

The Buzău river alluvial fan – a groundwater modeling approach to sustainable exploitation

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Abstract

Knowledge of groundwater resources is a key challenge for hydrogeologists, especially due to a continuous increase in demand for drinking water.

This paper aims to investigate the consequences of overexploitation of the phreatic aquifer from the Buzău River alluvial fan and to assess alternatives operating programs related to achieving a sustainable groundwater exploitation.

The study was achieved using data (groundwater level and general information from 97 hydrogeological boreholes) from the National Institute of Hydrology and Water Management, Romania, and collected in the field between July 18-19, 2017 (river stages for Buzău and Călmățui).

The aquifer data was statistically analyzed and the obtained results allowed the design of a conceptual model for the hydrostructure and a mathematical model for the groundwater flow, using the FREEWAT software. Continuous exploitation of the phreatic aquifer through the catchment fronts that supply the city of Buzău (Crâng, Zahăr I, and Sud fronts) was simulated using the hydrodynamic model, in a transient regime.

The maximum allowable flows were defined for each hydrogeological borehole that exploits the phreatic aquifer, using the mathematical model (values between 4.0 and 19.0 l/s). The exploitation of these flows was performed for 10 years, with time steps that allowed an analysis of the depression cone extension and drawdown value after 90 days, 180 days, one year, and five years of continuous pumping. After ten years, the resulting depression cone reached a diameter of 9.8 km and the groundwater level decreased with a maximum of 8.26 m, in a hydrogeological borehole.

For stationary simulation (which is not influenced by the time parameter), it was observed that pumping with the maximum allowable flows resulted in a drawdown that exceeds one-third of the water column, which indicates overexploitation.

Keywords: Buzău river alluvial fan, hydrogeological borehole, groundwater, phreatic, aquifer, mathematical model, overexploitation

Rezumat. Conul aluvionar al râului Buzău - o abordare a modelării apelor subterane pentru o exploatare durabilă

Cunoașterea resurselor de apă subterană este o provocare cheie pentru hidrogeologi, în special datorită creșterii continue a cererii de apă potabilă.

Acest articol își propune să investigheze consecințele supraexploatării asupra acviferului freatic din conul aluvionar al râului Buzău și să prezinte soluții de exploatare astfel încât să se realizeze o valorificare sustenabilă a apei subterane. Studiul a fost realizat utilizând informații (nivelul apei subterane și informații generale de la 97 de foraje hidrogeologice) provenite de la Institutul Național de Hidrologie și Gospodărire a Apelor, respectiv colectate pe teren în perioada 18-19 iulie 2017 (cota luciului râurilor Buzău și Călmățui).

Datele caracteristice acviferului au fost analizate statistic, iar rezultatele obținute au permis realizarea unui model conceptual al hidrostructurii și al unui model matematic de curgere a apei subterane, utilizând programul FREEWAT. Exploatarea continuă a acviferului freatic prin fronturile de captare care alimentează orașul Buzău (fronturile Crâng, Zahăr I și Sud) a fost simulată folosind modelul hidrodinamic, în regim nestaționar.

Au fost definite debitele maxim admisibile pentru fiecare foraj hidrogeologic care exploatează acviferul freatic utilizând modelul matematic (valori cuprinse între 4.0 și 19.0 l/s). Exploatarea acestor debite a fost efectuată timp de 10 ani, cu pași de timp care au permis o analiză a extinderii conului de depresiune și a denivelării, după 90 de zile, 180 de zile, un an și cinci ani de pompare continuă. După zece ani, conul de depresiune rezultat a atins un diametru de 9.8 km, iar nivelul apei subterane a scăzut cu valoarea maximă de 8.26 m (în foraj).

Pentru simularea staționară (care nu este influențată de parametrul timp), s-a observat faptul că pomparea cu debitele maxime admise a rezultat dintr-o denivelare care depășește o treime din coloana de apă, ceea ce indică o supraexploatarea.

