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Geoindicators of changing landscapes — an example of karst development in North Lithuania

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During the last two decades of the 20th century and first years of the 21st century more intensive karst processes have been witnessed in North Lithuania. The intensity of the karst process is visible as new sinkholes appearing that severely damage crops, constructions and communication systems. Explanation and forecast of these hazardous phenomena requires knowledge based on systematic monitoring data and adequate interpretation with identification of relevant geoindicators of the intensive sulphate karst processes which are of primary significance for environmental planning and management of the region. Two geoindicators, gypsum chemical denudation and the intensity of appearance of new sinkholes, were selected for monitoring of karst processes in North Lithuania. Chemical denudation has been measured since 1964 in this region. These geoindicators show that since 1978 the intensity of karst denudation has increased by 30%, with more frequent formation of sinkholes. A correlation of this phenomenon with climate change — increasing air temperature and decreasing of the duration of seasonally frozen ground — is proposed and discussed in this paper.

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INTRODUCTION

Rapid geological changes driven by exogenic and endogenic causes often are very hazardous e.g. landslides, collapses of sinkholes and so on, and visibly affect landscape. However, processes, that are comparatively slower (e.g. changes of groundwater level or chemistry) also affect other components of environment, primarily biotic, and also cause landscape change . The crucial issue is to reveal indicators of geological change and to carry out systematic and cost-effective monitoring. The International Union of Geological Sciences has developed the geoindicator concept (Berger and Iams, 1996; Tools…., 1996; Berger, 2002) which brings together in a convenient format various measures for assessing significant geological change that can occur on human time-scales. Geoindicators are measures (magnitudes, frequency, rates, trends) of geological processes and phenomena, occuring at or near the Earth's surface and subject to changes that are significant for understanding environmental change over periods of 100 years or less (Tools…, 1996). The National State of Environment Reports (SoER) of Lithuania in 2001–2004 has included a number of geoindicators. These include environmental changes due both to natural and anthropogenic driving forces and reflect both environmental pressures and states. The application of geoindicators in producing SoERs may be exemplified by results of karst monitoring in Lithuania (Satkūnas and Taminskas, 2004).

Karst is a type of landscape found on carbonate rocks (limestone, dolomite, marble) or evaporites (gypsum, anhydrite, rock salt) and is typified by a wide range of closed surface depressions, a well-developed underground drainage system, and a paucity of surface streams (Beck, 1989; Tools…, 1996). Karst is currently called a particular kind of landscape where landforms due to solution processes prevail over other kinds of landforms (Jennings, 1985; Ford and Williams, 1989). The highly varied interactions among chemical, physical and biological processes have a broad range of geological effects including dissolution, precipitation, sedimentation and ground subsidence. Diagnostic features such as sinkholes (dolines), sinking streams, caves and large springs are the result of solution by circulating groundwater, which may exit to entrenched effluent streams.

It is estimated that karst landscapes occupy up to 10% of the Earth's land surface, and that as much as a quarter of the world's population is supplied by karst water. The karst system is sensitive to many environmental factors. The presence and growth of caves may cause short-term problems, including bedrock collapse, disparities in well yields, poor groundwater quality because of lack of filtering action, instability of overlying soils, and difficulty in designing effective monitoring systems around waste facilities.

Gypsum is a very soluble mineral, which can dissolve at a rapid rate. Where natural dissolution of exposures has occurred adjacent to rivers it is common for one meter of gypsum to be dissolved away in a year or so. Because the dissolution rate is so rapid, gypsum cave systems can enlarge at a considerable rate, ultimately become unstable, and collapse causing subsidence problems at the surface. The mechanism of collapse causes subvertical breccia pipes to develop with subsidence hollows where these break through to the surface.

In most countries where gypsum occurs in contact with water there are associated subsidence problems. In farmland these are inconvenient, but in urban areas they constitute a geological hazard that can seriously affect development and human safety. Gypsum geohazards affect the towns of Biržai and Pasvalys in Lithuania and Ripon and Darlington in England (Paukštys *et al*., 1997). Elsewhere in Europe gypsum geohazards are present in many towns and cities. For example, in Spain they have been recorded in the city of Zaragoza and the town of Calatayud; in France they affect the outskirts of Paris and, in Germany, Stuttgart and many towns peripheral to the Harz Mountains suffer subsidence. In addition to these examples, gypsum dissolution and subsidence affects many more urban and rural areas in these and many more countries (Beck, 1989; Tools..., 1996). Some of these areas may be the sites of future roads, reservoirs or urban growth. Thus, an appreciation of gypsum geohazards is important for planning and development on a national, provincial and local scale.

