On the results of the joint Russian-Dutch project SUBURBIA

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Abstract: The joint Russian-Dutch project "Development of Risk Analysis Procedures for Subsurface Management in Urban and Industrial Areas" (SUBURBIA) was undertaken as a bilateral research cooperation program between the RFBR (Russian Foundation for Basic Research) and NWO (Nederlandse Organisatie voor Wetenschappelijk Onderzoek); it lasted two years, from May 21, 2002 to May 21, 2004. In Russia it was carried out at the Institute of Environmental Geoscience of the Russian Academy of Sciences (IEG RAS) and the State Unitary Enterprise on Karst Control and Bank Protection of Gosstroy of the Russian Federation (Dzerzhinsk, the Nizhnii Novgorod region). In Holland the research took place at the Netherlands Institute of Applied Geoscience (NITG-TNO) and the Delft Technical University (TU Delft). The research aimed to progress the theoretical and practical fundamentals of natural risk assessment and management. It developed GIS-technology to solve problems related to sustainable development in karst areas. It has done this by generating risk maps of hazardous geological processes followed by the development of practical recommendations for subsurface management in urban and industrial areas. Karst and suffosion development was studied at two key sites in Moscow and Dzerzhinsk where the results are being implemented.

At the Moscow site, engineering geological data analysis, performed in key areas, proved karst hazard prediction may be based on deterministic engineering geological models. At the Dzerzhinsk study site, the method based on understanding the stochastic distribution of surface karst features proved more appropriate. Combining both approaches using computer modelling in a GIS environment have allowed information and recommendations to be given on risk mitigation. Decision-making regulations were suggested to city authorities aimed at preventing emergencies related to karst process in urban and industrial areas. With adjustment for the local engineering geology conditions, these recommendations may be applicable to other cities.

Résumé: Le projet collectif russe-hollandais "Etude de procédure de risques de l'analyse pour gérer l'espace souterrain des terrritoires urbains et industriels (SUBURBIA)" s'est réalisé dans le cadre du programme de la coopération bilatérale russe-hollandaise entre le Fonds russe de recherches fondamentales (FRRF) et l'organisation de Pays-Bas pour le soutien de recherches scientifiques (NWO). Les recherches d'après ce projet ont été menées durant deux ans et demi (21 mai 2002 - 21 septembre 2004) de la Partie russe par – l'Institut d'Ecologie Géologique de L'Académie de Sciences de Russie et par l'Entreprise d'Etat fédérale et unitaire "Défense côtière et anti-karstique" G sstroy de Russie (ville de Dzerginsk, région de Novgorod), de la Partie hollandaise par - l'Institut de Pays-Bas de recherches géologiques appliquées (the Netherlands Institute of Applied Geoscience - NITG - TNO) et par L'Université technique, ville de Delfta (TU Delft). Le présent projet russe-hollandais avait pour objectif l'approfondissement de base théorique et pratique destinée à évaluer et à gérer le risque naturel. Outre cela, l'élaboration de technologie de pointe destinée à la résolution de problèmes du développement stable a été également visée par ce projet. La cause finale de ce projet consiste en rédaction des cartes sur le risque de développement des processus géologiques dangereux et en élaboration des recommandations pratiques pour gérer l'espace souterrain des territoires urbains et industriels à partir de l'exemple du phénomène karstique de suffosion développé sur deux aires dans la ville de Moscou et de Dzerginsk.

Le traitement de l' information géotechniques de ces aires a démontré la chose suivante. Afin de réaliser la prévision du danger karstique sur l'aire de Moscou il est préférable d'avoir recours à la méthode basée sur les modèles déterminés géotechniques alors que sur l'aire de Dzerginsk il est plus utile d'appliquer la méthode qui fait voir les lois stochastiques de la karstification superficielle. A partir des résultats obtenus on a établi la liste de recommandations pour diminuer le risque en tenant compte de l'information des cartes électroniques et des résultats de simulation.

Keywords: Collapse, geographic information systems, geological hazards, subsidence, numerical models, risk assessment.

INTRODUCTION

The project Development of Risk Analysis Procedure for Subsurface Risk Management in Urban and Industrial Areas, acronym: SUBURBIA, was conducted in the framework of the bilateral research programme between the

RFBR (Russian Foundation for Basic Research) and NOW (Nederlandse Organisatie voor Wetenschappelijk Onderzoek). This project lasted for 28 months; it started on May 21, 2002 and closed by 21 September 2004.

