: from below, above and laterally (Fig. 4).

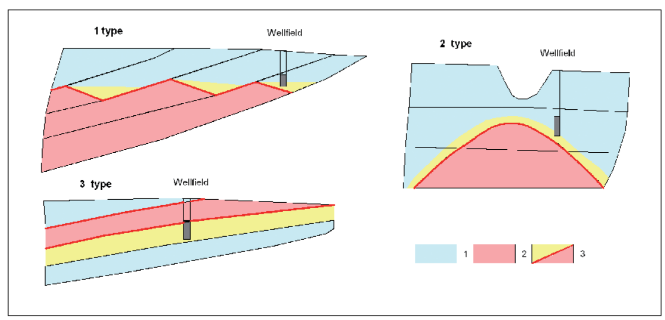

Fig. 4: *Types of fresh/salt groundwater transition zones:*
1 – fresh groundwater; 2 – salt groundwater; 3 – fresh/salt groundwater interface (red line) and transition zones (yellow).

Usually a fresh/salt groundwater interface is not sharp and the width of fresh/salt groundwater TZ varies from some metres up to tens of metres vertically, but laterally its extent, as will be seen, can reach some hundreds of metres or even several kilometres.

The main indicators, used for fresh/salt groundwater TZ delineation, are concentrations of sulphates and chlorides – most typical ions, determining groundwater salinity. As mentioned above, the accepted 'threshold value' for Cl and SO_4 is 250 mg/l.

Therefore an isocone 250 mg/l is an outer limit, the border of the fresh water zone or fresh/salt interface line. The other, inner border of this zone is delineated according to Directive requirements, that the significant and sustained upward trends of selected indicators should be stopped and reverted.

Directives also recommend defining a starting point for trend reversal as a percentage of the TV, which should not exceed 75%. For selected indicators (Cl and SO_4) it gives a concentration of 195 mg/l for each. Two examples of fresh/salt groundwater TZ are given in Figure 5.

DOI 10.4409/Am-019-10-0020

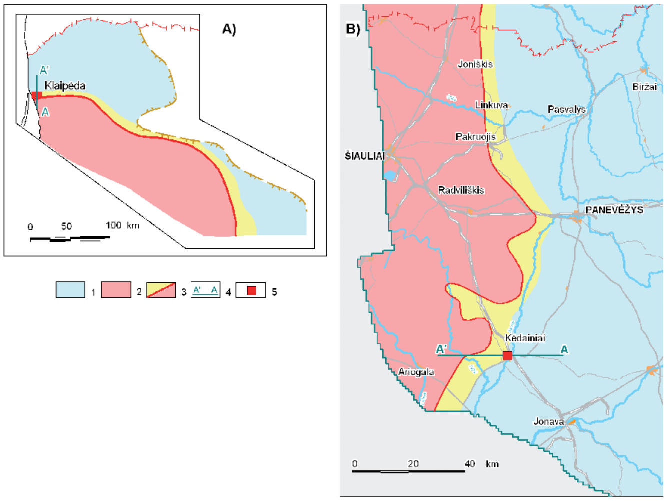

Fig. 5: *Fresh/salt groundwater TZ in Upper Permian (P_2) aquifer (A) and in Upper–Middle Devonian (D_3sv+D_2up) aquiferous system (B). 1 – fresh groundwater. 2 – salt groundwater. 3 – fresh/salt groundwater interface. 4 – section lines. 5 – wellfields.*

Operation of wellfields in fresh/salt groundwater transition zones

Groundwater extraction in fresh/salt water transition zones (TZ) is always risky because it can disturb the natural equilibrium existing in not-pumped aquifers and groundwater systems. Especially risky is groundwater extraction in TZ of the 2nd and 3rd types (see Fig. 4), where fresh groundwater lies immediately on salt water or underlies salt water. When the fresh water layer is thin, pumped water quality can deteriorate in double-quick time. Many small wellfields, located on the territory of GWB 'at risk ' are exploited in this way (No. 5(V), see Figs. 2, 3). Some wellfields, located on the territory of GWB 'at risk' Nos. 1(I), 2(II) meet a problem of salt water leakage from overlying gypsiferous strata (3rd type of TZ, see Fig. 4). Less problematic is groundwater extraction from aquifers with 1st type TZ (see Fig. 4), where fresh groundwater is gradually substituted by salt water, especially if those wellfields are fairly distant from the fresh/salt water interface. Nevertheless, the following example shows that long-term and fair-sized extraction can provoke groundwater quality deterioration even in such a case.