GEOLOGICAL AND HYDROLOGICAL SETTING OF THE NORTH LITHUANIA KARST REGION

At present karst processes highly active in the North Lithuania and are related to Upper Devonian gypsum and dolomites that occur beneath the Quaternary cover (Narbutas *et al*., 2001).

The North Lithuania karst region is located in the eastern part of the Baltic artesian basin (Fig. 1). The active water exchange zone is up to 270 m thick and includes aquifers in the Quaternary and in the Įstras–Tatula, Kupiskis–Suosa, Sventoji–Upninkai formations of the Upper Devonian (Table 1). This series of aquifers is underlain by the 60–100 m thick regional aquitard of the Narva Formation. The main source for recharge of the Įstras–Tatula and Kupiskis–Suosa aquifers is shallow groundwater and surface water. Variations

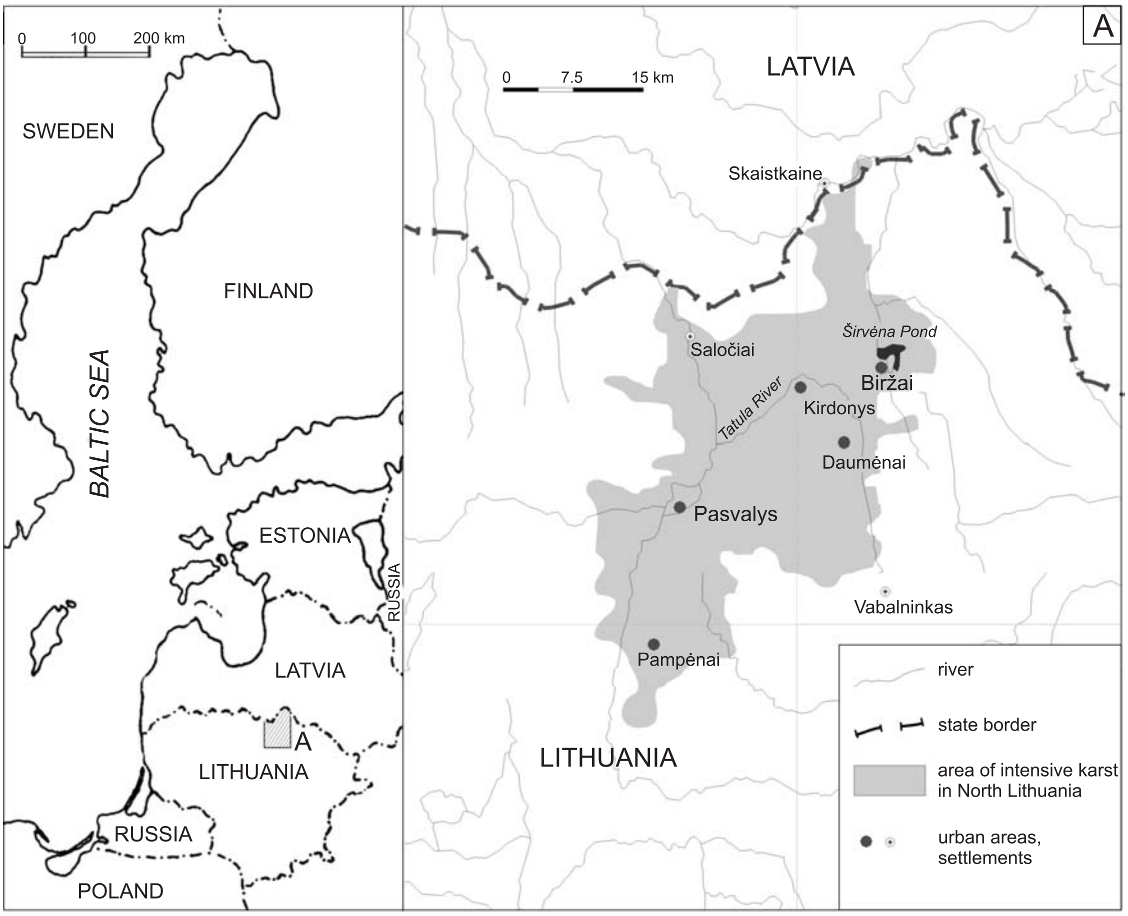

Fig. 1. Intensive karst zone in North Lithuania

Table 1

Middle and Upper Devonian stratigraphic scheme

GLOBAL STRATIGRAPHIC SCALE				REGIONAL STRATIGRAPHIC UNITS					Thickness [m]	Lithology
SYSTEM	SERIES	STAGE	SUBSTAGE	REGIONAL STAGE	Group	Formation	Member	Geological index		
DEVONIAN	UPPER	FRASNIAN	UPPER	PAMUSIS		Pamusis		D_3pm	3–2.5	clay, dolomite, marl
			MIDDLE	DAUGUVA		Įstras		D_3t^{is}	2–4.5	dolomite
						Tatula	Nemunelis	D_3t^{nm}	6–20	gypsum, dolomite, dolomitic marl
							Kirdonys	D_3t^{kd}	4–8	dolomitic marl, dolomite
			LOWER	DUBNIK			Pasvalys	D_3t^{ps}	6–25	gypsum, dolomite, dolomitic marl
				PLAVINAS		Kupiskis		D_3kp	5–10	dolomite
						Suosa		D_3s	12–19	dolomite with gypsum
						Jara		D_3j	4–8	dolomitic marl
				SVENTOJI		Sventoji		D_3sv	90–100	sandstone, siltstone, clay
	MIDDLE	GIVETIAN		BURTNIEKI	Upninkai	Butkunai		D_2bt	100–130	sandstone, siltstone, clay
				ARUKULA		Kukliai		D_2kk		
		EIFELIAN		NARVA		Kernave		D_2k	6–20	clay, siltstone, sandstone
						Ledai		D_2ld	60–80	dolomite, maryl dolomite, clay