In Russia, the project was carried out at the Institute of Environmental Geoscience of the Russian Academy of Sciences (IEG RAS) and at the State Unitary Enterprise on Karst Control and Bank Protection of Gosstroy of the Russian Federation (Dzerzhinsk, the Nizhnii Novgorod region). Project contributions from the Dutch side were undertaken mainly in the Technical University in Delft and in the Netherlands Institute of Applied Geoscience (TNO-NITG). The project Leader from the Dutch side was Prof. Dr. Eduardo F.J. de Mulder (TU Delft and TNO-NITG) and the co-leader representing the Russian partners, including the Research Group in Moscow, was Academician (RAS) Prof. Dr. Victor I. Osipov. The Dzerzhinsk Research Group was represented by Dr. V.V.Tolmachev. From Russia, six additional key researchers and five junior scientists participated in the SUBURBIA Project, and from Holland two key researchers and one junior scientist also contributed.

GOAL AND TASKS OF RESEARCH

Geohazards are important because of the serious harm they cause to urban and industrial infrastructure. In particular, karst and suffosion, as studied by the SUBURBIA project, represent hazardous geological processes. In the context of this work, karst is taken to mean an assemblage of geological processes leading to rock dissolution and the development of subsurface cavities that vary in shape and size. These processes destabilize rock massifs and finally lead to surface collapse or settlement. Collapses may develop either due to the failure of the roof above a karst cavity or due to suffosion, the inrush of water-saturated sand, or other unconsolidated deposits into a cavity.

Karst, suffosion and subsidence are natural processes, but they may be intensified by human activities, such as loading by construction or modifications of groundwater flow regimes by activities such as groundwater extraction. Human interference is most significant in densely populated areas such as cities and in heavily industrialised zones.

In these areas, it may result in significant economic, social and ecological consequences (ruining buildings and engineering structures, human deaths, impermissible environment contamination due to accidents at ecologically hazardous enterprises, etc.). Therefore, the risk and hazard assessment as regards karst and suffosion and the estimation of urban area stability under the intensifying human impact acquires great importance.

The joint Russian-Dutch research aimed to progress the theoretical and practical fundamentals of natural risk assessment and management. It also aimed to develop GIS-technologies to solve problems and allow sustainable development. Its goal was to generate risk maps for hazardous geological processes and to work out practical recommendations for subsurface management in urban and industrial areas. Karst and suffosion were studied at two key sites in the Russian Federation; one in a densely populated area in Moscow City, the other, in the sparsely populated, but heavily industrialised area of Dzerzhinsk, Central Russia. The final aim of the project was to implement the results in these areas.

KARST AND SUBSURFACE FEATURES IN THE STUDY AREAS

The studies were carried out at two key sites located in the urban area of Moscow and in the industrial zone of Dzerzhinsk (Nizhnii Novgorod oblast). Both sites are situated in the inner part of the ancient East European platform. In Moscow, the karst-prone Carboniferous rocks occur on the south-western and southern slopes of the vast Moscow syncline, in Dzerzhinsk the Permian karstic rocks occur in almost horizontal layers under the cover sequences.

Moscow

Karst and suffusion development in Moscow has mainly been caused by ancient and modern dissolution activity associated with erosive rivers and their valleys. The Carboniferous limestone is intensely karstified within the ancient buried river valleys and the degree of karstification gradually decreases towards the modern and buried watersheds. The human-induced intensification of karst processes was first recorded in Moscow in the 1960s and 1970s, when several disastrous land collapses occurred in the north-western part of the city. It was found out that these collapses resulted from the intense long-term pumping of groundwater from the Carboniferous aquifer. This caused a significant decrease in the groundwater head causing the transition from the natural ascending vertical filtration regime to descending filtration through the low-permeable Jurassic clay layer. The effects of the change in hydrodynamic pressure cause the destruction of clay above the cavities and fractures in the limestone, leading to subsidence at the surface.

Dzerzhinsk

The city of Dzerzhinsk is a large industrial centre with a concentration of potentially ecologically dangerous enterprises. An industrial accident here could cause a large-scale ecological disaster. Situated in the Oka river valley, the Dzerzhinsk territory is strongly affected by karst. This is developed in Permian gypsum and anhydrite deposits overlain by Quaternary alluvial and fluvioglacial sand layers. More than 4000 karst sinkholes and cases of surface subsidence have been recorded there. On average, five cases of collapses and numerous cases of settlement related to karst and suffusion are recorded every year in Dzerzhinsk.

