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THE ENVIRONMENTAL RISK ASSESSMENT FOR DECISION SUPPORT SYSTEM FOR WATER MANAGEMENT IN THE VICINITY OF OPEN CAST MINES (DS WMVOC)

Krzysztof Kochanek[1*], Suzanne Tynan[2]

[1]Institute of Geophysics, Polish Academy of Sciences, Księcia Janusza 64, 01-452 Warszawa, Poland, e-mail: Kochanek@igf.edu.pl
[2]Tynan Environmental, 7 Hillcrest Park, Strandhill, Co. Sligo, Ireland, e-mail: stynan@tynanenvironmental.com

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Abstract. The paper presents risk assessment methodology used within a Decision Support System for Water Management in the Vicinity of Open Cast Mines (DS WMVOC). The DSS was designed to aid in decision making regarding ground and surface water resources, by two potentially conflicting stake holders in Konin county (Central Poland) that is, the County Administration and the open pit mine industry. Estimates of potential changes in groundwater head are achieved by numerical modelling of the groundwater system in which the open cast mines and receptors are located. The evaluation of spatially and time-distributed environmental risk is obtained by means of GIS supported Monte Carlo methodology. Calculations can be run in the DS WMVOC resulting maps of the risk to different receptor types, and maps of relative risk for different abstraction or dewatering scenarios, as well as an overall risk value for the region. Estimation of the magnitude of any adverse impact is related to the element (type of receptor) being impacted and a sensitivity rating has been devised for each receptor type. The risk estimation methodology implemented in the DS WMVOC was illustrated by analysis of two hypothetical groundwater management scenarios.

Keywords: DSS, GIS, risk assessment, open cast mines, groundwater modelling.

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1. Introduction

One of the objectionable side effects of activities of open pit mines is the lowering of the groundwater level due to the depression cone caused by intensive dewatering of the pits. As a

[*] Corresponding author

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consequence, the mines' dewatering system perturbs also the hydrological balance of surface waters penetrating the aquifer and furthermore limits the access to water resources of other water users in the mining area. The specific water resource management problem in question is that of the Konin coal mining region, Central Poland where there are a number of significant stakeholders in the groundwater resource. Konin County administration has responsibility for the provision and maintenance of municipal and agricultural water supply, for environmental protection and also has a role as a representative of the local community. Importantly, the administration also makes decisions on the issue of permits for water abstraction.

Open cast brown coal mining is the main industry in the Konin region. It has a large impact on the surrounding environment. Apart from causing extensive damage to the landscape, it has a significant impact on the water balance, which constitutes a negative anthropogenic impact in addition to the natural changes in water environment observed lately in low-land Poland. This impact is largely due to the dewatering wells installed in open cast mines in order to enable safe and efficient working of the heavy machinery required to work the mines. Modelling work by Warsaw University of Technology (Nawalany *et al.* 1998) has shown that the cone of depression created by mine dewatering is one of the main reasons for a drop in surface water level in a group of nearby lakes (see map – Fig. 1) and for decreased availability of water in domestic wells and irrigation systems. The area of impact also includes Goplo Lake, which is considered to be particularly important in terms of Polish cultural heritage, as well being a valuable natural resource. In particularly disadvantageous hydrological condi-

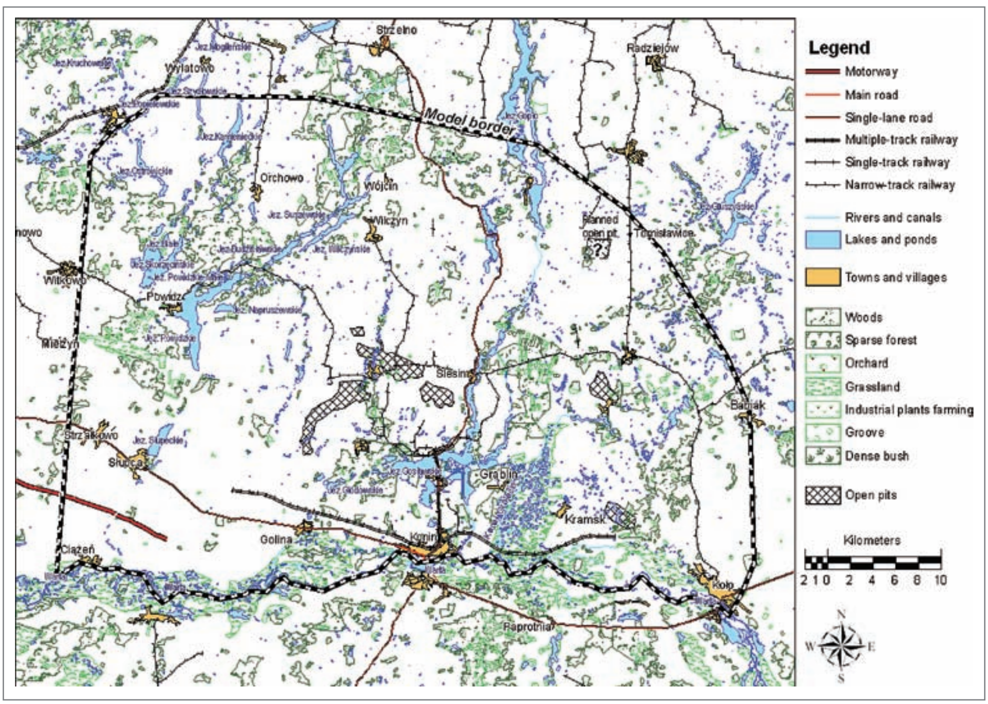

Fig. 1. Map of modelled area

tions, such as a prolonged drought, the groundwater deficit can also cause diminishing crop yields in the area. Land subsidence due to long term dewatering of geological formations has also been observed.