in level and chemical composition of groundwater are determined by the rate of infiltration of precipitation. In the northern part of Lithuania the active recent karst activity takes place in the Tatula and Suosa formations of the Upper Devonian (Table 1), represented by gypsum, dolomite-gypsum, gypsum-dolomite with clay, dolomite and dolomitic marl interlayers and lenses. The Pasvalys and Nemunelis members of the Tatula Formation (Table 1) contain gypsum interlayers and lenses, the thickness of which is up to 2–3 m. These lithological characters determine the most favourable conditions for formation of cavities due to gypsum dissolution.

Fig. 2. The sinkhole formed in January 7th, 1999 in Pasvalys, the urban area most affected by karstic sinkholes in the North Lithuanian karstic area (photo by V. Mikulėnas)

Karstic sinkholes appear frequently where the Quaternary cover is particularly thin and is underlain by layers that contain gypsum.

Active karst landscapes are highly vulnerable and complicate regional economic development and environmental protection. The phenomenon is hazardous and severely impacts on constructions, crops, pipelines and so on by sudden ground collapses and the opening of karstic sinkholes (Fig. 2).

Where the (Fig. 3) Quaternary deposits are 1–5 m thick, sinkholes abound and their number is continually increasing. Ground collapse usually affects the Quaternary cover and permits ready recharge of surface water into the Upper Devonian aquifers. Areas with such intensive water circulation in open gypsum systems (Fig. 1) are referred to as the intensive karst zone (Drake, 1980).

CHARACTERS OF KARSTIC LANDSCAPE

During last decades of the 20th century century karst sinkholes were observed to form more frequently. Due to this, many communication systems and buildings were damaged. This phenomenon stimulated studies into the reasons for this more intensive karst process. It is thought that the main reason involves water balance changes of natural (as regards climate change) and anthropogenic origin in the precipitation–surface water–groundwater–surface water system. For evaluation of changes in these water balance elements and in gypsum denudation, a program of surface water monitoring in the karst region was prepared and implemented (Taminskas, 1999; Taminskas and Marcinkevičius, 2002).

