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Proposal for the integrated management of mineral water deposits

Introduction

The term "mineral water" has different meanings in various industries. Mineral water in hydrogeological terms is groundwater with the total-dissolved-solids content of at least 1000 mg/dm^3. However, it is a common term used for bottled groundwater (Dowgiałło et al. 2002) or water with mineralization from 1 to 35 g/dm^3 (Pazdro and Kozerski 1990). In legal terms, water, according to the Regulation of the Minister of Health of March 31, 2011 on natural mineral water, spring water and table water should meet the following criteria: the concentration of potentially toxic elements of natural origin, maximum permissible concentration of natural mineral components, constant chemical composition, and other properties (within natural fluctuations) (RMH 2011). If a groundwater contains more than 1000 mg/dm^3 or contains the specific components listed in the Geological and Mining Law (GML) of 2011, it is classified as a mineral water (curative waters are classified as minerals) (GML 2011).

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Waters with increased mineralization (above 1000 mg/dm^3) are found in formations older than Quaternary throughout Poland. However, their exploitation and bottling are carried out in selected regions, which is mainly due to the abundance of water meeting the abovementioned requirements in the respective areas. Water bottling plants are located in the Carpathian Mountains, the Sudetes and in selected regions of the Polish Lowlands (Ciechocinek, Busko Zdrój, and Konstancin).

Mineral water resources are mostly non-renewable resources, which, because of their great importance, should be protected. This can be achieved by, among others, proper management of mineral water deposits. In Poland, mineral (curative) waters are treated as minerals (classified as raw materials). Hence, the term "mineral water deposits" is being used. According to the GML, "a mineral deposit is a natural accumulation of minerals, rocks and other substances that through excavation can bring economic benefits". The provisions of this Act were established for solid, liquid, and gas minerals; the use of the term "deposits" in relation to groundwater is controversial among hydrogeologists. The term "deposit" has been used in Poland for groundwater classified as minerals since the 1950s (Ciężkowski et al. 2004). However, this is not a formal definition and is used by analogy to other mineral deposits (Sokołowski et al. 2015).

The stages in the life of a mineral deposit, including groundwater deposit, are as follows: prospecting, exploration, development, and exploitation. Integrated deposit management is the key to a balanced and successful economic process of making full use of the resources in the deposit. Deposit management is used, among others, in the oil industry, where proper preparation and execution of crude oil and natural gas production is crucial for oil and gas companies. The concept of hydrocarbon reservoir management was introduced in the 1970s and means the use of all possible means (human, technical, technological, and organizational) to maximize the profits from the exploitation of the deposit while minimizing capital expenditure and operating costs and maximizing the depletion rate. The management of hydrocarbon deposits is a long-term and complex process. It starts with prospecting, through to exploratory work, deposit exploitation, ending with the liquidation and reclamation of the post-mining area. Achieving economic success and optimum use of the deposit's resources is possible thanks to the application of an integrated deposit management system (Satter et al. 1994; Satter and Thakur 1994; Thakur 1990, 1996).

The reservoir management concept has been developed since the 1990s (eg. Capello et al. 2016 or Dudek et al. 2019). In the 2000s, a new approach to the management of the hydrocarbon reservoir was introduced – closed-loop reservoir management. Closed-loop reservoir management by considering the impact of future measurements within the optimization framework. This is a combination of frequent life-cycle production optimization and data assimilation (computer-assisted history matching) (Janssen et al. 2009; Hou et al. 2015; Barros et al. 2020).

The question of effective management of mineral water deposits has not yet been considered. Such an approach is not applied in the exploitation of water deposits; therefore the authors decided to address the issues that should be taken into account in the case of mineral water deposit management process. The article describes the basic elements of the process; special attention has been paid to the mineral water deposit development plan conditioning the effective and economically justified exploitation.

1. The concept of mineral water deposits management

Integrated reservoir management in the hydrocarbon industry means using the human, technical, technological and organizational means necessary to achieve maximum profits from oil or gas production. The authors believe that in the case of mineral water deposits, this concept should be supplemented by the aspect of resource protection and the consideration of environmental aspects, mainly related to the impact of exploitation on other aquifers.