In west Lithuania, in the port of Klaipeda the first groundwater extraction wells were drilled at the end of 19th century (Bieske, 1929). Those 250 metres deep wells opened fairly aquiferous, fissured Upper Permian (P_2) and Upper Devonian (D_3zg) limestones and dolomites, containing groundwater of good quality, but some new wells, especially deeper ones, drilled later on in southward direction, provided groundwater of increased salinity (Fig. 6).

Increased drinking water demand at Klaipeda seaport and the pumping rate of two groups of production wells, named wellfields Nos. 1 and 2, brought serious groundwater quality changes, determined by slow, but permanent, increasing presence of chlorides and sulphates concentrations (Fig. 7).

This trend is especially evident in the wells of wellfield No. 2, located near the fresh/salt groundwater interface (see Fig. 6). From Fig. 7 it can also be seen that during the period 1980–1990 Cl, SO_4 concentrations in some wells were the highest and exceeded the TV, i.e., 250 mg/l. Besides, the decade 1980–1990 was the period of highest extraction of drinking water from the production wells of wellfields

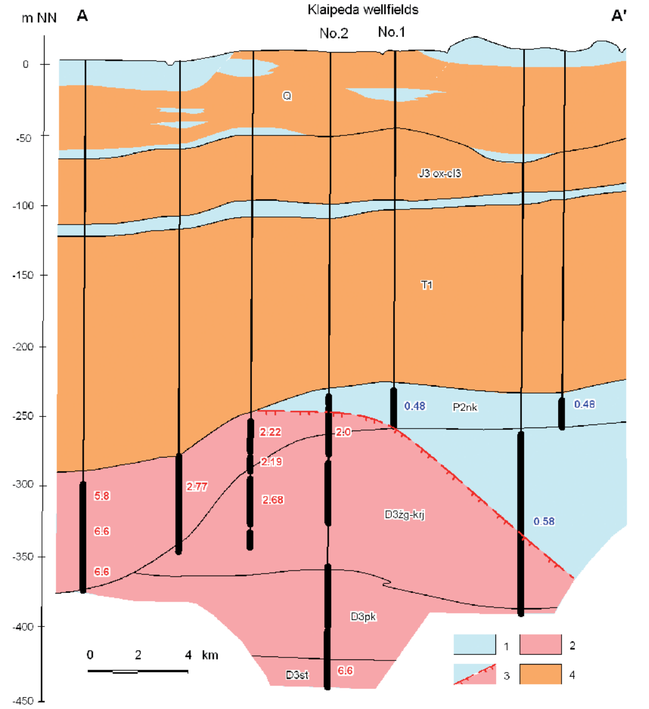

Fig. 6: *Cross section through Klaipeda wellfields Nos. 1 & 2. 1 – fresh groundwater. 2 – salt groundwater. 3 – fresh/salt groundwater interface (black and red numbers – total dissolved solids, TDS in g/l). 4 – confining beds.*

Nos. 1 and 2, which ammounted to 60 thou. m^3/d (0,7 m^3/s).

Salt water intrusion into the Klaipeda wellfields has been well studied for many years (Klimas, 1979, 1991, 1994, 2001, 2006; Juodkazis and Klimas, 1991; Juodkazis, 1994). Available data from these studies show, that isocone 250 mg/l of sulphates and chlorides ('threshold value') moved toward the wellfields at an annual rate of 60–70 m per year, but this rate slowed after the year 1990 due to the significant decrease of groundwater extraction. Anyway, in 2009 Cl–250 mg/l isocone was fixed in the SW corner of wellfield No. 2 and SO_4–250 mg/l concentration occupied a major part of this territory (Fig. 8).

From this figure we can also see that the predicted position of 250 mg/l isocone in 2059–2066 will be inside wellfield No. 1. Decreased drinking water demand enabled municipality to close wellfield No. 2. Groundwater simulation results show, that safe yield of wellfield No. 1 should not overstep 30 thou. m^3/d or 0,5 m^3/s (Klimas, 2006).