Systematic monitoring of sulphate karst in Lithuania was carried out in the period 1994–2004 and included hydrological and hydrochemical observations of surface and underground run-off, analysis of long-term meteorological data, and tracking of changes of karst relief. While evaluating the karst intensity it is necessary to distinguish two related processes: chemical denudation and the formation of surface karst forms. Variations in the intensity of these processes may not coincide, though the more frequent occurrence of sinkholes is an outcome of former rapid karst denudation close to the Earth's surface.

Fig. 3. Karstic sinkholes also affect rural areas. The sinkhole formed in the village of Daumėnai in July 2004 (photo by V. Mikulėnas)

Karst pits, karst wells and kettles, sinkholes and so on comprise the surface karst landscape. Underground forms, which are unevenly distributed, include fissures, channels and cavities of various shapes. More than 8500 surficial sinkholes were counted in the sulphatic karst region of Lithuania (Marcinkevičius and Bucevičiūtė, 1986). In some places more than 200 sinkholes of different size, could be counted in a square kilometre. Some sinkholes are permanently or seasonally filled by water (karst lakes). Karst lakes and dry sinkholes make natural drainage systems, through which precipitation, snow melting and overland flow access gypsum strata of the Lower Devonium.

The run-off coefficient (ratio of run-off depth to precipitation depth) is 0.23–0.25 in the karst region. The average annual depth of run-off in the region varies from 126 to 221 mm (Bukantis *et al*., 1998). The greatest discharge occurs during spring floods (Taminskas, 1994–1995).

The minimum run-off occurs in the drought periods of warm (months VII–X) and cold (XII–II) seasons. The groundwater discharge into the karst rivers of the region makes up from 25 to 40% whereas in non-karst rivers it comprises only 8–16% of the annual run-off. The run-off of karst rivers in drought periods always exceeds the run-off of non-karst rivers. During the spring flood the karst system regulates the run-off and accumulates *ca*. 15% of the spring floodwater, except in particularly wet years, when the karst aquifers are fully saturated. This water significantly increases the minimum river run-off of the summer drought period (Taminskas, 1994–1995;Taminskas *et al*., 2005).

THE IMPACT OF CLIMATE CHANGE ON WATER BALANCE

Since 1850 the annual mean and maximum temperature in the karst region has been constantly increasing (Lizuma, 2000). Air temperature observations in the active karst zone were started only in 1924, but we can observe a trend of air temperature increasing during this period (Fig. 4). Significant increases in mean annual temperature have been observed since 1990 (6.8°C).

Particularly significant increases of winter season temperature near ground surface were observed during the last decades of the 20th century, extending to the present (Table 2). Warmer winters in 1974–2000 may be related to the shift in the last 25 years of NAO (North Atlantic Oscillation) northern atmosphere activity centred in the region extending from the South-East Greenland to the Norwegian Sea (Hurrell and van Loon, 1997; Hilmer *et al*., 1998; Corti *et al*., 1999; Hilmer and Jung, 2000). A particularly distinct increase in air temperature has been observed since 1960. In the period 1961–1990, compared to 1931–1960, the mean temperature of January and February in the karst region increased by 0.5°C (Bukantis *et al*., 1998).

Mean temperature in summer decreased until 1980, and then started to increase. Significant increases in annual, winter and summer temperatures were observed in 1994–2004. Increases in air temperature, during both cold and warm seasons, influenced other hydrometeorological characteristics and the solubility of gypsum.

Atmosphere circulation changes determined other climatic characteristics. During this period significant changes in winter precipitation and in the thickness and duration of seasonal freezing were observed (Bukantis *et al*., 1998). During 1960–1979 the duration of seasonal freezing of 90% probability was 121 days, but in 1980–2000 it was only 91 days. The mean depth of freezing decreased from 42 to 30 cm. Because of the shorter duration of seasonal freezing, the period of active water circulation became longer and more frequent thaws increased winter surface run-off to karst lakes and sinkholes. From 1924 to 1979, a trend of a slight decrease in annual precipitation was observed in the karst region (Fig. 5), though in general the 20th century, according to Lizuma's data (Lizuma, 2000), is characterized by a trend of annual precipitation increase. The lowest amount of annual precipitation was observed in 1961–1980. However, amounts of precipitation started to increase during the last two decades of 20th century, particularly in winter (Table 3).