Cuvinte-cheie: conul aluvionar al râului Buzău, foraj hidrogeologic, apă subterană, freatic, acvifer, model matematic, supraexploatarea

Introduction

Alluvial fans in piedmont areas are major groundwater resources (Bowman, 2019). Water research, such as overexploitation of groundwater resources (e.g., Munevar & Marino, 1999) or runoff processes on hillslope (Rodrigo-Comino et al., 2017; Minea et al., 2019) are few examples for study

direction. However, overexploitation of groundwater resources is a subject that has been investigated and studied especially in areas that are scarce in surface water and in those that are susceptible to pollution from anthropic sources (Rodriguez-Estrella, 2012). As is known, the groundwater represents a volume of water that is naturally filtered and recharged continuously, as such if properly managed an aquifer

can sustain the population and industry over a great surface and period of time (Șerban et al., 1989).

Investigation of overexploitation has intensified in the last decades, as several consequences of this phenomena have surfaced. For example, irrational exploitation along the coastline can lead to saltwater intrusion (Meyer et al., 2019), if the abstraction rate of a groundwater catchment is greater than the recharge rate of the aquifer, it can lead to a continuous decrease of the water level and impact singular wells (Custodio, 2002).

To manage such situations several mathematical and legislative instruments have been created. To better estimate the effect groundwater exploitation has on an aquifer, the mathematical models that simulate groundwater flow have been improved and several special modules have been created to simulate specific phenomena: saltwater intrusion, dewatering, farm process (e.g., FREEWAT - EU HORIZON2020 project). To put in practice the information collected in the research phase, several specific economic and legislative instruments have to be implemented. Of course they differ depending on the type of situations each country is encountering (Montginoul et al., 2016).

The Buzău river alluvial fan is an important geological structure and from a hydrogeological point of view presents great potential. Some of the oldest studies were made by Frugină (1978), Tomescu (1979), in which they studied and evaluated the dynamics of groundwater resources in the Buzău alluvial fan and created a base on which future studies of the area were made. The most recent studies in the area were made for dimensioning of sanitary protection areas and hydrogeological protection perimeters for the groundwater catchments of Buzău city (Radu & Manea, 2017). Currently, there is a lack of graphic and spatial information to illustrate the result in time that groundwater exploitation has. The parameters of a catchment are calculated only at its level, without studying the impact it has on existing hydrogeological boreholes and wells. It is likely that this lack of information might be due to the complexity of the processes involved.

In this context, this study aims to investigate the consequences of overexploitation of the phreatic aquifer from the Buzău River alluvial fan and to assess alternatives operating programs related to achieving a sustainable groundwater exploitation.

Study area

In this paper the phreatic aquifer studied is the one from the Buzău river alluvial fan. This structure is part of the Buzău Plain (Badea & Buza, 2011) and it extends between the Vernești village, in the north-

west, to the course of the Călmățui river in the south, then follows the line formed by the Albești, Bentu and Săgeata localities in the south-east, and the north-eastern limit is represented by the Buzău river.

The altitude decreases from 125 m near Vernești, down to 62.5 m in Albești. The alluvial fan continues slowly towards the neighboring plains without morphological changes, thus explaining the difficulty of its delimitation in the south-eastern region.

The Buzău river alluvial fan is located in an area characterized by a temperate-continental climate, with an average multiannual rainfall of 407 mm (amounts range from 450 mm at Brăila to 520 mm at Buzău), and a mean annual potential evapotranspiration of around 700 mm (Mitof, 2015). The high quantity of precipitation represents the main water source for the phreatic aquifer.

The alluvial fan has a surface of about 294 km² and Buzău city covers over 25% of this area. The Buzău municipality provides the water for approximately 131.000 inhabitants, by primarily exploiting the groundwater resources from the phreatic and deep aquifers.