The common exploitation of the regional aquifers by various stakeholders, on the one hand by the mines, whose principal objective is dewatering the pits at the lowest possible cost, and on the other hand by other abstractors and the environment, as represented by the Konin county administration, results in significant potential for conflict. Essentially, these conflicting hydrological demands already exist, and will become more crucial as implementation of the Water Framework Directive proceeds, but appropriate hydrological/hydrogeological tools to support decision making to avoid and resolve these conflicts did not.

The main objective of this work is to present a risk analysis methodology within the framework of a decision support tool, a **D**ecision **S**upport System for **W**ater **M**anagement in the **V**icinity of **O**pen **C**ast Mines (DS WMVOC), which will facilitate the effective water management decisions to be taken. The DSS platform integrates risk analysis, decision making algorithms and groundwater modelling in a Geographical Information System (GIS) environment. It is important to point that the water management problems briefly described above as well as the proposed solutions do not consider insufficient quality but quantity (scarcity) of groundwater resources in the vicinity of mining area, which is a problem often neglected. In case of Konin mines, water quality is not an issue, because water pumped out by dewatering wells is of superb quality: a part of it is bottled as drinking water but the lion's share is diverted straight to the nearby canals or lakes. On the other hand, the majority of authors dealing with risk analysis concentrate mostly on quality of groundwater (e.g. Ducci 1999; Valentukeviciene and Rimeika 2005; Werz and Hötzl 2007), therefore, an unique approach of groundwater scarcity risk evaluation presented in this paper and implemented in the DSS was highly appraised both by mines' management and local authority of Konin County who face the water scarcity problems on every-day basis. Currently a new version of the DS WMVOC is being prepared with the use of new data and the next generation GIS programming languages and before soon the pilot edition of the software will be implemented by both institutions.

This paper is a further development of work by Tynan and Kochanek (2002) and for brevity focuses on one of the functionalities implemented in the DS WMVOC only, i.e. the risk analysis tool, rather than on decision and modelling modules which both are described in detail in Kochanek (2003). The risk estimation methodology implemented in the DS WMVOC is illustrated by a case study which considers the analysis of two hypothetical groundwater management scenarios.

2. Water management problems in the vicinity of open cast mines

Effective groundwater resource management in the vicinity of open cast mines entails the multiple and potentially conflicting aims of protecting groundwater resources, and connected surface waters and dependent ecosystems, while also managing the usage demands imposed by various groundwater users. Achieving these aims requires therefore, an understanding of the combined effects of outputs from, and inputs to the groundwater system, and some measurement of the impact of these effects on associated ecosystems.

This approach of treating groundwater in an integrated manner with surface water systems, and protection of ground and surface waters for their ecological as well as resource value is becoming mandatory across the EU as member states adopt the provisions of the EU Water Framework Directive (2000/60/EEC) and 'daughter' Groundwater Directive (2006/118/EC). Since joining the European Union (EU) in 2004 Poland has been moving towards implementing EU standards with respect to sustainable water resource management and protection. The Water Framework Directive requires *inter alia* that 'good' status for groundwaters and surface waters not only qualitative but also quantitative, be achieved by the end of 2015. The prescribed process of implementing the directive includes characterisation of all water bodies, and assessment of their risk of failing to achieve good status. Good status includes quantitative and qualitative parameters, and in the case of groundwater includes the requirement that the status of the groundwater body does not cause a connected surface water body, or groundwater dependent ecosystem to fail to achieve good status. Intrinsic to this risk assessment is the identification of pressures, and analysis of the impacts of these pressures on the system. Managing those pressures which have been identified, during the preliminary or further characterisation phases, as resulting in a risk of a water body failing to achieve good status is mandatory, and is achieved via a programme of measures. The purpose of the programme of measures is to result in the achievement of good status by each water body by 2015.

Effective management of water resources for public supply requires that the future impacts of current abstraction, as well as the consequences of changes to the groundwater system in the future (for example the natural changes in groundwater regime, addition of a new municipal supply well, or dewatering associated with the movement of open cast mining), will be predicted. In other words, decision makers face the difficult problem of *prediction* of the pressures impact (at least with known or estimated probability) on the *unpredictable* groundwater system. The decision makers usually find it difficult to accept the fact that one often cannot obtain a 'one-number result' and at the same time fully eliminate environmental uncertainty but only minimise it by proper use of modelling, uncertainty and risk analysis techniques (critical comments on difficult co-operation and misunderstandings between scientists and decision makers was presented by Liu *et al*. 2008 as well as by Sakalauskas and Zavadskas 2009, and Vlasenko and Kozlov 2009). Consequently, the knowledge of probability or risk of environmental adversity would allow effective decisions to be taken by administrators about the optimum strategy for water resource management while also providing tools to support implementation of a number of the requirements of the Water Framework Directive.

There are at least a few definitions of environmental risk available in the literature which vary depending of the purpose of risk evaluation; for instance Belousova (2006) defines *hazard* and *risk* as separate concepts where the previous concerns the state of nature that threatens the human's well-being and the latter reflects the diverse between nature and society. In this paper however, risk analysis methodologies have as a basis the concept that risk may be defined as the probability of occurrence of an adverse impact multiplied by a measure of the magnitude of the consequence of that impact (e.g. Ganoulis 1994, and Singh *et al.* 2007: 669). In hydrological and hydrogeological terms however, both components are difficult to estimate. Conceptually, and in practice, this definition can be utilized effectively in the context of the requirements of groundwater management provided that the information available about the environment and processes enables the evaluation of both the probability and magnitude. Integrated with groundwater modelling, risk analysis can provide a powerful decision support tool for achieving the type of resource management outlined above and required under the Water Framework Directive.