METHODS APPLIED

The accurate time and space prediction of karst and suffosion-related geohazards is currently impossible. However, approximate predictions can be made using risk-analysis procedures. Such procedures may develop from the improved understanding of the relevant geological processes (such as limestone or gypsum dissolution history determined from many geological datapoints) this is the deterministic method. Alternatively it can be derived from the statistical analysis of karst/suffosion phenomena in time and space, this is the statistical method. The first method was tested in the Moscow area and the second in Dzerzhinsk. A third method of geohazard risk-analysis is through direct observation from space. Automatic comparison of repetitive radar interferometry images by satellites may reveal modifications in topographic heights related to local land subsidence due to karstification. This third, GIS-coupled approach was conducted for the Moscow site by the Dutch counterpart, Delft Technical University. The SUBURBIA project has proved that the first two mentioned risk-analysis procedures worked successfully for karst and suffosion hazards, work on the third method is still in progress (de Mulder, Osipov 2004)

Probabilistic-statistical method of karst hazard and risk assessment

The statistical method was applied in the Dzerzhinsk area situated in the Oka River valley. Since 1955, 66 karst incidents have been recorded here. In addition, karst deformation was assessed in 237 out of 339 boreholes and the information stored in a database.

The database includes the following parameters:

- *Surface karst manifestations*: location in plan; types of karst forms (i.e., collapses, local earth settling, karst-suffosion subsidence); the year of development; geometrical shape (i.e., diameter, depth, volume).
- *Subsurface karst manifestations* (according to the data of earlier surveys): position in plan and section (depth, elevation a.s.l.), lithological composition of enclosing rocks, type of karst manifestation, and geometrical size.
- *Geological and hydrogeological conditions:* geological and tectonic structure; ground-water levels of alluvial and fracture-karst aquifers and their time variation.
- *Human impacts*: leakage from sewerage and pipes, ground-water pumping; static and dynamic loads.
- *State of buildings and engineering structures:* specifics of building design; the presence, time, and type of damage; year of building; the presence and type of karst protection measures.

The availability of such information makes the Dzerzhinsk site suitable for the stochastic statistical approach. An average sinkhole number was determined at $\lambda = 1{,}4$ per year. The distribution law of sinkhole numbers per year is in fair correspondence with Poisson's law: $P(x) = e^{-\lambda} \lambda^x / x!$ (Tolmachev 1970; Tolmachev, Mamonova 2004)

This statistical method is, however, only applicable for assessing karst hazard in the areas where sinkholes and surface settling are recorded. As this is more difficult in densely populated areas such as Moscow City, the statistical approach could not be applied there.

Probabilistic-deterministic method of karst hazard and risk assessment

The deterministic method of karst/suffosion risk analysis is based on a full understanding of the subsurface geological, hydrogeological and geotechnical conditions, including the stratigraphic succession recorded in numerous well-described boreholes. Geological investigations in the Moscow study site revealed that karst hazards are confined to certain zones, which are generally inherited. Intensive karstification occurred, over millions of years of continental erosion, in two pre-Quaternary river valley systems. Since mid-Quaternary times, it has also occurred in the current Moscow river system (Osipov & Medvedev, eds. 1997). In addition, highly fractured geodynamic zones also appear to be linked with the karstification. Concurrence of these paleo river valleys and/or the geodynamic zones can increase the risk of karstification, whereas such risks decrease further away from such zones.

The deterministic method is based on the study of the details the rock formations and distribution of the variation in rock stress state. The calculation of the stability coefficient of the rock massif is derived from these data plus information about the lithostatic and additional human-induced stress within it. In the areas of covered karst, the insoluble deposits overlaying the karstified rocks (a clay layer), and the way groundwater moves, are particularly important. In these areas, the rock massif stability is closely related to the maximum (hypothetic) gradient of vertical filtration through the low-permeable clay layer. The maximum (hypothetic) gradient of vertical filtration develops in the clay divide when the overlying sandy massif is fully saturated with water (with the ground-water table being at the surface) and the groundwater level in the underlying limestone aquifer is severely lowered (with the level of karst-water aquifer being located at or below the limestone roof). The modelling and calculations indicate that karst and suffosion starts developing when the vertical filtration gradient through the low-permeable clay layer exceeds 3 (Kutepov, Kozhevnikova 1989).