The next example is from central Lithuania, where Kedainiai city is supplied from the wellfield located in a fairly wide fresh/salt groundwater 'transition zone' (see Figs. 3, 5). The pumped D_3sv+D_2up aquifer (aquifer system) occurs at a depth of about 100 m, and is 200 m thick (Fig. 9).

From Figure 9 we can see that in the Kedainiai area only the upper part of this thick groundwater system contains fresh water, because the central Lithuanian lowland is regional groundwater discharge territory, and this discharge of salt, NaCl-type groundwater is especially active in the valley of the river Nevezis, complicated by tectonic fractures (Klimas, 1974, 2006). Dipping westward from Kedainiai D_3sv+D_2up aquifer system occurs a groundwater low intensity circulation zone, where fresh water is completely absent. Moreover, this thick aquifer system in Kedainiai area is overlaid by fissured, gypsiferous dolomites, where groundwater circulates with increased concentrations of sulphates.

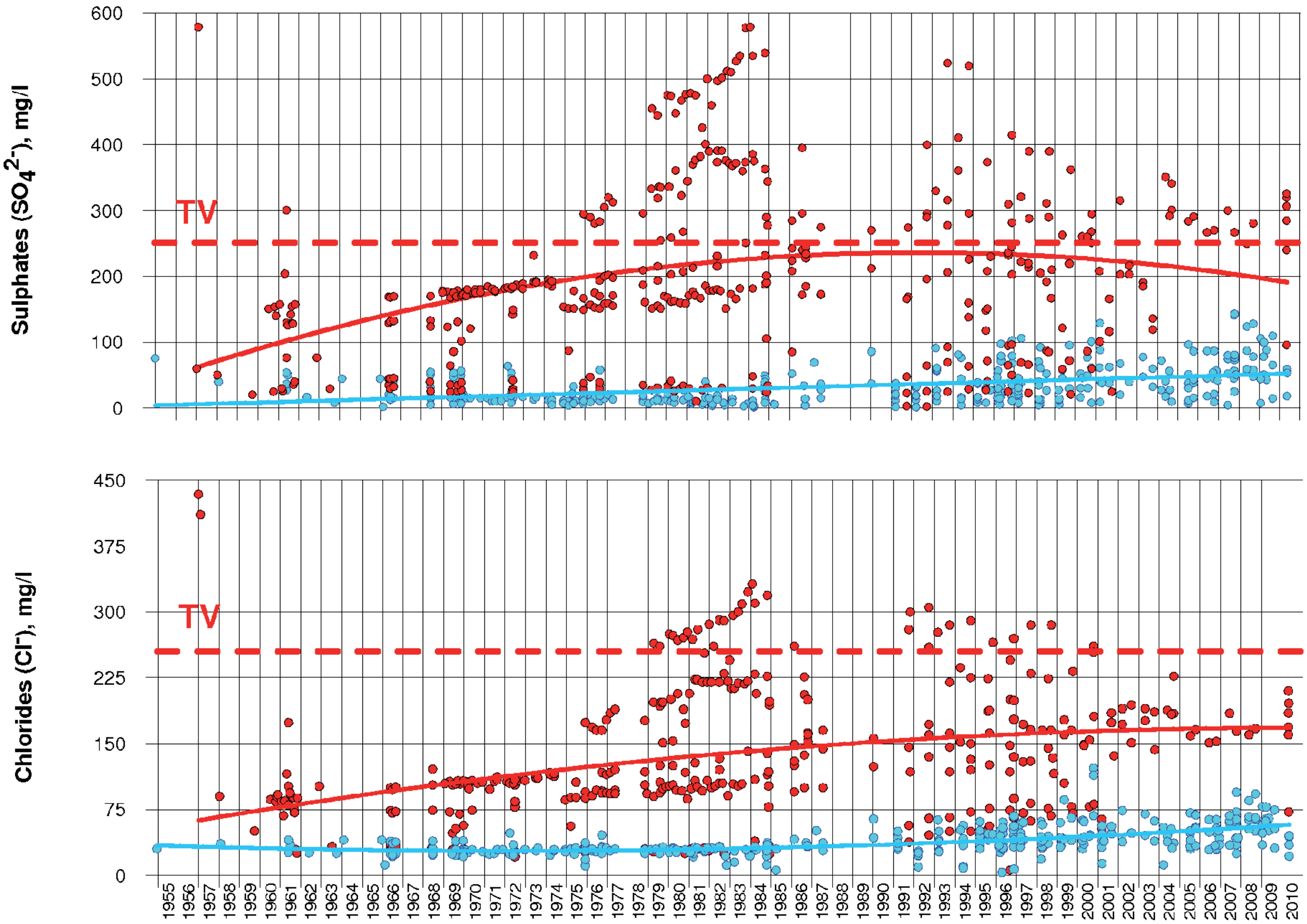

Fig. 7: *Trends in chlorides and sulphates concentrations at Klaipeda wellfields No. 1 (1 – blue dots) and No. 2 (2 – red dots), 3 – TV, 'threshold value'.*

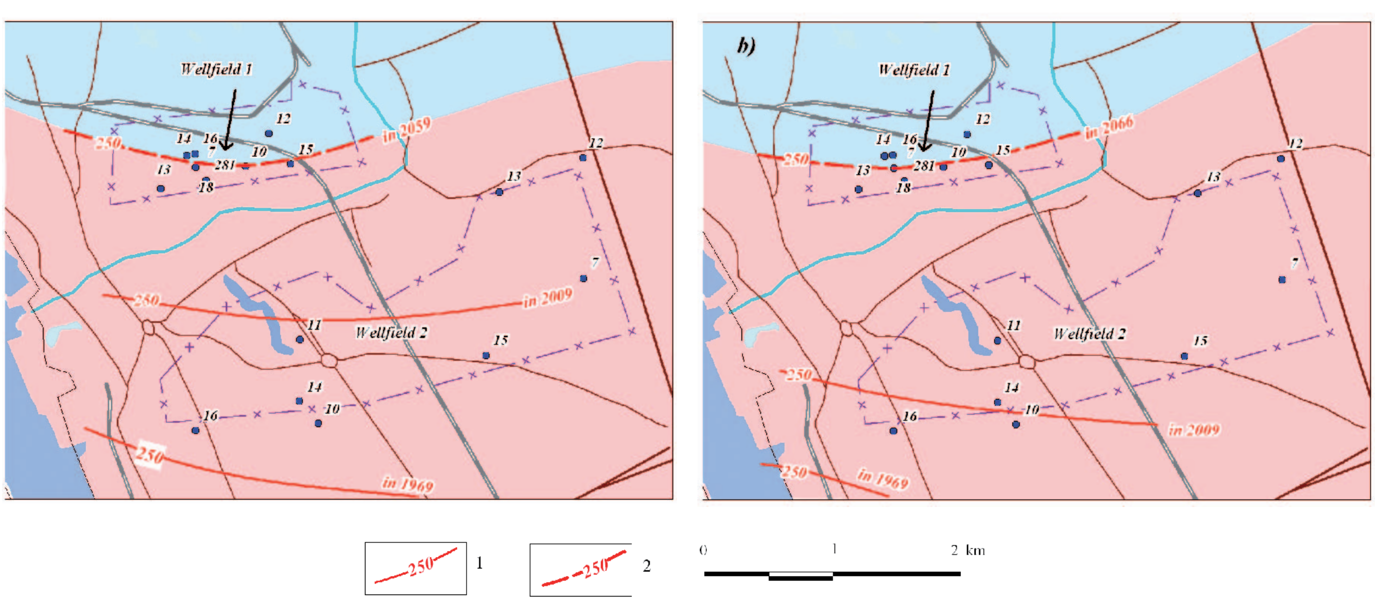

Fig. 8: *Klaipeda wellfields Nos. 1 and 2 – location of isocones 250 mg/l of sulphates (a) and chlorides (b) in different years, 1 – actual. 2 – predicted.*