As previously mentioned, the goal of managing mineral water deposits should be economic optimization of the exploitation process taking environmental conditions, which can be obtained through the following activities, into account:

- defining the hydrogeological parameters of mineral water aquifers and the physicochemical properties of waters;
- defining mining areas and areas and determining water resources;
- scheduling future exploitation;
- minimizing unnecessary drilling;
- determining and, if necessary, modifying the surface and downhole well equipment;
- monitoring of exploitation and utilization of water resources (deposit parameters);
- taking into account economic and legal factors.

Successful deposit management requires the cooperation of a multidisciplinary team. Decisions regarding the number of drilled wells and exploitation method must be discussed and made by the whole team. The effective planning and execution of activities related to the management and exploitation of mineral waters requires the cooperation of: hydrogeologists, geologists, geophysicists, drillers and water exploitation specialists. The deposit management integrates the issues of Earth sciences and engineering and includes: human resources, technology, tools, and source data (Fig. 1). This is based on a combination of: the exchange of information, implementation of accepted ideas, joint support of activities and teamwork (Satter et al. 1994; Satter and Thakur 1994; Thakur 1996, 2008).

The process of mineral water deposit management should define the objective, strategy and plan for its implementation, including implementation, control, monitoring, and evaluation of the obtained results (Fig. 2). All of these elements are interdependent, and their combination forms the basis of a successful integrated deposit management process. This process is dynamic and continuous and should be complemented and verified when new data is obtained (Satter et al. 1994; Satter and Thakur 1994).

The first stage in the deposit management process is to identify the needs and define objectives to be achieved. The objectives and strategy of the deposit management process are determined taking into account: deposit characteristics, external conditions (environ-

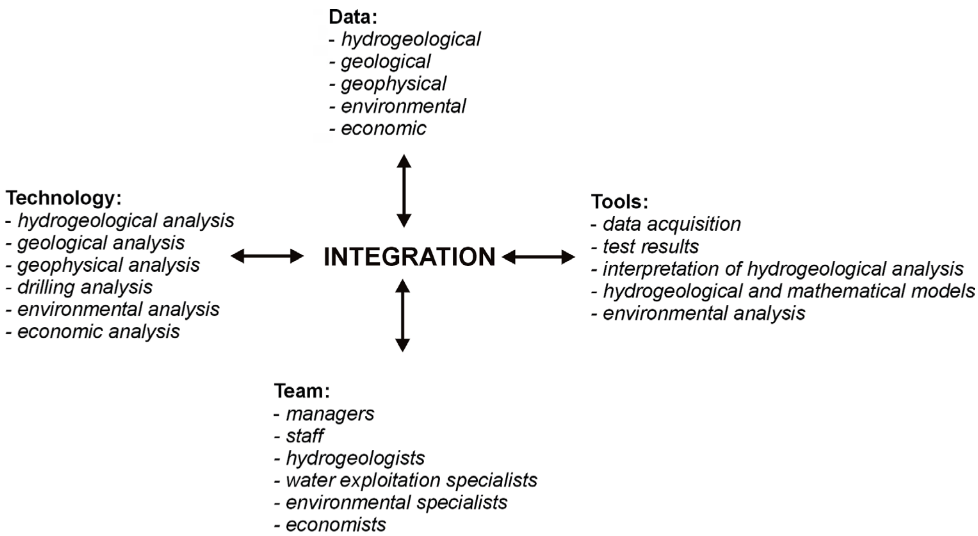

Fig. 1. The integration of human resources, technologies, and data in mineral water deposit management (based on Satter et al. 1994, as amended)

Rys. 1. Integracja zasobów ludzkich, technologii, danych w zarządzaniu złożem wód mineralnych

Fig. 2. Scheme of the deposit management process (based on Satter et al. 1994)

Rys. 2. Schemat procesu zarządzania złożem mental, social, and economic) and the best available technique and technology of deposit development. Another element is the formulation of a correct and detailed deposit development plan, which determines the success of the project. It needs to be developed in great detail. The implementation of this plan is one of the main objectives of the integrated deposit management process. To be implemented successfully, the plan should be flexible, supervised and strictly controlled by the management, precisely implemented and executed by the staff, with periodic checks, meetings and trainings (Thakur 1990). The management process should be continuously supervised and monitored. In the case of new conditions (technical, technological and/or economic) a revision of the plan should be considered. A revision of strategies and plans is necessary if the data obtained in the course of exploitation does not match the project or if hydrogeological, deposit, exploitation, or other conditions change. In such a case, one should check for errors and make adjustments to the plan (Satter et al. 1994; Satter and Thakur 1994).