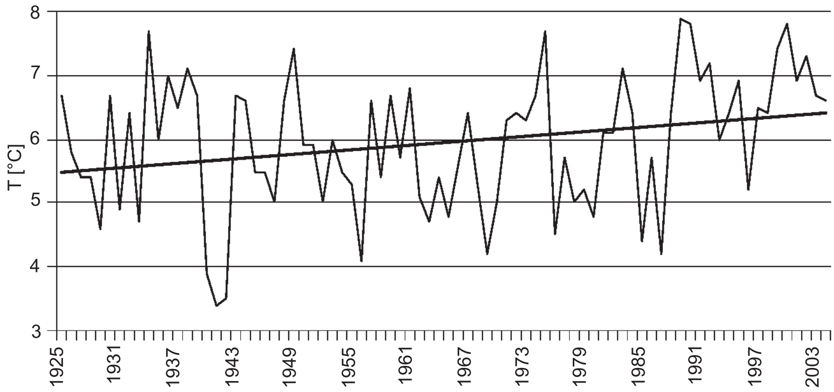

Fig. 4. Mean annual temperature in North Lithuania karst region

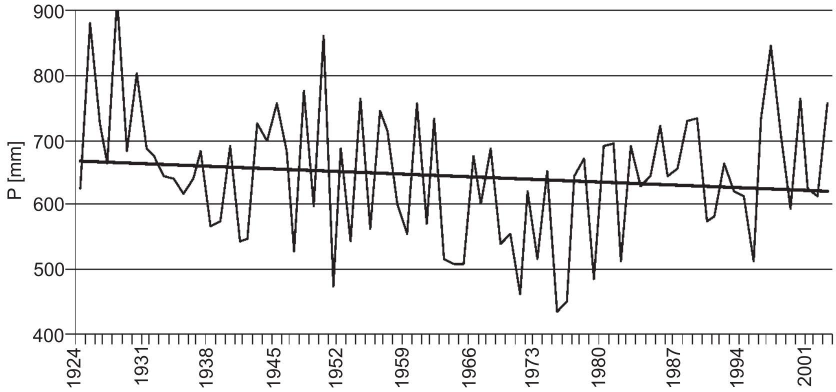

Fig. 5. Mean annual precipitation in North Lithuania karst region

During the period 1949–1975 annual and warm season precipitation generally decreased, whereas in cold seasons it decreased only until 1964. These trends of precipitation variations in cold and warm seasons are characteristic for the entire Lithuanian territory (Bukantis *et al*., 1998).

In 1980 the sum of precipitation for the there winter months exceeded 100 mm and by 2004 it was lower than 95 mm. During 1981–2000, in comparison with 1961–1980, amount of winter precipitation increased by 36% (Table 3) and it comprised 21% of annual precipitation.

Since 1980, due to increased amounts of winter precipitation and higher air temperatures, groundwater level in the Tatula aquifer (D_3t) increased. The mean level of groundwater in winter increased by about 0.27 m and the mean annual level of the D_3t aquifer increased by about 0.2 m (Fig. 6). Such high levels of groundwater remained until the end of the 20th century. Increasing resources of groundwater in winter increased winter run-off up to 74 mm in 1981–2000. The minimum 7 days run-off in the Tatula River increased from 0.348 m^3s^{-1} in 1962–1980 to 0.718 m^3s^{-1} in 1981–2000.

Due to higher water levels throughout the year larger amounts of Devonian gypsum were dissolved. Increased discharge to fractured karst rocks increased the velocity of water flow. Water circulation in karst system lakes (or sinkholes) and rivers associated with the D_3t aquifer become more active.

Table 2

Mean annual and winter temperature in North Lithuania karst region [°C]

	1924–1940	1941–1960	1961–1980	1981–2000
Annual	6.0	5.6	5.6	6.5
Winter	–5.1	–4.8	–5.1	–3.3

Table 3

Mean annual and winter precipitation in North Lithuania karst region [mm]

		1924–1940	1941–1960	1961–1980	1981–2000
Annual	Average	690	656	576	660
	Min.	567	473	434	513
	Max.	921	852	733	846
Winter	Average	96	108	89	139
	Min.	56	16	53	95
	Max.	154	165	136	192

The run-off coefficient of karst rivers decreased until 1976 (from 0.67 to 0.13) and from 1977 it started to increase (Fig. 7). During the last two decades of the 20th century run-off of karst rivers increased by 25%, from 0.28 in 1961–1980 to 0.37 in