DOI 10.4409/Am-019-10-0020

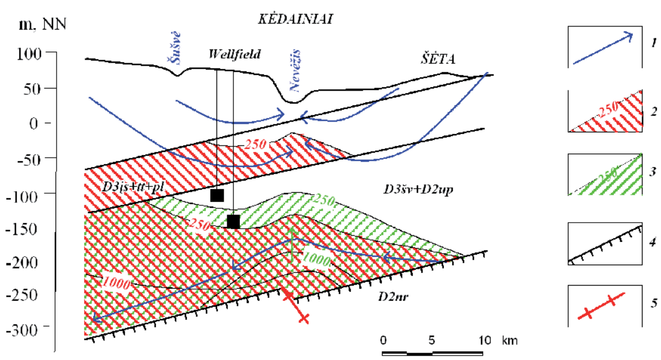

Fig. 9: *Conceptual cross section through fresh/salt groundwater transition zone near Kedainiai wellfield. 1 – flow lines. 2 – sulphates >250 mg/l; 3 – chlorides >250 mg//l; 4 – aquiclude. 5 – tectonic fracture.*

Groundwater simulation results show that salt water input into the budget of Kedainiai wellfield from below is 16–23 %, and from above, 13–20 % (Gregorauskas et al., 2008). These inputs regulate Cl and SO_4 trends, and are demonstrated by Figure 10.

Trends in Figure 10 show, that production wells, installed in the middle part of this aquifer system already provide groundwater of 'poor' quality: concentrations of Cl and SO_4 exceed TV value. This figure also demonstrates, that groundwater quality in the upper part of the exploited aquifer system was and is 'good'. Further we shall see, that it will also be 'good' in the future.

Available groundwater resources considering TZ

EU directives did no particularize environmental and ecological criteria, suitable for the procedure of assessing available groundwater resources: it is only declared, that the total volume of those resources limits the necessity to avoid any significant damage to 'good' quantitative and chemical status of groundwater and of associated surface waters and terrestrial ecosystems (Directive 2000/60/EC, Article 2). Considering the relative abundance of groundwater resources of 'good' quality in Lithuania, some additional, particular criteria for this procedure were applied, e.g.:

- modelled drawdown of pumped aquifer/groundwater system should not exceed established safe limit,
- simulated drawdown of water table of phreatic aquifers should not have negative environmental, ecological consequences,
- impacted subsurface runoff to rivers should not be less than minimal 30 days runoff of those rivers,
- predicted values of chosen groundwater quality indicators should not exceed established threshold values (TV) of those indicators.

Available groundwater resources of Lithuania were calculated using 3D groundwater flow and transport models. The main problem was an assessment of those resources in the above named fresh/salt groundwater transit zones (TZ), because increasing pumping rates of the wellfields located in those TZ, changes the budget of groundwater resources and activates leakage from adjacent aquifers, often containing not fresh water.