2. Scheme of mineral water deposit development plan

Of all the above mentioned elements included in the mineral water deposit management process, the most important is the deposit development plan. The plan should be treated as a process that consists of many elements (Fig. 3).

Fig. 3. Scheme of mineral water deposit development plan

Rys. 3. Schemat planu zagospodarowania złoża wód mineralnych

The first and very important element in the process of mineral water deposit management is the development of a strategy. The formulation of the strategy should be based on the best available hydrogeological, geological, and technical knowledge related to the availability and exploitation of mineral waters. The strategy should take the method of deposit development (including the number and location of drilled wells) and the method of mineral water exploitation into account.

Another element is to take the external conditions affecting the management of the deposit into account, the most important being legal and environmental aspects. Both groups of conditions can significantly affect the course of mineral water exploitation. In accordance with the Geological and Mining Law (2011), mineral waters (total solid dissolved mineral content at least 1000 mg/dm^3) are extracted under a license issued by the Minister of the Environment or the local Marshal of the Voivodeship. According to the GML, the mineral resource extraction charge should be paid for the extraction of these waters. A fine is imposed for exploitation without a license. In accordance with Article 34(1) of the Act of 25 August 2006 on Food and Nutrition Safety, natural mineral waters marketed in Poland must be recognized as natural mineral waters by: 1) the Chief Sanitary Inspector, if the water is extracted from a well located in the territory of the Republic of Poland (FNS 2006). Environmental aspects should be taken into account. The location of wells should take the occurrence of nature protection areas, main groundwater reservoirs, and intake protection zones into account. Depending on the type of area, water extraction may be subject to certain restrictions or in some cases (e.g. national parks or reserves) prohibited.

The effective exploitation of mineral waters requires the collection of geological data (lithology of deposits and tectonics in the deposit area) and information on hydrogeological conditions (aquifer, hydrogeological parameters, and physicochemical properties of waters). Designing exploitation should be based on both archival data from tests performed in the analyzed area as well as newly performed tests and measurements (e.g. test pumping, hydrodynamic tests).

An important element is the development of a deposit model. In order to correctly determine the range of the mining area and plan exploitation, a hydrogeological (conceptual) model should be prepared, which is a description of the structure and course of processes within the actual aquifer. This model simplifies the actual hydrogeological conditions that prevail in the analyzed aquifer system (Herbich et al. 2013). The second model, developed to reproduce water flow conditions and used to calculate the available resources, is a mathematical model. In this model a hydrogeological model is schematized. The prepared models allow for the transition from reality (aquifer system) to the calculation tool (mathematical model). The development of a reliable hydrogeological model is of key importance in the preparation of a mathematical model and is an important element in determining the available groundwater resources (Herbich et al. 2013; Michalak et al. 2011). Correctly prepared models of mineral water deposits should form the basis for planning their future exploitation. During water extraction, the model can be updated based on the results of exploitation and deposit parameters obtained from deposit monitoring.

Mineral waters are considered as minerals and are not subject to the provisions of the Water Law Act, so the principles of water quantity and quality protection do not apply to them (WLA 2017). Furthermore, there is no obligation to establish intake protection zones. When it comes to waters classified as minerals, the provisions of the Geological and Mining Law, which require the designation of mining areas and sites for these deposits, shall apply. According to the GML, the mining area is a space within which an entrepreneur is entitled to mineral exploitation, underground non-reservoir storage of substances or underground storage of waste, as well as necessary mining work to execute concessions. On the other hand, a mining (extraction) area is the space covered by the predicted harmful effects of mining (extraction) activities (GML 2011). The rules for establishing these zones are simple in the case of deposits of solid minerals, while in the case of groundwater they are complicated due to the specificity of the latter. In the case of solid minerals, mining areas are clearly defined as a detached part of a deposit designed for exploitation. On the other hand, in the case of groundwater, the interpretation can be different, e.g. the intake area, resource area, or the area occupied by water extraction and transmission equipment. Another difficulty stems from the fact that the groundwater is in constant motion; in many cases it is not possible to unambiguously define the groundwater boundaries. Moreover, the range of the depression cone is variable and depends on various factors, including the exploitation model. Groundwaters that are classified as minerals often coexist and remain in hydraulic connection with normal groundwaters. For this reason, when delineating mineral water extraction areas, the hydrogeological conditions should be taken into account. In the case of water deposits, the boundaries of extraction areas may extend beyond the boundaries of the deposit itself. This is due to the fact that the impact of exploitation (depression cone) in some cases affects large parts of the hydrogeological unit. The extent of the impact of exploitation on groundwater is variable over time and may accumulate with the impact of other groundwater intakes. When extracting groundwaters classified as minerals, it is also difficult to precisely determine the harmful impact of exploitation. In the case of mineral waters from springs, there is no harm to the deposit itself. However, in the case of water extraction pumps, lowering the pressure in the deposit may cause changes in the rate and directions of groundwater flow, and thus changes in the chemistry of the water, which can lead to the degradation of the deposit (Ciężkowski and Kapuściński 2011).