The stress state analysis proves that the stable state for the rock massifs over karst zones occurs when the restraining forces are equal or exceed the shifting forces. The ratio between the restraining and shifting forces are estimated by the coefficient of rock massif stability over the weakened karstified zone. To assess the groundwater influence on the alteration of the stability of the overlying sand and clay layers, the stability coefficient is calculated for the known dimensions of the weakened karstified zone for various positions of near-surface groundwater level and karst-water head.

The calculation scheme for estimating the rock massif stability was developed from the ratio of the shifting and retaining forces affecting a cylinder of radius R above the karst cavity. For the given radius, the stability coefficient K of the rock massif is calculated as the ratio between the retaining and shifting forces:

$K = F_h / F_v = A/R$

where the reduced coefficient of stability A corresponds to the stability for the collapse radius of 1 m.

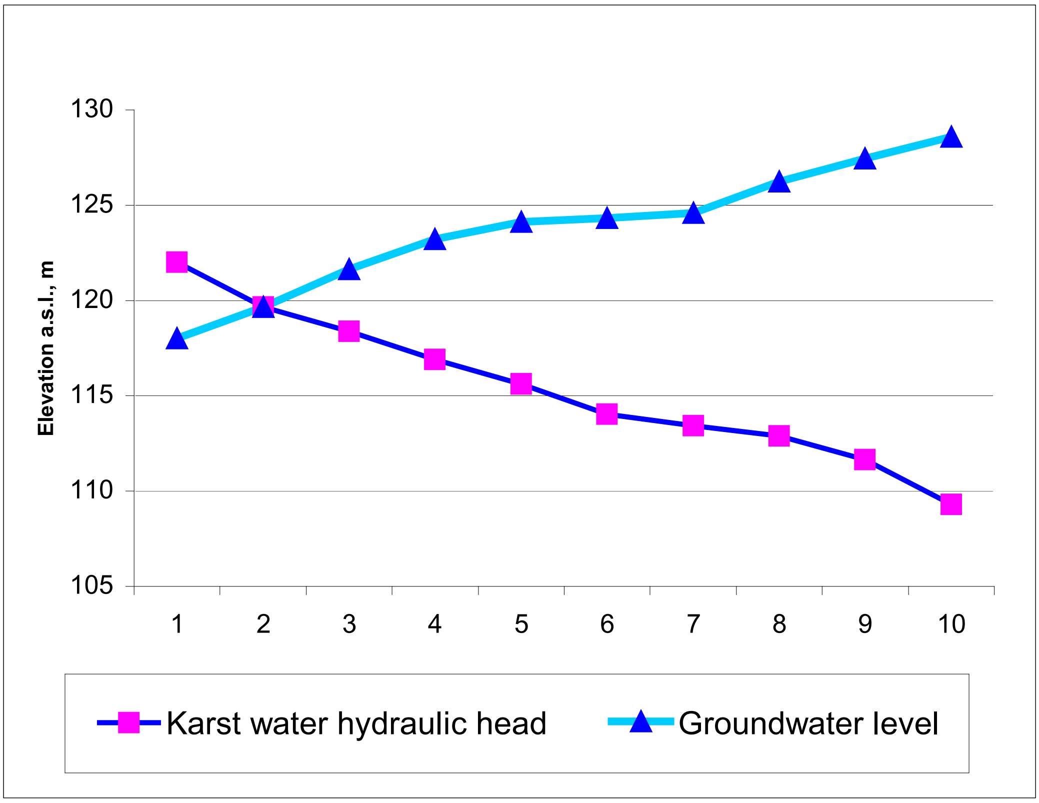

Figure 1. The nomogram for the stability coefficient calculation

The nomogram is calculated from levels obtained from groundwater monitoring and the predicted future changes in groundwater level. The nomogram shows the relationship between the stability coefficient and the positions of groundwater level and karstwater head for different time instants.

From the nomogram analysis, we may calculate the rock massif stability for any groundwater level and karst-water head. From this we can predict collapse development and, if necessary, make decisions about groundwater level changes that preserve the desired stability coefficient.

The calculations (based on the ILWIS 3.1 academic software developed in ITC, the Netherlands) resulted in the digital model of areal distribution of the adjusted stability coefficient "A" providing its values for each raster point. The map of the zoning by the adjusted stability coefficient values is created by the routine methods of Mironov (2003).

COMBINED ASSESSMENT OF KARST HAZARD BY PROBABILISTIC-STATISTICAL AND PROBABILISTIC-DETERMINISTIC METHODS

The advantages and disadvantages of both methods revealed in the course of the SUBURBIA project implementation are listed in Table 1.