The phreatic aquifer from the Buzău river alluvial fan develops to depths between 3.0 m and 37.5 m and it can be found in deposits consisting of sand, gravel and boulders with lenses of up to 5.0 m of clays, marls or sandy clays. The age of this formation is Upper Pleistocene – Holocene. On the left bank of the Buzău, the aquifer presents covering formations made of rocks with low permeability, with thicknesses of 1.0 - 5.0 m (Manea, 2017).

Compared to other alluvial fans, the one created by the Buzău River is on the smaller side both horizontally and in-depth. The fans that can be found in the state of California (U.S.A.), for example, are characterized with vadose zones of thicknesses up to 80.0 m, while the one created by the Buzău river has an unsaturated area of maximum 5.0 m (Munevar & Marino, 1999). As such, the quantity of information and the methodology used to define an alluvial fan varies from case to case.

In the Buzău river alluvial fan, there are numerous groundwater catchments for drinking purposes (population use), technological purposes (industry), and irrigation (Macaleț et al., 2008). Phreatic aquifers are suitable for technological purposes and irrigation, due to the fact that they are qualitatively susceptible to pollution and often exceed the potability indices (Radu & Rădescu, 2007). Thus, the high-depth aquifer is recommended as a drinking water source for the population, while the phreatic aquifer is recommended for industrial aspects.

Data and methods

To better understand groundwater dynamics and to be able to predict how an aquifer will behave in the future, the complexity of the hydrostructure needs to first be simplified in the form of a conceptual model. In this analysis, the basics of the aquifer are defined: its extent, the spatial variation of the parameters and the energy of the groundwater. After creating the static conceptual model, the information collected is used to create a dynamic schematization. The final result is a mathematical model in which the descriptive information collected (point measurements, aquifer parameters, amount of precipitation, etc.) can be tracked and adjusted to reflect as accurately as possible the underground reality.

The methodology of simplifying a complex structure is not a new one. The first model created to understand natural phenomena was a physical one, where the structure was downscaled using material similar to that encountered on the field, just at a different dimension. Computer development allowed the creation of conceptual and mathematical models with a high amount of information that can better describe reality. As such this approach can be encountered in various science fields.

The phreatic aquifer from the Buzău river alluvial fan was studied and simplified in the form of a conceptual model. In this schematization the geometry of the hydrostructure, the spatial variation of its mineral matrix and aquifer parameters, respectively the dynamics of the groundwater in an uninfluenced regime, were studied. This model was subsequently transposed, using the FREEWAT software, into a mathematical schematization.

The study covers only the exploitation of the phreatic aquifer by the catchment fronts of Buzău city: Crâng, Zahăr I and Sud (Figure 1).

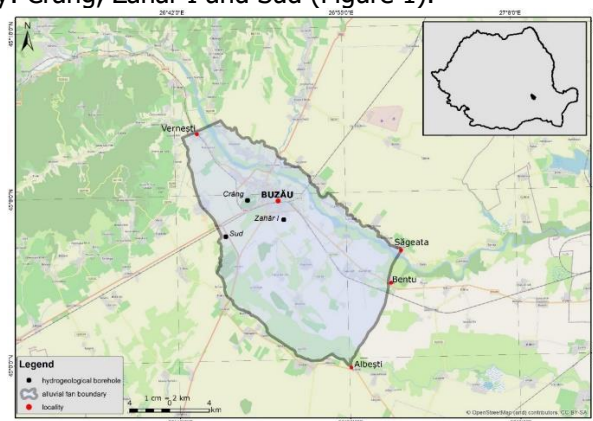


Fig. 1: The location of the study area

To achieve management for the entire phreatic aquifer, information is needed regarding all the catchments, those that are for the purpose of

supplying water to the population and those that are for irrigation purposes or other industrial aspects.