An important element for the trouble-free operation of the drilled well is the proper development of the aquifer exploitation. Depending on the depth of occurrence, mineral waters can be extracted using drilled wells, dug wells, and spring arrangements. Most often, mineral waters are extracted from wells of varying depth and design, depending, among other things, on the lithology of aquifers and hydrogeological conditions. Downhole well equipment depends, among others, on the lithological development of aquifers; in the case of carbonate rocks there is no need to use filters, as is the case of clastic rocks.

The most important element of the groundwater borehole is the filter. The high efficiency of groundwater flow and its high hydraulic efficiency depend largely on the right type, construction, and dimensions of the filter in relation to the hydrogeological conditions.

The correct choice of filter design is important, especially when designing wells intended for long-term use.

The basic tasks of the filter include maintaining stability of the borehole walls, the ability to supply great water flow with minimal hydraulic resistance, and protection of the aquifer from suffosion. The fulfillment of the above conditions is necessary for the proper and long-term operation of the drilled well. During the development of new aquifers, the type and dimensions of the filter, the height position of the filter in the aquifer, and the length of the sub-filter and super-filter tubes should be selected. The operation of a mineral water well is also affected by the method of its filtration, which depends on the purpose of the well, development of aquifers, nature of the water table, planned capacity, type of pumping equipment, and the groundwater quality (Gonet and Macuda 1995; Gonet et al. 2011).

At the stage of preparation of the plan it is also necessary to develop the project of surface and downhole well equipment. Depending on the hydrodynamic conditions, the extraction can be conducted automatically or by means of a suitably selected submersible pump; moreover, the well should be equipped with other devices, e.g. production packers. In the case of water extraction, the borehole must be equipped with a production head selected according to the appropriate working pressure and resistant to the influence of deposit factors (e.g. hydrogen sulfide or carbon dioxide present in the exploited water). The production head should enable the exploitation and provide a borehole tightness. In addition, it should be capable of measuring the well pressure, taking samples, and providing the possibility of penetrating the well with deep gauges. Apart from the production head, the surface equipment may include other elements such as: fixed or adjustable throttling orifices (pressure-differential devices), separators, gas pressure reducing and metering stations, storage tanks, degassing devices, and other equipment (Ciężkowski ed. 2002; Duliński and Ropa 2005).

Proper management of mineral water deposits should be carried out in a way that prevents changing physicochemical and hydrodynamic parameters of water (Paczyński ed. 2002). The chemical composition and physical properties of groundwater, including mineral waters, are changing. Fluctuations in groundwater chemistry are a natural process. The improper exploitation of mineral (curative) waters may lead to changes in their chemical composition and physical properties. Decreases in the content of main, specific components or the volume of mineralization caused by excessive water intake can result in a decrease in water value. In some cases this may lead to a change in the classification of this water (due to changes in its chemical composition), and in extreme cases to the deprivation of its mineral status (Ciężkowski and Kapuściński 2011; Lewkiewicz-Małysa and Winid 2013). Changes in the chemical composition of waters during their exploitation result from hydrodynamic changes in the water circulation system or changes in hydrogeochemical conditions. This may result in the deterioration of the quality of the exploited waters (e.g. decrease in the content of certain ions or reduction of water mineralization), and in extreme cases reduce the volume of exploitation or lead to the closure of the well (Błaszyk and Górski 1981; Custodio 2002; Dąbrowski et al. 2004; Górski 2010).