Table 1. Advantages and disadvantages of the applied methods of karst hazard assessment

Probabilistic deterministic method	Probabilistic statistical method
Advantages	
The possibility of assessing the development of subsurface karst hazards; geoenvironment contamination, or hydraulic works construction The possibility of assessing karst hazards in areas with little or no data about karst sinkholes The possibility of taking into account the human impact on changing hydrogeological conditions The possibility of quantitative measurements of the mantle deposits resistance to collapse	The suitability of the method given the stochastic nature of karst processes Consideration of the entire complex of environmental conditions influencing sinkhole formation The possibility of quantitative assessment of probability of sinkhole formation, based on certain sizes and for a certain periods (for example, for the calculated operational life of a building) The possibility of quantitative risk assessment taking into account the expected risks The possibility of the quantitative assessment of the risk caused by karst and suffosion in comparison with the total risk caused by other natural hazards The possibility of the quantitative assessment of the efficiency of karst-control measures
Disadvantages	
Qualitative (verbal) characteristics of karst hazard and risk Limited possibility of applying this method for designing particular engineering structures and assessing the efficiency of karst-control measures	Limited possibility of assessing the effects of karst hazards upon subsurface development, geoenvironment contamination, or hydraulic works construction Impossibility of applying this method in the areas with little information on karst sinkholes Limited possibility of applying this method where there is intense human impact on the geological environment

A comparative analysis of both methods at the Dzerzhinsk key site revealed that sinkhole diameters calculated with the deterministic method were close to the average sinkhole diameters found from the distribution histograms of newly formed sinkholes. In addition, the most hazardous cavities of small critical dimensions proved to be confined to the recorded zones of karst funnels. The maximum possible gradient of vertical descending filtration (one of the principal criteria of assessing karst and suffosion hazard in the deterministic method) was calculated for this key site using GIS-technology. Karst/suffosion risk maps for the Dzerzhinsk site were successfully produced from both methods. The map of karst-suffosion hazard built for the Dzerzhinsk key site is shown in Figure 2.

This map distinguishes:

- the hazardous zone, where the karst hazard currently manifests itself in the form of karst sinkholes and recent sinks (coloured red);
- the potentially hazardous zone, where the possibility of sinkhole formation is low at present; but in future karst and suffosion may be sharply intensified due to a decrease in a karst-water head or (and) an increase in the ground-water level induced by human impact (coloured yellow);
- nonhazardous zone, where karst and suffosion processes are improbable, but areal surface settling caused by suffosion may occur (coloured green)

In this case, the bulk of the area interpreted by statistics as non-hazardous turns is shown to be potentially hazardous when considered using the deterministic approach. Added value was achieved by combining both geohazard risk maps thus discerning potentially hazardous zones in areas earlier indicated as non-hazardous

This collaborative investigation has shown that the joint application of probabilistic deterministic and probabilistic statistical method appears to be very efficient and promising for use in all karst-prone regions. It is applicable to both those with abundant and those lacking surface karst manifestations, and is particularly applicable to the prediction of karst hazards and risk in areas where environmental changes occur due to the impact of external sources.

The combined use of probabilistic-deterministic and probabilistic - statistical method may be evidently be very efficient upon the following studies:

- The prediction of the most probable time and place for collapse formation
- The quantitative estimation of human impact on karst hazards
- Assessment of the probability of collapse in situations where there is little reliable data on karst subsidence occurrences.