The conceptual model of the phreatic aquifer from the Buzău river alluvial fan was created based on the following data:

- the structure of the aquifer was defined on the information collected from 97 hydrogeological boreholes (lithology, construction details of the well), provided by the National Institute of Hydrology and Water Management, Romania;
- the spatial variation of the hydraulic conductivity based on values calculated using the pumping tests made in 66 observation points;
- the amount of precipitation recorded at hydrometric stations;
- the stage of the Buzău and Călmățui rivers collected on the field between July 18-19, 2017, in 19 observation points;
- the groundwater elevation from July 18-19, 2017, in 26 hydrogeological boreholes, provided by the National Institute of Hydrology and Water Management, Romania.

This information was statistically analyzed using directional variograms, surface variograms, izovariograms, to define a structural model characteristic to the spatial variation of the respective parameter (lithology, hydraulic conductivity, groundwater level, etc.).

The analysis of the spatial distribution of the characteristic parameters led to the creation of a conceptual model, with a high degree of fidelity to reality, of the phreatic aquifer from the Buzău river alluvial fan.

Based on the hydrodynamic spectrum, made using the information from July 18-19, 2017, the boundaries of the mathematical model for the groundwater flow were defined. This domain was discretized using square cells with a side of 30.0 m, creating a network of 535.040 cells. The active area of the model, in which the Buzău river alluvial fan is located, occupies 280.071 cells.

The influence that a groundwater catchment has on an aquifer was chosen to be simulated using the catchment fronts that supply the city of Buzău with water. The Buzău city is being provided with groundwater by seven catchment fronts. Those that exploit the phreatic aquifer are the following:

- Crâng - consisting of 20 boreholes; eight of which capture the phreatic aquifer (F1-F3, F5-F8, F10);
- Zahăr I - consisting of 22 boreholes; five of which capture the phreatic aquifer (F10, F12, F14, F18, F20) and the medium depth one from the Căndești Formation;
- Sud - consisting of 15 boreholes; three of which capture the phreatic aquifer (F12, F13, F15) and the medium depth one from the Căndești Formation (Radu & Manea, 2017).

Based on this information, the first stage in the simulation of groundwater exploitation consisted of determining the maximum flows with which the hydrogeological boreholes can be exploited so that the drawdown produced in them does not exceed one-third of the water column.

It started with the simulation of the exploitations in each capture front. This run was performed in a stationary regime.

The Crâng capture front contains eight boreholes that capture the phreatic aquifer (F1-F3, F5-F8, F10). The hydrostatic level recorded in them is found at depths between 9.1 m (F10) and 11.6 m (F5), and the water column has thicknesses that vary between 14.1 m (F1) and 16.9 m (F7).

For this capture front, pumps were simulated with flow rates between 3.0 - 8.0 l/s/borehole. It was observed that at a flow rate of 8.0 l/s/borehole, the cells in which the boreholes are found in the grid dried up, which means that the drawdown reached the aquifer bed.

This analysis revealed that the maximum allowable flow, to avoid overexploitation of the aquifer, is 4.0 l/s/borehole for the F1, F2, F3, F5, F6 hydrogeological boreholes and between 4.0 - 4.5 l/s/borehole for F7, F8, F10. The variation of the drawdown according to the exploited flow and the exceeding of the value that represents a third of the water column (orange line) can be seen on the graphs from Figure 2.

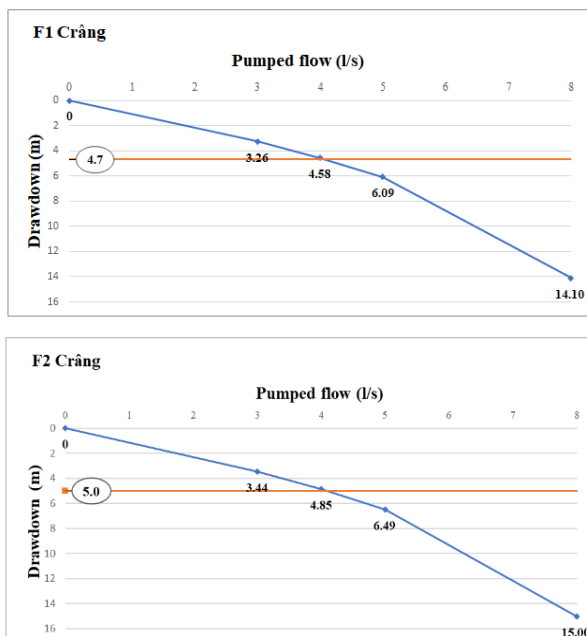


Fig. 2: Defining the maximum allowable flow for the F1, F2 hydrogeological boreholes from Crâng capture front