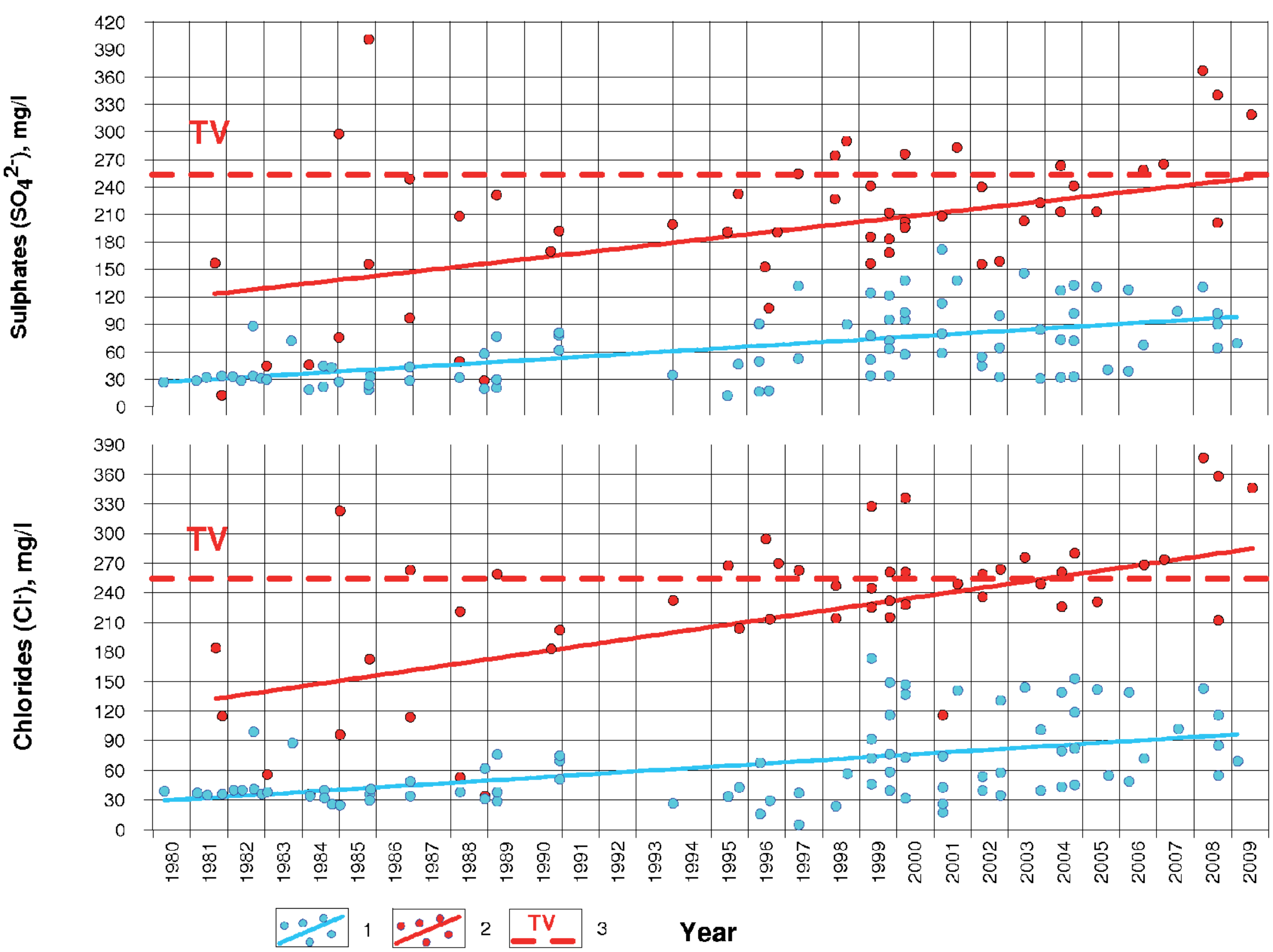

Fig. 10: *Trends in chlorides and sulphates concentrations in upper (1) and middle (2) part of pumped aquifer, wellfield Kedainiai; (3) 'threshold value', TV*

DOI 10.4409/Am-019-10-0020

This problem can be illustrated by the history of the operation of the Kedainiai wellfield. Simulation results, presented in Figure 11, show that the present pumping rate of this wellfield (4000 m^3/d), extrapolated to the next 25 years, can only slightly increase concentrations of chlorides and sulphates, which will not exceed 75 % of the defined TV (250 mg/l for both). The planned doubling of groundwater extraction in the future (up to 8000 m^3/d) can increase concentration of chlorides up to 195 mg/l, i.e., it will exceed accepted limit (75 % of TV). Nevertheless, simulation results show, that even the maximum possible groundwater extraction at this wellfield (15600 m^3/d) will not cause prohibited increase of chlorides or sulphates concentrations above TV, although the limit of 75 % of TV will be violated (see Fig. 11).

Simulation results also demonstrate that available groundwater resources in TZ form a notable part of the groundwater resources of certain groundwater bodies 'at risk' and even of the total available groundwater resources of regional groundwater systems (Table 2).