3. Risk analysis framework and research methodology

The process of analysing risk to the environment can be described in terms of risk assessment which consists of two components: Risk Estimation and Risk Evaluation.

- Risk Estimation. The U.K. Department of Environment (1995) defined five stages leading up to risk estimation. These are: Description of the proposed activity; Hazard identification; Identification of consequences; Estimation of magnitude of consequences; and eventually: Estimation of probability of consequences.
- Risk evaluation, which is concerned with determining the significance of the estimated risks to those affected.

Risk management is then the process of implementing decisions regarding accepting or altering the defined risks.

In the context of the Konin mining region, the process of risk estimation is supported by this work, but risk evaluation and management are the responsibility of the end-users, that is the Konin County Administration and the Mine Management. Risk estimation is an iterative process and must be carried out for all possible scenarios of the potential risk, taking into account the uncertainty of every aspect having impact on the analysis. Based on this information, the risk evaluators and managers can choose the optimal solution to the problem. Additionally, risk should be considered as a spatially varying phenomenon and, therefore, its analysis should take into account the spatial variability of the risk as well as it's magnitude (Chen *et al*. 2003).

Key elements of the risk estimation process are:

1. Collecting information and data which *may* be particularly useful in a decision analysis process; selecting information that *will* be used for a decision process (Kofi Asante-Duah 1993).
2. Model appropriateness or correctness, which applies to the risk model itself and to any component models. The model must be able to represent the salient features of the system in question and validation calculations should be carried out to check the accuracy of model results.
3. Recognition of uncertainty within the risk model and any component models. All models include elements about which there is a lack of knowledge, and about which assumptions are made, introducing uncertainty. Uncertainty arises from the form of, or incompleteness in mathematical functions used to represent elements of the risk estimation process. Parameter uncertainty arises from possible errors in the values assigned (often due to lack of data) or in probability density functions used to estimate errors in these parameters. As a result, in the proposed risk analysis method the groundwater system is regarded as 'grey' one, i.e. basing on a number of uncertain factors (Yeh and

Chen 2004; Zhang and Yu 2007) which requires special approach to the groundwater flow modelling and the statistical interpretation of results. Specifically, in groundwater scenarios, uncertainty arises from :

- Errors in the values of derived system parameters such as aquifer properties or system geometry caused by insufficient data or errors in the data.
- Measurement errors in input data or their inaccurate interpretation or extrapolation. This is often due to the high cost of acquisition and verification of the original data.
- Simplification of the geological and hydrogeological situation in order to enable its implementation in computerised numerical models. Simplifications are unavoidable because of the limitations of numerical groundwater flow models, such as being confined to two dimensional layer structures and simple geometric (rectangular or triangular) approximations of irregular elements of nature (Lerche 1997).

4. Estimation of statistical probabilities (Kite 1988; Montgomery and Runger 1999) which is coupled with.
5. The identification of which parameters are probabilistic and which are deterministic.
6. Assessment of what constitutes 'harm' to a given groundwater resource, and estimation of the magnitude of that harm.

4. Risk estimation methodology implemented in the DSS

A generic methodology for the estimation of risk from open pit mine dewatering has been developed. The generic methodology would allow the application of this methodology to other geographical areas, and could facilitate the implementation of the objectives of the Water Framework Directive in other open cast mining areas. Within the decision support system, it is implemented at a level which is suitable for non expert users, that is, the County Administration and the open cast mine Management. A high importance has been attached to creating an effective but user friendly risk estimation system for the end user (Fig. 2). The methodology implemented in the DS WMVOC comprises algorithms and numerical methods which are both reliable and have a relatively high robustness to user errors. There are core elements of the DSS which can only be implemented by experts, but once these are integrated into the DSS, the DS WMVOC functions as a 'black box' with respect to these elements.

Generic methodology

i) Hazard identification

The feature of the mining operations that could lead to adverse impact is the dewatering process. The dewatering process, by pumping water from the surrounding groundwater body, imposes stresses on the system, which change the distribution of hydraulic head values. The hazard is described in terms of change in hydraulic head values. It constitutes a hazard that can potentially affect a number of different receptor types. Other hazards that can be added to the regional groundwater regime are new water abstraction wells and/or new hydrological regime affecting potentially the groundwater head.