The Zahăr I capture front contains five boreholes that exploit the phreatic aquifer (F10, F12, F14, F18, F20) and the medium depth one from the Căndești Formation. The hydrostatic level recorded in them is found at depths between 6.7 m (F14) and 9.8 m (F20), and the water column has thicknesses ranging between 20.3 m (F20) and 24.6 m (F10). For this capture front, pumps were simulated with flow rates between 5.0 - 13.0 l/s/borehole. This analysis revealed that the maximum permissible flow rate, in order to avoid overexploitation of the groundwater aquifer, is approximately 11.0 l/s for F10, 10.0 l/s for F12, between 9.0 - 10.0 l/s for F14, 8.0 l/s for F18 and 9.0 l/s for F20. The F18 and F20 hydrogeological boreholes allow exploitation with the lowest flow, due to the fact that the thickness of the water column in them is the smallest.

The Sud capture front contains three boreholes that capture the phreatic aquifer (F12, F13, F15) and the medium depth one from the Căndești Formation. The hydrostatic level recorded in them is found at depths between 4.7 m (F12) and 5.4 m (F13), and the water column has thicknesses ranging between 16.7 m (F15) and 17.5 m (F12). For this capture front, pumps were simulated with flow rates between 5.0 - 20.0 l/s/borehole. This analysis revealed that the maximum allowable flow, to avoid overexploitation of the groundwater aquifer, is between 12.0 - 13.0 l/s/borehole for the F12 and F13 hydrogeological boreholes, and for the F15 borehole the flow can reach values of 19.0 l/s. The high-value characteristic of F15 is due to its proximity to the Călmățui river, which is a continuous source of water.

These maximum allowable flows were determined by pumping only on one front at a time. When the catchment fronts operate at the same time, this flow decreases because the effect of each exploitation is felt in time in the other boreholes. The maximum allowable flows were still used to run a non-stationary simulation. The evolution of the hydrodynamic spectrum and the depression cone was observed over time.

In the first stage, the result of continuous pumping was observed in all boreholes over a period of 90 days. The introduced flows vary between 4.0 l/s in the hydrogeological boreholes from the Crâng capture front and 19.0 l/s in the F15 borehole from the Sud capture front. The maximum drawdown recorded has the value of 3.66 m in the F15 Sud borehole and the minimum is equal to 0.81 m in the F10 Crâng. The resulting depression cones have radii between 326.0 m (Crâng) and 541.0 m (Zahăr I) – Figures 3 and 4.