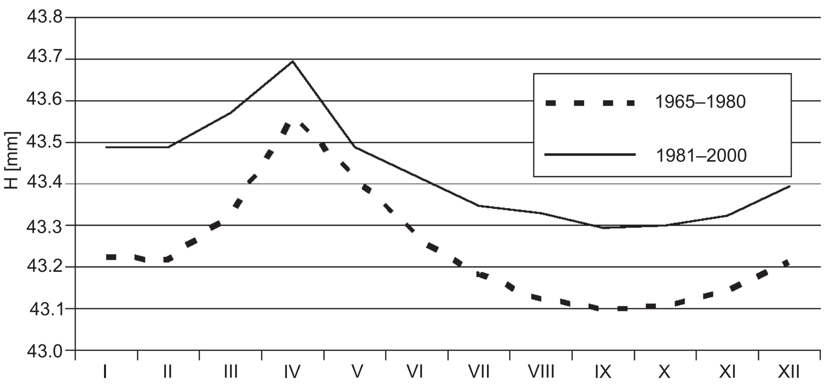

Fig. 6. Mean monthly groundwater level of the Tatula (D_3t) aquifer in the periods 1965–1980 and 1981–2000

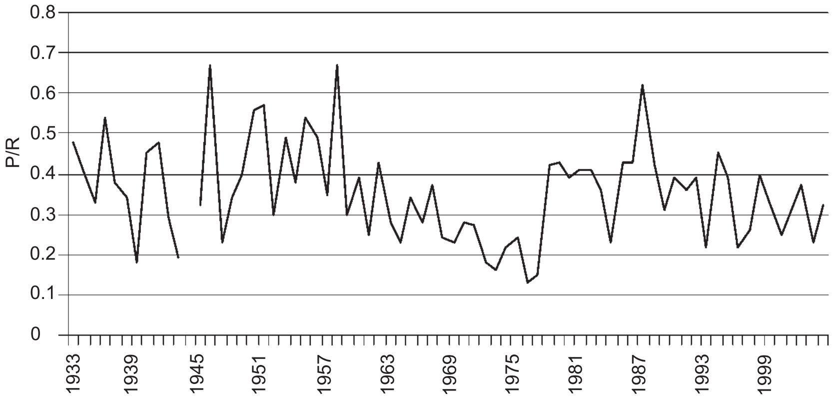

Fig. 7. Annual run-off coefficient in North Lithuania karst region

1981–2000. This made more favourable conditions for gypsum dissolution and denudation.

CHANGES IN CHEMICAL DENUDATION AND IN THE DEVELOPMENT OF SINKHOLES

Under normal conditions the concentrations of Ca, SO_4, Mg, HCO_3 ions in the Lithuanian surface waters rarely exceed the maximum concentration limits (MCL) adopted in Lithuania, which are as follows: Ca — 180 mg/l, SO_4 — 100 mg/l, Mg — 40 mg/l. However, in the karst landscape these concentrations are often higher due to dissolution of gypsum ($CaSO_4 \times 2H_2O$) and dolomite (Ca Mg $(CO_3)_2$).

Ca, SO_4, Mg, HCO_3 ion concentrations were determined in water samples taken twice a month during the monitoring period. The concentration of calcium was determined by a complexonometric method. The concentration of magnesium was calculated by subtracting the concentration of calcium ions from the total hardness. The concentration of sulphates was determined by a turbidynamic method. Hydrocarbonates were determined by direct titration (Unifikuoti ..., 1994).

When determining the denudation products of gypsum in the water by the hydrochemical method at least one of the following requirements must be met: SO_4^{2-} >180 mg/l, Ca^{2+}> 100 mg/l, SO_4^{2-}/Ca^{2+} ~2.4. If SO_4^{2-}> Ca^{2+} (mmol/l) the intensity of sulphate rock denudation is determined by the content of calcium in the water. If $SO_4^{2-} < Ca^{2+}$ (mmol/l) the intensity of carbonate rock denudation is determined by the sulphate content. In determining the denudation products of carbonate rocks (dolomite) by the hydrochemical method at least one of the following requirements must be met: Mg^{2+} >40 mg/l. HCO_3^- >300 mg/l, HCO_3^-/Ca^{2+} ~2. If $HCO_3^- < Ca^{2+} + Mg^{2+}$ the denudation is calculated according the content of HCO_3. Ca^{2+} ions may be the denudation product of sulphate rocks. For this reason the denudation intensity of carbonate rocks should be calculated according to the content of magnesium.