Hydrodynamic changes associated with groundwater exploitation may have a positive or negative impact on the chemical composition of water. Positive changes occur in two cases: when the hydrogeochemical conditions at the recharge area, or catchment area, are more favorable than at the location of the well or in the case of intense water circulation. The improper exploitation of mineral waters may in some cases lead to the deterioration of their quality. Changes in the chemical composition of water depend on two factors: the volume of extracted water and hydrogeochemical conditions at the catchment area. If the extraction does not alter the direction of water circulation or the hydrogeochemical conditions in the recharge are homogeneous, no significant changes in water chemistry are observed. In the case of heterogeneous hydrogeochemical conditions at the recharge area or excessive water intake, significant changes in the chemical composition of groundwater can be observed (Dąbrowski et al. 2004). A disturbance in the natural water circulation system can also lead to the mixing of waters with different mineralization or to the inflow of anthropogenically polluted waters.

The most important rule that should apply to the extraction of mineral waters is that the exploitation cannot exceed the available resources. The aquifers from which natural mineral water is extracted must be protected from infiltration from the surface (surface contamination). Water extraction shall be conducted in such a way that the dynamic water table in drilled wells should not fall below the documented level (Paczyński ed. 2002). The excessive exploitation of groundwater may lead to imbalance between the amount of extracted water and the disposable resources of mineral waters. In the case of mineral and mineral water exploitation, in the determination in advance of the amount of available resources, so licenses for the extraction of curative and mineral waters are issued without major restrictions, is not required. Licensing authorities cannot set a limit on the total volume of water that can be extracted. This creates a potential threat of the excessive depletion of natural resources as a result of intensive exploitation (Szczepański and Szklarczyk 2005).

Other factors that can affect the quantity of water resources include the lowering of the erosion base and the lowering of the water table. They can be triggered by mining and construction works or drainage (drainage in the construction industry, agricultural drainage, groundwater exploitation, or surface water regulation).

Taking the potential mineral water quality changes during exploitation, which may eventually lead to deprivation of its mineral status into account, it is necessary to monitor the extraction process. The monitoring should not only assess the environmental impact of the exploitation, but also monitor the water supply for impurities and prevent mixing of waters with different chemical composition. Moreover, monitoring of changes in water resources in the extraction area are of key importance for forecasting changes and enable undertaking protection measures (Paczyński ed. 2002).

The monitoring of mineral waters should be performed in accordance with the research program including hydrodynamic and physicochemical measurements conducted directly at wells, as well as meteorological measurements. The tests should be adapted to the type and conditions of water occurrence, as well as to technical capabilities. General requirements for stationary tests are given in the "Mineral and therapeutic water intakes" standard (PN-Z-11002: 1997), specifying the scope and frequency of testing.

The tests are conducted at different frequencies. The frequency of water sampling for the determination of chemical composition and physical characteristics, just like the measurement of water levels, depends on the type of aquifer (porous, fissured, or fissured karst) and the type of intake (observation wells, springs, or piezometers). Measurements of operational parameters (static mirror, dynamic mirror, and performance), physical properties of water (temperature), selected chemical (indicator ions and gases) and meteorological components (ambient temperature, precipitation, wind direction and speed) are performed daily. With less frequency, from 3 months to even 10 years (depending on the type of hydrogeological structure), water control analyses (from 3 months to 1 year) and full water analyses (from 3 to 10 years) are performed. For each water deposit, the frequency of measurements and the quantity and distribution of the observation network should be designed separately, taking the specific features of the rock medium and groundwater circulation systems into account (Paczyński ed. 2002).

Economic optimization is the ultimate goal of mineral water deposit management. With the estimated water efficiency, available capital, anticipated operating costs and financial data, as well as the risk of the project, the overall economics of the project is assessed.

The last stage is the approval of the mineral water deposit development plan together with management's support for its implementation.

Conclusions

Mineral waters are natural resources that must be protected in a special way. In the case of bottled or mineral waters, one of the ways for their protection may be to apply the idea of deposit management.