Tab. 2: *Available groundwater resources (AGWR) of large Upper and Middle Devonian (D_3sv+D_2up) groundwater system (GWS) considering fresh/salt groundwater transition zone (TZ).*

Area of GWS, thou. km²		AGWR, thou. m^3/d		% of AGWR in TZ
In total	Area of GWB 'at risk'	In total	In TZ	
17,75	1,65	782,5	74,5	9,6

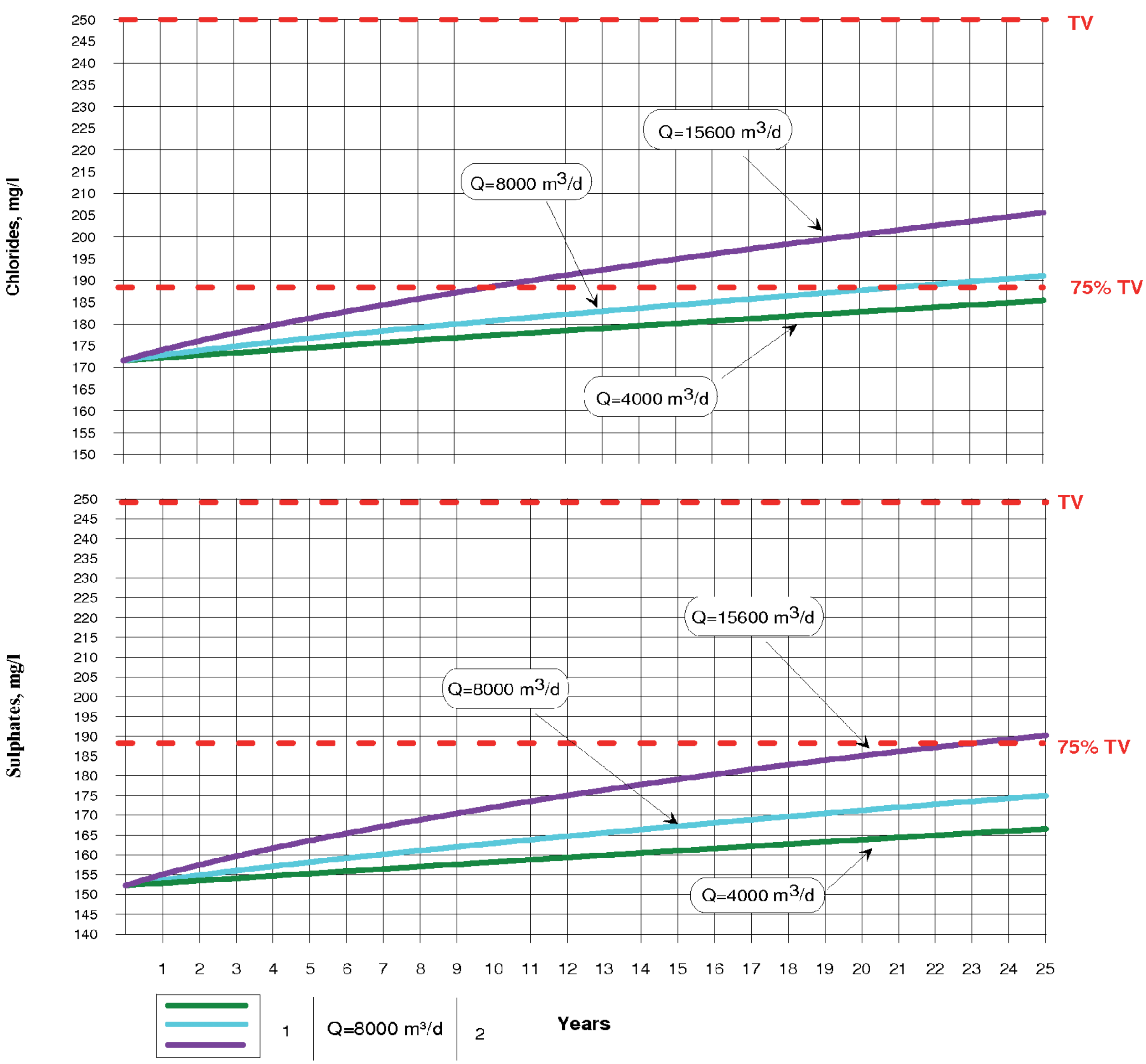

Fig. 11: *Trends of predicted concentrations of chlorides and sulphates, related to pumping rates of Kedainiai wellfield. 1 – simulated trends. 2 – pumping rate.*

DOI 10.4409/Am-019-10-0020

Conclusions

The concept of available groundwater resources defined by EU Directives 2000/60/EC and 2006/118/EC implies, that good chemical status of groundwater, *inter alia*, means the absence of saline or other intrusions into the groundwater body. Lithuania has large groundwater resources of good quality, used for drinking water. Potable groundwater pollution is a minor, local problem. Nevertheless, some groundwater bodies, categorised as being 'at risk', already exhibit symptoms of saline water intrusion or such intrusion is very probable in the future. From this point of view areas especially at risk are fresh/salt groundwater transition zones.