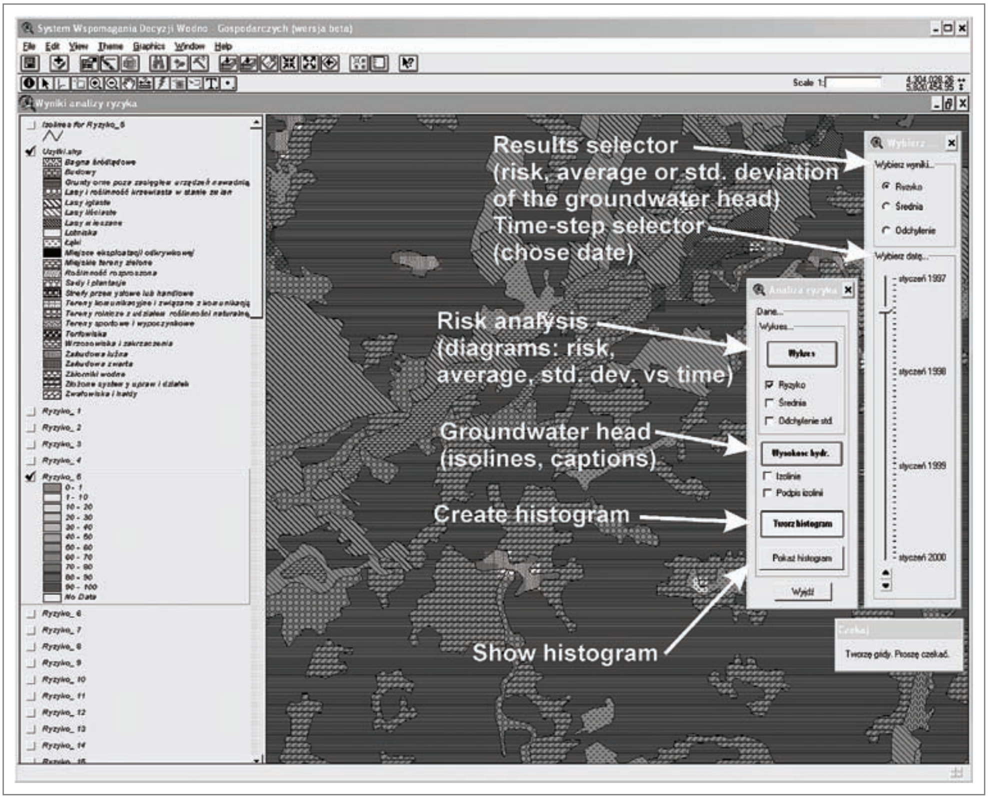

Fig. 2. The Decision Support System – the interface of risk analysis module

ii) Pathway identification

The pathway through which this hazard is propagated towards a receptor is the groundwater flow system, the hydraulics of which are described by the physical equations governing groundwater flow. Prediction of the distribution of hydraulic heads across the region is carried out by numerical modelling of the groundwater flow system using the standard software, MODFLOW. MODFLOW has been verified and validated through extensive use by groundwater modellers and the previous modelling of the mine area verifies that the equations and numerical methods are appropriate for modelling the Konin groundwater system. Due to the strong connection between the aquifers and the lakes within the modelled area, the lakes were implemented in the groundwater model since their water surface is expected to reflect the dynamics of the upper groundwater head. This approach to modelling lake levels was used successfully by Wollschläger *et al.* (2007). The calibrated groundwater model can be run in predictive, steady state or transient mode, for hypothetical dewatering scenarios. Run in this fashion, the model can produce a single deterministic estimate of hydraulic head for each element of the grid for each time step. The conceptual model of the groundwater flow system, implemented in MODFLOW, forms the core of the decision support system. The quality of the modelling of this pathway within MODFLOW is critical to the accuracy of the results of the risk estimation.

iii) Identification of consequences

The receiving environment in the context of mine dewatering, or additional abstraction points, comprises ground and surface water features. Although the groundwater system as a whole could be regarded as a receiving environment, only certain resources, that is, lakes and municipal wells and groundwater linked ecosystems (such as forestry, meadows, some species of cereal) have been chosen as receptors, due to their importance to the County administration in terms of water management. Where these targets are in hydraulic connection with the aquifer system from which water is being abstracted by mine dewatering, hydraulic head values may change, constituting a risk, and harm where that resource is negatively impacted. To cope with the potential spatial diversity of consequences, GIS techniques are used in the DS WMVOC. Grid analysis techniques are used to group spatially distributed receptors of a given type, and to represent and analyse spatially varying hydraulic head values in the GIS environment in order to facilitate estimation of the magnitude of the consequences.

iv) Estimation of the magnitude of the consequences

The idea of a critical threshold has been adopted through which to estimate the magnitude of consequences or harm to receptor resources. The form of the hazard which is considered important in the case of municipal wells is a drop in hydraulic head below the elevation of the well bottom or well screen, i.e. its critical threshold. This risk could be described in terms of monetary value, since there is a cost involved for the County administration in providing an alternative water supply. In the case of private wells, an impacted owner may take another abstractor to court to settle the costs of replacement. The form of the hazard which is considered important in the case of lakes is the change in water level which will have a negative impact on the ecology of the lake. There has been little work done in the region on the relationship between lake hydrology and associated ecology. Nevertheless, the approach taken is one consistent with the Water Framework Directive referred to above. Current work in Poland and Ireland on best practice of implementation of the Directive focuses on the concept of exceedance of a critical threshold in the definition of reference conditions for lake ecosystems. That is, damage to a given ecotype would occur, when certain threshold values are exceeded (level moves above or below depending on a threshold's meaning) for longer than a specified length of time. Arbitrary thresholds have been defined for Konin to illustrate the methodology.

v) Evaluation of probability

Potential sources of probabilistic input

Within the groundwater model of the Konin region there are a number of sources of uncertainty (including those listed in Table 1) whose difficulty of estimation varies.

In theory, a distribution (probability distribution function) of values based on statistical analysis of existing observed values, and/or taken from the literature, is prepared for each of these uncertain variables. Random number generation from a characteristic distribution function is then used to generate a probabilistic set of input data for the groundwater flow model for any of these variables within a certain range of allowable values. In practice, however, the hydrogeological parameters of hydraulic conductivity and recharge are the

Table 1. Sources of uncertainty in the groundwater model

Source of uncertainty	Difficulty of estimation
Geological structures	Difficult/impossible
Hydrogeological parameters and their spatial and time distributions	Difficult
Groundwater head (model's initial conditions)	Average to difficult
Hydrological data	Relatively easy
Meteorological data	Relatively difficult
Dewatering well yields	Easy

two key variables that are used, due to their relative sensitivity (Krause *et al*. 2007) and thus, their perceived importance in modelling scenarios. In this case theoretical distributions of recharge and hydraulic conductivity have been prepared. In addition a statistical model of recharge, based on analysis of a long rainfall series combined with hydrometeorological data has been prepared. This resulting distribution includes a measure of both uncertainty and variability in time and space.