The average gypsum denudation over the period 1962–1977 in the Tatula River basin was 117 m^3 from 1 km^2. Since 1978 gypsum denudation has increased considerably. The average measured gypsum denudation in 1994–1999 was 217 m^3 from 1 km^2 (Taminskas and Marcinkevičius, 2002). During 2000, 2002 and 2003 the intensity of gypsum denudation decreased slightly, but the rate remained high; in 2004 it increased again to 245 m^3 from 1 km^2 (Fig. 8).

Climatic changes are suggested as a main cause of karst process intensification: the higher amount of precipitation, especially in cold seasons, the increase in temperature and warmer winters that in turn determine a longer active period of water circulation between surface and groundwater. Therefore, it may be assumed that climate is the main factor driving the karst processes that in turn constrain economic use and environmental management of the karst areas. On other hand the karst is a geoindicator that reflects changes in the environment at a broader scale. Because of intensive chemical denudation, washed-out underground cavities provide favourable conditions for the development of sinkholes. Some authors consider that the formation of underground cavities lasts hundreds or even thousands of years (Narbutas *et al*., 2001), while others consider that under favourable hydrodynamic conditions underground cavities may be formed over more shorter periods (Taminskas and Marcinkevičius, 2002)

Large number of sinkholes that formed during last two decades of the 20th century and the first 4 years of the the 21st century lead us to consider that significant gypsum dissolution can occur over very short periods.

In 1961–1970, in the study area of 10 km^2 there appeared annually 6 large (up to 20 m in diameter) sinkholes, while in 1971–1980 11 appeared and in 1981–1997 9 sinkholes formed. Thus, 1970 stands out as a period of the most intensive formation of large sinkholes. This might have been induced by an abrupt increase in the amount of precipitation in 1977 after a long period of dry years and by very intensive exchange between surface water and groundwater. An abrupt rise in

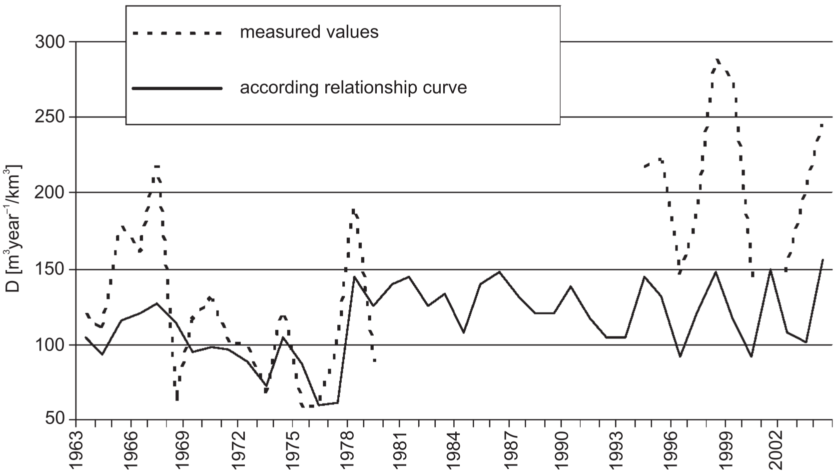

Fig. 8. The intensity of gypsum denudation in the karst region of North Lithuania evaluated as the amount of gypsum dissolved and carried out by the water run-off from the karst region

groundwater level and an increase in the amplitude its annual variation also support this suggestion.

The average volume of a sinkhole 10–20 m in diameter is approximately 200 m^3 (Taminskas, 1999). Thus, the total volume of new sinkholes that appeared annually per 1 km^2 in 1961–1970 was 120 m^3 per km^2, in 1971–1981 — 220 m^3 per km^2, 1981–1997 — 170 m^3 per km^2. The total volume of new sinkholes is similar to the volume of dissolved gypsum determined by means of hydrochemical monitoring (Taminskas and Marcinkevičius, 2002).