Groundwater monitoring data show, that the ultimate hazard is salt water intrusions into pumped aquifers from adjacent aquifers. Lateral salt water intrusions take much more time and are less dangerous. Simulations of those processes show that available groundwater resources, calculated considering fresh/salt transition zones, may be notably reduced.

References

Bieske E. (1929) - Rohrbrunnen. Verlag von R.Oldenburg; Munchen und Berlin, 214 s.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.

Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the Protection of Groundwater Against Pollution and Deterioration.

Freeze R.D. and Cherry J.A. (1979) - Groundwater. Englewood Cliffs; N J. Prentice-Hall, 604 p.

Gregorauskas M.M., Joksas K.K. and Mokrikas R.V. (1986) - Hydrogechemical aspects of fresh groundwater flow to Baltic Sea (in Russian). Vodnyje resursy 4: p. 13–22.

Gregorauskas M., Klimas A., Plankis M. (2003) - Evaluation of groundwater resources after EC Directive 2000/60 (in Lithuanian); Geologijos akiraciai 3–4 (51–52): p. 30–34.

Gregorauskas M., Juodkazis V., Klimas A. (2008) - Groundwater safe yield assessment principles (in Lithuanian). Geologijos akiraciai 3–4 (71–72): p. 21–34.

Juodkazis V. (1980) - Occurrence and use of groundwater resources in Baltic States (in Russian). Mokslas, Vilnius, 176 p.

Juodkazis V. ed. (1988) - Regional hydrogeology of Baltic States (in Russian). Mokslas, Vilnius, 220 p.

Juodkazis V. (1994) - Groundwater quality and its monitoring in the Baltic states. GeoJournal 33 (1): p. 63–70.

Juodkazis V., Arustiene J., Klimas A., Marcinonis A. (2003) - Organic matter in fresh groundwater of Lithuania. A Monograph. Vilnius University Publishing House, Vilnius, 232 p.

Juodkazis V., Klimas A., (1991) - Change of groundwater quality in the Baltic artesian basin. Scientific Papers of the Geological Society of Lithuania 1: p. 1–39.

Klimas A.J. (1974) - Groundwater and surface water levels and chemistry relations in the middle part of the basin of Nevezis River (in Russian). Problems of groundwater resources occurrence in South Baltic region, Works of Institute of Geology of Lithuania 23: p. 138–143.

Klimas A. (1979), Ground-water quality prediction under long-term development conditions (in Russian). Memoirs of the XV IAH Congress, Vilnius, Lithuania. Nauka, Moscow, p. 279–282.

Klimas A. (1991) - Groundwater quality formation in a course of intensive abstraction and contamination (in Russian). Sovietskaya geologija 12: p. 62–70.

Klimas A. (1994) - Fresh groundwater quality formation regularities under technogenic impacts. Scientific papers 5: 1–56 p.

Klimas A. (2001) - The problems in formation of H_2S in deep aquifers and its removal. Proc. of the XXXI IAH, Munich, Germany. Balkema, Lisse, vol. 1, p. 537–541.

Klimas A. (2003) - Hydrogeochemistry of drinking water (Manual, in Lithuanian). Vilnius University Publishing House, Vilnius, 140 p.

Klimas A. (2004) - Environmental impact of groundwater abstraction (in Lithuanian): in Evolution of Earth Crust and its Resources in Lithuania, V. Baltrunas (ed.). Vilnius, p. 541–546.

Klimas A. (2006) - Groundwater quality trends in Lithuanian wellfields (in Lithuanian). LVTA, Vilnius, 487 p.

Klimas A., Gregorauskas M. (2002) - Groundwater abstraction and contamination in Lithuania as geoindicators of environmental change. Environmental Geology. Vol. 42, Nº 7, p. 767–772.

Satkunas J., ed. (2010) - Lithuanian Geological Survey. Annual Report. Vilnius, 107 p.