Producing probabilistic output from the regional groundwater model

A Monte Carlo (MC) type procedure is then run (Fishman 1999; Gentle 1998). Use of MC simulations is well established in groundwater flow simulation. Due to the lack of knowledge of the detailed geometry of geological layers and exact hydrogeological conditions, it is very hard to derive formulae (if at all) for estimation of groundwater management risk. Therefore, the MC techniques seem to be the only effective way of risk and uncertainty estimation of the compound phenomena as groundwater flow.

The MC procedure replaces a single deterministic value estimate of input to the groundwater model with a random variable drawn from the probability density functions of chosen parameters. The model run is iterated with new values of the random variable each time. The results of the calculations for each MC loop iteration, each model time-step and each finite-difference cell are processed and stored to constitute the basis for the statistical analysis of the groundwater level.

vi) Estimation of risk

GIS datasets of the receptor resource locations and critical threshold values can be combined with any one of the hydraulic head probability parameter grids. Since the lakes are represented as an integral part of the MODFLOW model, their calculated hydraulic head value represent the lake surface level which, due to limitations in the groundwater model, may vary across the area of the lake. The dataset of the MC groundwater head realisations (e.g. 90% probability head value) can be intersected with the threshold values to give the probability of exceedance of the critical threshold where it occurs. Similarly the different probability functions can be intersected with the well threshold values to give the chosen probability of hydraulic head dropping below the critical threshold, where this occurs. Since the determination of the critical threshold is difficult and error prone the users are advised to calculate risk for several scenarios (related to the same threshold), compare results and choose the optimal solution.

5. Implementation of the risk methodology in the decision support system

The methodology described in Section 3 *Risk Estimation Methodology Implemented in the DSS* does not require the end user to have any knowledge or experience of working with groundwater models. The calibrated MODFLOW model is embedded in a user-friendly GIS application. The hydrogeological parameters of the model cannot be edited by the user but only by an experienced hydrogeologist (e.g. a mine employee). Pre-planned dewatering schedules, comprising dewatering wells with pre-determined abstraction rates are set up by the mine management as part of the on going extraction planning. In order to test the impact of these dewatering schedules the DSS users in mine management can input 'What if?' scenarios by entering new dewatering wells (see Fig. 3) and choose a recharge scenario reflecting dry, average or wet season. They then run a risk analysis procedure which will use either a recharge or hydraulic conductivity probabilistic input to the model via the Monte Carlo type algorithm, in a black-box context from the users' point of view.

Being the result of a random input, the modelled groundwater head should be such that it can be described by statistical methods. However, MC simulation experiments verified that the groundwater head result exhibited large random variability in both time and space, and therefore groundwater head could not be described by a single, or even a number of probability distribution functions (Kochanek 2003). Therefore, in the DS WMVOC the risk analysis is based on spatially varying frequency histograms that can be automatically drawn

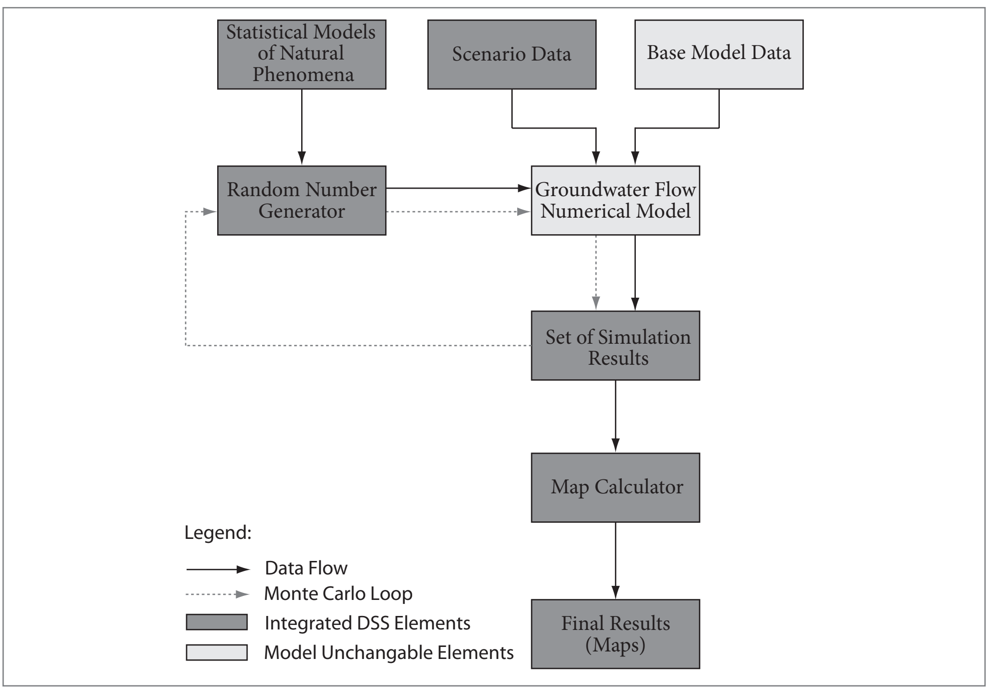

Fig. 3. Algorithm of Monte Carlo risk assessment analysis implemented in the DSS

for a selected position and period covered by the model. Additionally, for each time-step the DS WMVOC calculates expected values of the groundwater head via the same histogram method. The standard deviation from the mean is also calculated for a given location or time step, which can then be transformed into a GIS raster dataset geo-referenced to the receptor data and visualised in the DS WMVOC in the form of maps. Comparison with target resources is run and calculations carried out to estimate risk. A risk map is output to the user. Alternatively the user may use a sensitivity rating, by changing the input, e.g. well yields or recharge scenario. The resulting raster and vector maps can be also processed by GIS software.