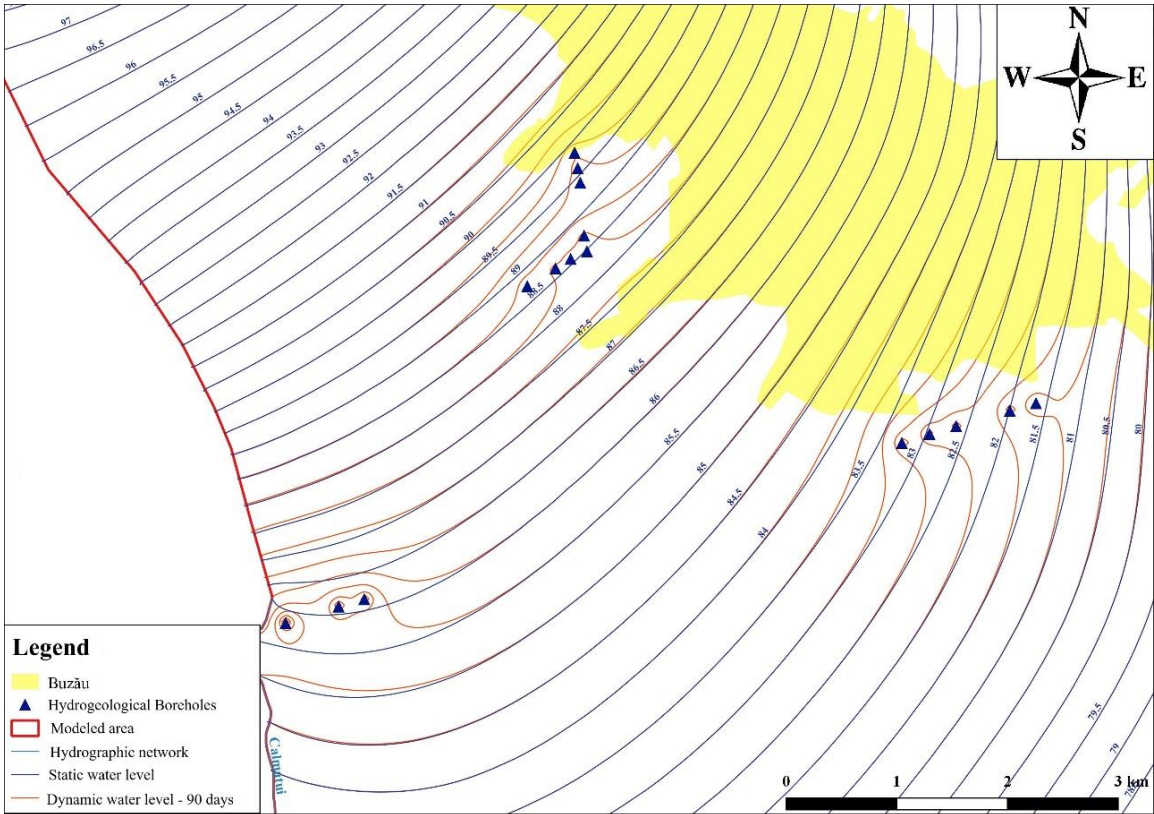


Fig. 3: Hydrodynamic spectrum after 90 days of exploitation

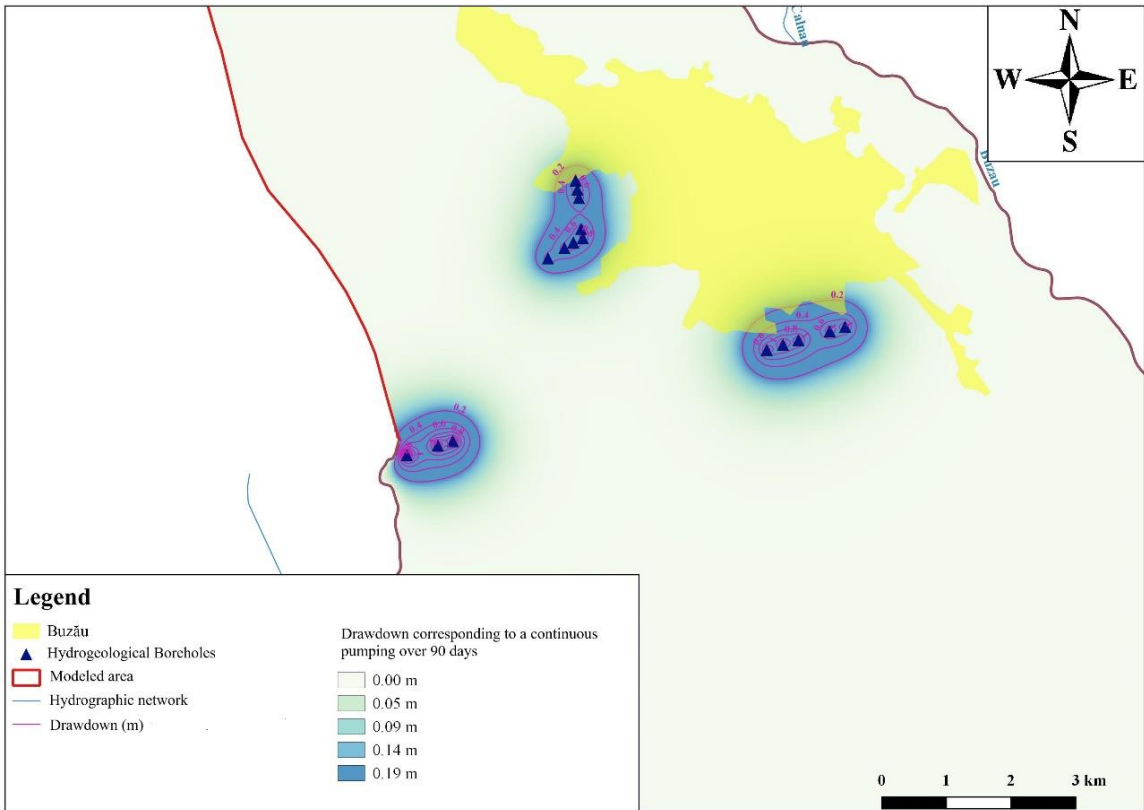


Fig. 4: The depression cones after 90 days of exploitation

The simulated exploitation of the maximum allowable flows was continued up to 10 years to observe the effect that the simultaneous pumping of all the hydrogeological boreholes from the three catchment fronts has and to determine the extension of the depression cones. The latter affects the depth of the groundwater level in the catchments in the respective area. Figure 5 shows the increase of the depression cone corresponding to each capture front. Following this development, the next observations can be made:

- The depression cone corresponding to the Crâng catchment front is characterized by a radius of 600.0 m, following continuous exploitation for 180 days. It increased to 1010.0 m in one year;
- The depression cone corresponding to the Zahăr I catchment front is characterized by a radius of 827.0 m, following continuous exploitation for 180 days. It rose to 1263.0 m in one year;
- The depression cone corresponding to the Sud catchment front is characterized by a radius of 752.5 m, following continuous exploitation for 180 days. It rose to 1080.0 m in one year;
- In five years, the depression cones of the three catchment fronts unite. The result is characterized by a length of 7.6 km and a width of 9.8 km. On this surface the minimum elevation difference is 0.2 m and reaches 3.6 m near the boreholes in the Zahăr I and Sud catchment fronts, respectively 2.8 m near the boreholes in the Crâng front;