An integrated approach to the prospecting, exploration, opening, and exploitation of mineral waters combining the knowledge of specialists from various disciplines (hydrogeologists, geologists, drillers and producers) will enable the appropriate management of these resources.

The most important element in the integrated deposit management process is its development plan. This plan should take the development strategy and legal and environmental conditions into account. Based on the collected hydrogeological, geological, and other data, hydrogeological and mathematical models of mineral water deposits should be made. This data will also be used to determine the extent of the mining area and to estimate resources. The plan should also specify the development, exploitation, and monitoring methods. This plan should be optimized and accepted.

The application of mineral water deposit management will allow the producer to achieve profits from the exploitation, rational use of their resources and ensure the protection of groundwater resources.

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PROPOSAL FOR THE INTEGRATED MANAGEMENT OF MINERAL WATER DEPOSITS

Keywords

mineral water, exploitation, deposit management, deposit development plan

Abstract

Waters with mineralization above 1000 mg/dm^3, classified as mineral waters, are exploited in many regions of Poland. Their resources are usually not renewable and their excessive exploitation can lead to the deterioration of their physical and chemical properties and negatively affect their quantitative status.

The stages in the life of a groundwater deposit involve prospecting, exploration, development, and exploitation. Deposit management is the basis for a sustainable and economically successful process of using water resources.

The problem of effective management of mineral water deposit management has not been raised so far, which is why the authors decided to address issues that should be taken into account in the above-mentioned process. An integrated approach to the prospecting, exploration, opening, and exploitation of mineral waters combining the knowledge of specialists from various disciplines (hydrogeologists, geologists, drillers and producers) will enable the appropriate management of these resources.

The article describes the basic elements of the process, special attention has been paid to the mineral water deposit development plan conditioning the correct and economically justified exploitation of these waters. This plan should take the development strategy and legal and environmental conditions into account. Hydrogeological and mathematical models of mineral water deposits developed as part of the plan provide the basis for determining the extent of the mining area and estimating water resources. The deposit opening, exploitation, and monitoring methods are important elements of the deposit development plan.

ZARZĄDZANIE ZŁOŻAMI WÓD MINERALNYCH – PROPOZYCJA

Słowa kluczowe

wody mineralne, eksploatacja, zarządzanie złożem, plan zagospodarowania złoża

Streszczenie

Wody mineralne o mineralizacji powyżej 1000 mg/dm^3, zaliczone w Polsce do kopalin, są eksploatowane w wielu regionach. Są to wody, których zasoby nie są w większości odnawialne, a zbyt intensywna eksploatacja tych wód może prowadzić do pogorszenia ich właściwości fizyko-chemicznych oraz do zagrożenia ich stanu ilościowego.

Życie złoża wód podziemnych rozpoczyna się wraz z pracami poszukiwawczymi, które prowadzą do odkrycia złoża, poprzez prace rozpoznawcze i zagospodarowanie, po jego eksploatację.

Zarządzanie złożem jest podstawą zrównoważonego i zakończonego pełnym ekonomicznym sukcesem procesu wykorzystania zasobów wód.

Problem odpowiedniego zarządzania zasobami wód mineralnych nie był dotąd poruszany, dlatego autorki podjęły się określenia zagadnień, które powinny być brane pod uwagę w procesie zarządzania złożem wód mineralnych. Zintegrowane podejście do poszukiwania, rozpoznania, udostępnienia i eksploatacji wód mineralnych, łączące wiedzę specjalistów z różnych dyscyplin (hydrogeologów, geologów i eksploatatorów), umożliwi odpowiednie gospodarowanie ich zasobami.

W artykule scharakteryzowano podstawowe elementy procesu, szczególną uwagę zwrócono na plan zagospodarowania złoża wód mineralnych warunkujący poprawną i ekonomicznie uzasadnioną eksploatację tych wód. Plan ten powinien uwzględniać strategię zagospodarowania oraz uwarunkowania prawne i środowiskowe. Modele: hydrogeologiczny oraz matematyczny złoża wód mineralnych opracowane w ramach planów stanowią podstawę do wyznaczenia zasięgu obszaru i terenu górniczego oraz oszacowania zasobów wód. Ważnym elementem planu zagospodarowania złoża są także określone w nim sposoby udostępnienia i technologii eksploatacji wód wraz z ich monitoringiem.