6. Case study

The case study considers a hypothetical water management scenario based on data provided by the Konin Open Cast Mines on a given mine dewatering scenario. It also assumes that a new abstraction well of significant yield, 2,000 m^3/d, intended to supply drinking water to the town of Wilczyn, will be installed south of the Wilczyńskie Lake (Fig. 4). The question which requires answering is the following: 'in what way and by how much would the proposed abstraction well influence the risk to groundwater levels in the surrounding area and in particular in Wilczyńskie Lake?' In order to model the hydrological situation posing the greatest threat, the scenario was based on the data for the months with the lowest average groundwater level, generally December and January. This is due to relatively low

Fig. 4. The illustration of the case study, scenario 2

precipitation, as well as to snow coverage limiting permeability, and results in the annual minimum aquifer recharge. Since the upper Quaternary aquifers have the most connection to the receptors in question, the risk analysis will be confined to assessing changes to water level in these upper aquifers.

Monte Carlo simulations for two scenarios were carried out, with every realisation of groundwater head for both scenarios calculated using the model implemented in the MODFLOW modelling software. The two scenarios were: (1) Reflecting the situation arising from a typical mine dewatering scenario but without the proposed 2,000 m^3/d abstraction well and (2) the same mine dewatering scenario, with the addition of the proposed abstraction well. The results of each scenario were compared with receptor specific critical thresholds, and also compared with one another, in order to answer the question posed about the changes in risk to groundwater levels and particularly in Wilczyńskie Lake.

6.1. Scenario 1

Scenario one is the baseline reference for scenario two. It is assumed that the risk of a drop in groundwater levels calculated for scenario one results solely from the mine dewatering schedule, which is required to enable lignite excavation according to the planned extraction schedule. Any additional abstraction of significant yield can presumably only worsen the situation in the groundwater environment, provided that the other factors affecting groundwater flow stay the same.

In the groundwater model incorporated in the risk analysis mechanism of the DSS the mine dewatering wells penetrate mostly the second, lower Tertiary aquifer. However, the findings of Nawalany *et al.* (1998) suggest that there are local spots of relatively good hydrological connection with the upper Quaternary aquifers. Therefore, the cone of depression created by the mine dewatering directly influences the upper groundwater levels in the Quaternary aquifer (penetrated by shallow private wells and by the roots of some plants), as well as surface water levels in lakes and rivers.

The calculations for scenario one indicated that the groundwater head in the vicinity of the Wilczyńskie Lake is higher than the critical thresholds and is stable in terms of variability and thus poses no threat to the environment or shallow wells. The critical thresholds are receptor specific. In the case of shallow private and public wells, it is the bottom of the well screen. Critical thresholds for different vegetation types (e.g. coniferous and deciduous forestry, meadow, different crop types) were also set, based on information relating to rooting depths. The distance from the mines (ca. 15 km) appears to render the influence of the dewatering wells on the groundwater in the lake's vicinity negligible.

However, the risk of a drop in water level below the critical threshold in the Wilczyńskie Lake itself is very high at 70–100%. The risk was calculated as the probability of dropping below the critical threshold, i.e. the proportion of the results of the MC simulations dropping below the critical threshold. This means that in this case almost every water level realisation, out of 2,000 Monte Carlo simulation results, is below the critical stage based on historical measurements of the lake. The critical threshold value was calculated as the average stage in the lake over the period July 1992 to March 2003. This is in part because scenario one assumes minimum recharge conditions, and therefore the most adverse hydrogeological conditions, to which surface waters are particularly sensitive. Also, the critical threshold is based on an average stage value, which includes seasons when the water level was high, thus increasing the average value.

The results of the risk analysis for scenario one imply that stakeholders in the County Administration and the mining company should concentrate particularly on monitoring surface waters (lakes in particularly) when planning any investment affecting the groundwater level. Indeed, according to the unpublished historical measurements, the water surface in Wilczyńskie Lake has dropped by ca. 2.75 m within recent years, probably due to dewatering of nearby open pits. The results of scenario one will be treated as the baseline for scenario two.

6.2. Scenario 2

The second scenario assumes that an abstraction well yielding 2,000 m^3/d will be installed near Wilczyńskie Lake to supply drinking water to the nearby town of Wilczyn (see Fig. 4), while the mine dewatering schedule continues as in scenario one. Due to its large required yield, the well will be abstracting water from both the lower Tertiary and upper Quaternary aquifers. Given the locally high connectivity between the Tertiary and Quaternary aquifers and the dominant influence of the Quaternary water levels on the receptors, the results described in this section consider only the upper water level in the Quaternary aquifer. The geometry, boundary and initial conditions, parameters, recharge and any other features of the model remain the same as in Scenario one. The differences in results between scenario one and two will be discussed here, rather than the absolute values of the indicators.

Generally, the average groundwater head in the Quaternary aquifer dropped, when the additional abstraction well was included in the model, however, the difference between scenario one and two is surprisingly small outside the lake itself (Fig. 5). The greatest difference in the water levels can be observed in Wilczyńskie Lake and, although the difference in the drop in water level is a maximum of 0.5 m when compared to the scenario 1, in a relatively shallow lake such as the Wilczyńskie Lake, this could result in a significant impact. This has an even higher significance when translated into absolute values, as the results of scenario two indicate that this equates to a drop of the water surface in the lake by ca. 2 m below the critical threshold.

The standard deviation of the results of the MC simulations was calculated for each of the two scenarios, for each of the grid squares of the area modelled, as a measure of groundwater head stability. A considerable change is observed in the groundwater head stability (standard deviation) of scenario two, in comparison to baseline scenario one. The installation of the proposed abstraction well results in a significantly greater spatial variability in groundwater head values, with the greatest difference in standard deviation between the baseline scenario and scenario two occurring in the lake itself (Fig. 6). The differences in the standard deviations of the water level between the two scenarios ranges from 1.3 m at the outer margin of the modelled area to 2.0 m in the lake itself.