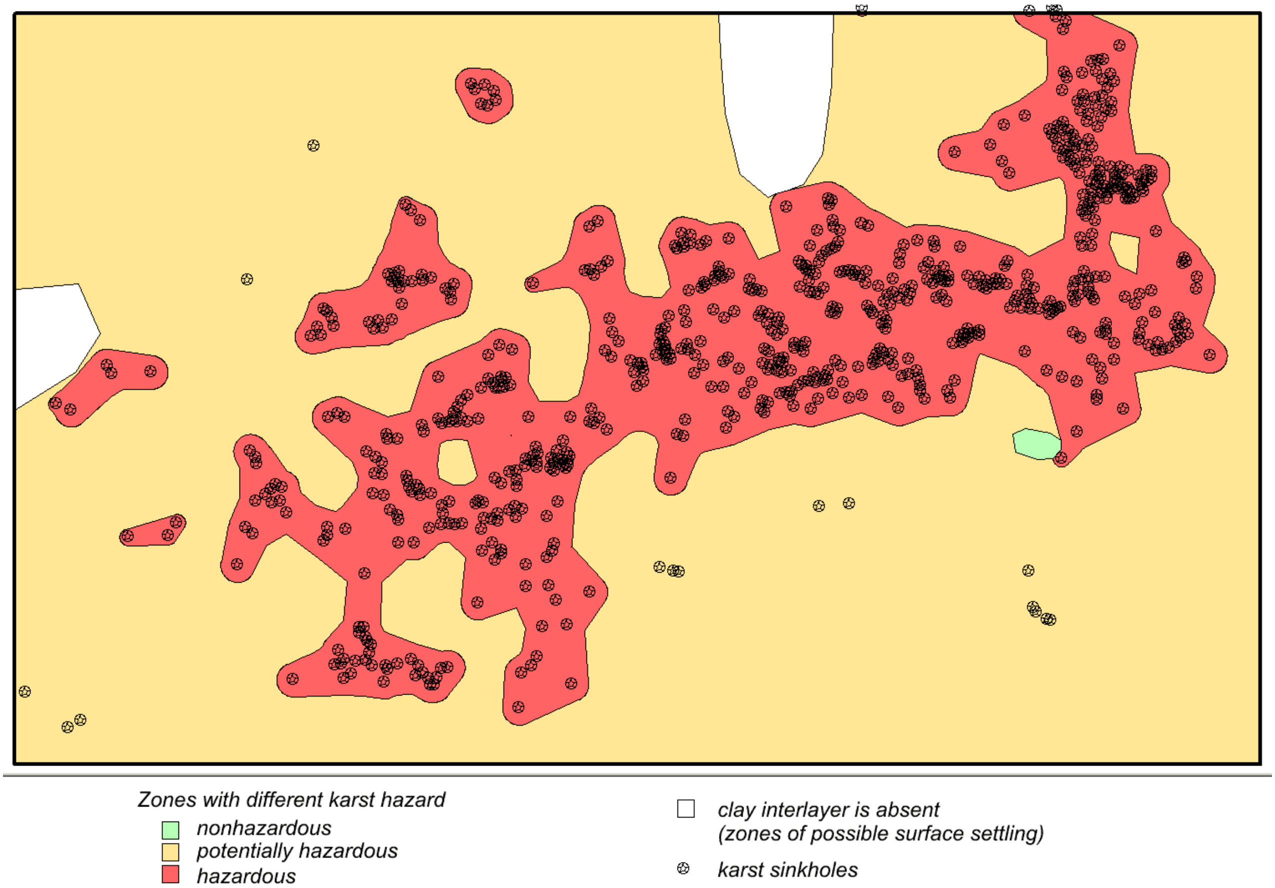

Figure 2. Zoning of the Dzerzhinsk key site by the degree of karst hazard using the probabilistic deterministic and statistical methods

CONCLUSION

The research by the SUBURBIA project found that the assessment of karst and karst-suffosion hazard should adequately reflect the stochastic character of these processes and should be based on comprehensive engineering geological study of both karstified and mantle deposits. In densely built-up urban and industrial areas where there is a significant anthropogenic load, the study of karst and karst-suffosion risk, and the prediction of karst collapses and surface settling, poses a very difficult problem, which cannot be solved using only one method. The results obtained proved that probabilistic statistical and probabilistic deterministic methods, if used in combination, appear to be the most promising methods of karst hazard assessment.

Recommendations for karst risk management were provided on the basis of GIS-produced geohazard risk maps. The recommendations include (a) strict regulation of human engineering activity; and (b) application of engineering protection measures. To prevent future damage by karst/suffosion hazards, city authorities were informed that the risks are controlled not only by former and existing geological and hydrogeological processes, but that new risks may be triggered by human interference in such processes. Excessive groundwater extraction and leakage from water-bearing pipelines into the ground-water aquifer are considered to be the main causes of such interference. Options for preventive risk-reducing measures were studied for various stages of the decision making process. For the Dzerzhinsk area regulatory recommendations for building codes could be presented. Karst/suffosion risk reduction measures may only be effective if urban planning takes into account the potential occurrence of geohazards and their management including risk prediction analysis and development of early warning systems.

In conclusion, the results on the joint Russian-Dutch SUBURBIA project are of great scientific and practical importance. They should be noted as a way of undertaking risk assessment and solving problems in karst hazard areas where there is a considerable anthropogenic load. In addition, the results obtained may be applied to the assessment of subsurface mine stability in areas which are unrelated to karst and suffosion processes.

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