The intensity of sinkhole formation varies across the territory. These differences are mostly determined by the structural characters of the Tatula Formation (e.g. the thickness of the soluble gypsum interlayers and lenses and the rock density), by the thickness of the deposits covering the karstic rocks and by the intensity of groundwater circulation. The upper surface of the Tatula Formation is uneven because of tectonic movements and local elevations of this horizon of several metres amplitude can be observed (Narbutas *et al*., 2001). These elevations are closer to the surface than neighbouring depressions of the Tatula layer, may be more fractured and therefore possess better filtration capacity, this in turn increasing the rate of water circulation and the dissolution of gypsum.

Over the study period the greatest number of hazardous sinkholes appeared in three areas: the town of Pasvalys, north-west of the Širvėna pond, and in the environs of the village of Kirdonys. To date, not all the anthropogenic impacts have been identified that might have influenced the formation of sinkholes in different parts of the karst region. However, greater numbers of sinkholes in Pasvalys and north-west of the Širvėna pond suggests that the formation of recent sinkholes might have been induced by water level differences and more intensive groundwater run-off due to the construction of dams across rivers. Similar causes of karst process activation were also noted by Newton (1981). In urban territories, karst processes may be activated by poor sewerage and water supply systems and landfills contributing to penetration of gypsum-aggressive water into karstic rocks (Taminskas and Marcinkevičius, 2002). However, the human impact on the intensity of karst denudation and the formation of sinkholes is in sufficiently determined. Correlation of human impact factors with the karst process requires more comprehensive monitoring of land use changes and other indicators.

DISCUSSION AND CONCLUSIONS

The karst system is sensitive to many environmental factors. The presence and growth of karstic caves may cause short-term problems, including ground collapse, disparities in well yields, poor groundwater quality because of lack of filtering action, instability of overlying soils, and difficulty in designing effective monitoring systems around waste facilities.

In Lithuania, gypsum occurs in contact with water and this causes subsidence problems. In farmland these phenomena are inconvenient, but in urban areas they constitute a geological hazard that can seriously affect human safety and the development of infrastructure. Gypsum geohazards in North Lithuania affect the towns of Biržai and Pasvalys and other smaller settlements.

Gypsum is a very soluble mineral, which can dissolve at a rapid rate. Where natural dissolution of exposures has occurred adjacent to rivers it is common for one metre of gypsum to be dissolved away in a year or so. Hydrological and geochemical measurements of springs, sinking streams and rivers provide records of short-term changes in water quality and chemical processes. Surface features and soils in karst terrains are notoriously unstable and can change rapidly, commonly at catastrophic rates. Sinkholes appear frequently where the Quaternary is particularly thin and underlain by gypsum. Most surface collapses occur during or soon after floods, when soil and debris is eroded from beneath incipient sinkholes. Ground collapse usually affects the Quaternary cover and permits ready recharge of surface water into the Upper Devonian aquifers.

From 1924 to 1979, a trend of slight decrease in annual precipitation can be observed in the karst region (Fig. 8), though in general the 20th century is characterized by a trend of annual precipitation increase. The lowest amount of precipitation was in 1961–1980, but during last two decades of the 20th century amounts of precipitation started to increase. In particular, amounts of winter precipitation increased significance. Rapid increases in annual precipitation have been observed since 1978. This period is synchronous with a period of increased gypsum denudation. Therefore, we can conclude that the intensity of gypsum denudation increased due to climate change (increases in precipitation and air temperature). Increases precipitation determined increases in the run-off coefficient and the groundwater level.

However, the possibility of anthropogenic causes in addition cannot be neglected. According to previous investigations the formation of recent sinkholes might have been induced by water level differences and more intensive groundwater run-off due to construction of dams.

The mean annual total volume of new sinkholes in the karst zone in 1961–1997 was 170 m^3 per 1 km^2. The measured intensity for this period was 191 m^3 per 1 km^2, and the estimated intensity was 122 m^3 per 1 km^2. Thus, the intensity of karst process evaluated by different methods is generally similar.

Summarizing the results of monitoring of the active karst zone we can assume that the more frequent occurrence of sinkholes in recent years has been caused by changes in climate. From historical climate data we can infer that the intensity of karst process at the beginning of 20th century was analogous. Forecasts of karst intensity can be based on the future meteorological and hydrological characteristics of the region. In the case of climate warming and an increase in the amount of precipitation, more intensive formation of sinkholes may be expected.

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