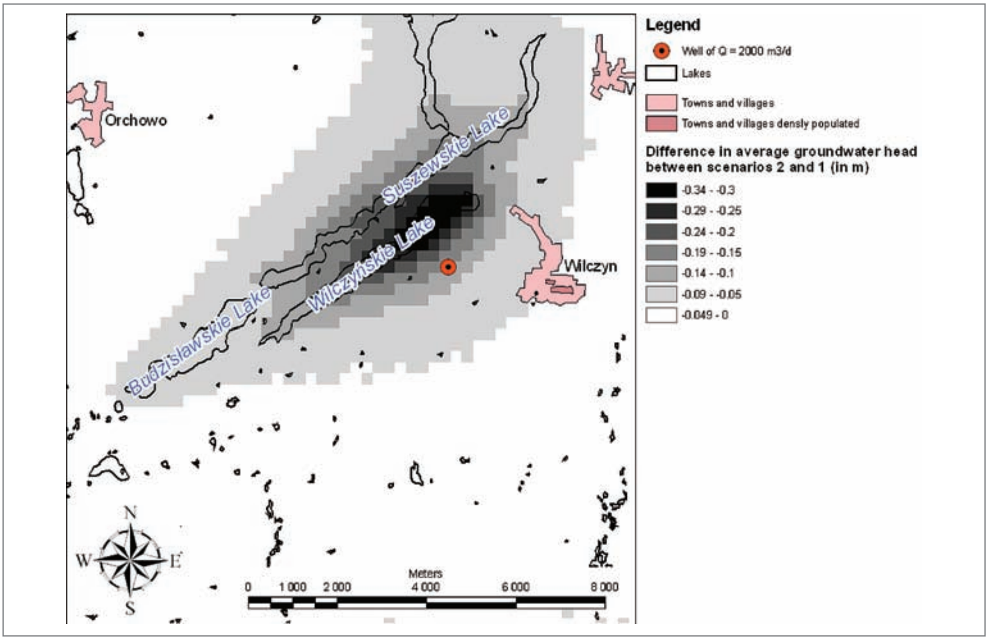

Fig. 5. Difference in average groundwater head between scenarios 2 and 1 (in meters)

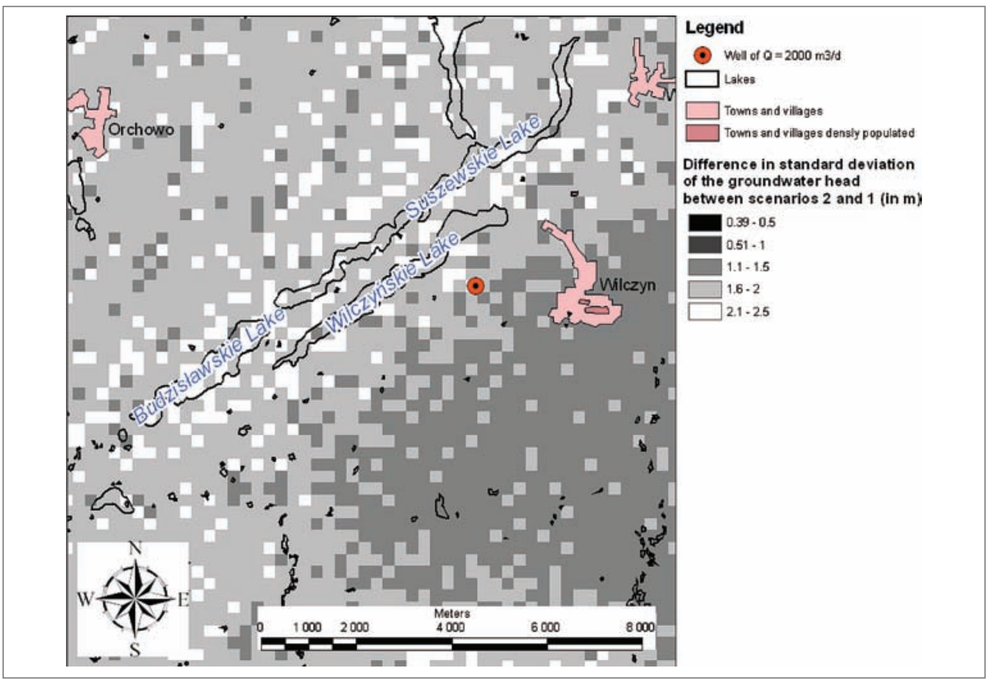

Fig. 6. Difference between standard deviation of the groundwater head between scenarios 2 and 1 (in meters)

The map of the differences between risk estimated for scenario two and the baseline scenario shows that the probability of a fall in the groundwater head below the receptor specific critical thresholds in the vicinity of the proposed abstraction well remains negligible or even equal to zero. The risk was calculated as the probability of dropping below the critical threshold, i.e. the proportion of the results of the MC simulations dropping below the critical threshold. The only noticeably difference is observed in Wilczyńskie Lake, where the risk rose by a range of values (0.5–15% in comparison with scenario one) across the lake area (Fig. 7). This means that the stakeholders can be almost 100% sure that the abstraction of 2,000 m^3 water per day from a proposed well near the lake, in conjunction with the baseline mine dewatering schedule, will definitely result in a drop of the lake's water level below the critical threshold. Therefore, the stakeholders should re-assess the assumptions of the project and either consider another location for the well or a reduction in the proposed yield.

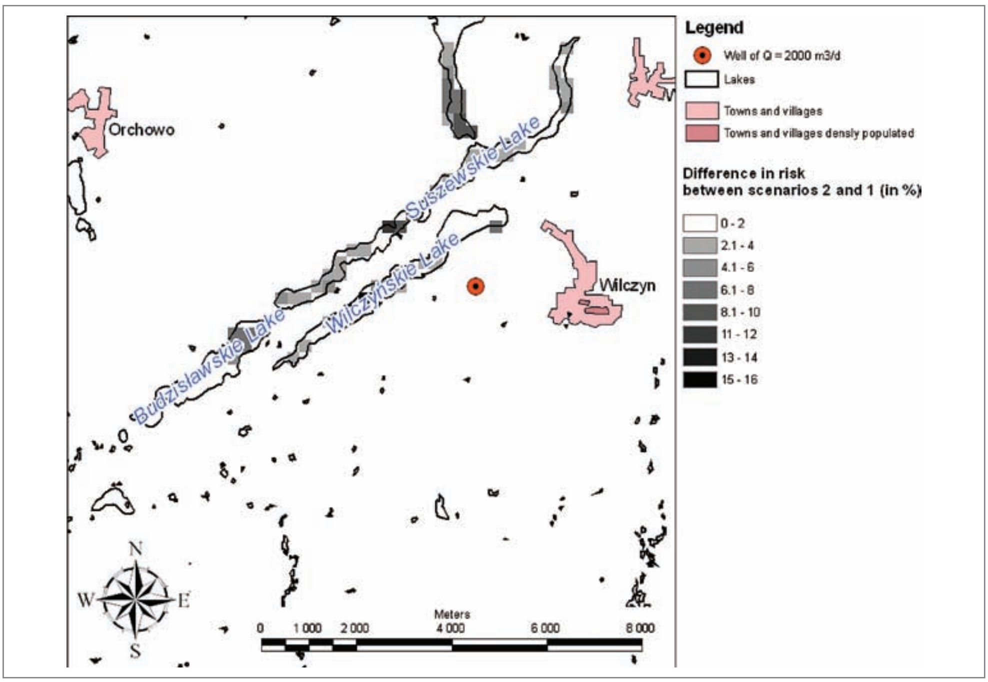

Fig. 7. Difference in potential risk of the groundwater head between scenarios 2 nd 1 (in %)

7. Conclusion

The purpose of this paper was to present the groundwater risk evaluation methodology within the framework of a decision support tool, a **D**ecision **S**upport System for **W**ater **M**anagement in the **V**icinity of **O**pen **C**ast Mines (DS WMVOC). The integration of risk analysis methodologies into the groundwater resource management process is a means of assisting administrators/stakeholders in the decision-making process. Risk analysis can provide a more objective framework for decisions which are reached in the context of a numerical model which is being used to represent the hydrological regime. In the instance of the Konin open cast coal mining area, risk analysis implemented in the DS WMVOC provides user-friendly tools for objectively assessing the relative impacts of abstraction and/or mine dewatering scenarios on water resource receptors. It supplements the simple predictive model and provides a means of resolving the demands of stakeholders, whether they represent the open cast mines, the County Administration, local abstractors or ecological habitats.

The DSS can be used on a continuing basis, as mining progresses or other changes to the hydrological regime occur. The results of the decision making tools are published in the condensed form of maps, thus they are simple to interpret and compare with outcomes obtained for other scenarios. To make the risk interpretation even simpler, the number of result maps is limited to maps of groundwater head, its variability (standard deviation) and risk. However, as the hypothetical case study based on a comparison of two scenarios revealed, these three maps are sufficient to enable a decision maker to estimate the risk of a negative impact on the groundwater and surface water environment resulting from specific interventions in the groundwater system.

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RIZIKOS APLINKAI VERTINIMAS NAUDOJANT NETOLI ATVIRŲJŲ KASYKLŲ ESANČIŲ VANDENS IŠTEKLIŲ VALDYMO SPRENDIMŲ PARAMOS SISTEMĄ

K. Kochanek, S. Tynan

Santrauka. Straipsnyje pateikiama rizikos vertinimo metodika, naudojama netoli atvirųjų kasyklų esančių vandens išteklių valdymo sprendimų paramos sistemoje. Sprendimų paramos sistema (SPS) buvo sukurta siekiant priimti naudingus sprendimus, priešingus interesų turinčioms šalims, dėl požeminio ir paviršinio vandens išteklių. Konino regione (Vidurio Lenkija) konfliktuojančios pusės yra apskrities administracija ir atvirų kasyklų pramonės įmonė. Galimi požeminio vandens lygio pokyčiai įvertinami atliekant skaitmeninį požeminio vandens sistemos modeliavimą. Rizika aplinkai erdvės ir laiko požiūriu vertinama taikant GIS ir Monte Karlo metodologiją. Skaičiuojant sprendimų paramos sistema sudaro specialius rizikos žemėlapius, atlieka bendrą rizikos įvertinimą regione. Sprendimų paramos sistemoje įdiegta rizikos vertinimo metodologija pritaikyta analizuoti du hipotetinius požeminio vandens valdymo scenarijus.

Reikšminiai žodžiai: sprendimų paramos sistema (SPS), GIS, rizikos įvertinimas, atvirosios kasyklos, požeminio vandens modeliavimas.

Krzysztof KOCHANEK is a researcher in Institute of Geophysics, Polish Academy of Sciences. His main fields of interest are extreme hydrological events and groundwater modelling. He is also interested in GIS techniques, and database programming and their implementation in hydrological case studies. Besides, he takes part in engineering projects concerning water resources management and occasionally teaches at the university.

Suzanne TYNAN is a consultant hydrogeologist and environmental scientist. She is the director of Tynan Environmental, Environmental and Hydrogeological Consulting. Her research interests include hydro-ecology, specifically in the areas of karst groundwater dependent wetlands and peat ecosystem hydrology, and the integration of these specialisations into environmental impact assessment.