- In ten years, the depression cone afferent to the three catchment fronts is characterized by a length of

10.6 km and a width of 10.2 km. On this surface, the minimum elevation difference is 0.2 m and reaches 4.0 m near the boreholes in the Sud catchment front, 3.8 m near the boreholes in the Zahăr I front, respectively 3.6 m near the boreholes in the Crâng front.

- In 10 years, the depression cone covers the city of Buzău and the entire central part of the alluvial fan.

The drawdown measured in the hydrogeological boreholes varies according to Figure 6. The following results were obtained:

- In the Crâng catchment front, the maximum drawdown is registered in the F6 borehole. In it the value increased from 1.46 m (180 days) up to 4.04 m (10 years). The maximum elevation difference has a value lower than one third of the water column in the respective borehole, more precisely 5.23 m (Figures 6 – a, b);
- In the Zahăr I catchment front, the maximum drawdown is recorded in the F12 borehole. In it the value increased from 2.38 m (180 days) up to 5.44 m (10 years). The maximum elevation difference has a value lower than one third of the water column in the respective well, more precisely 8.06 m (Figure 6 – c);
- In the Sud catchment front, the maximum drawdown is registered in the F13 borehole. In it the value increased from 3.34 m (180 days) up to 5.61 m (10 years). The maximum elevation difference has a value lower than one third of the water column in the respective well, more precisely 5.77 m (Figure 6 – d).

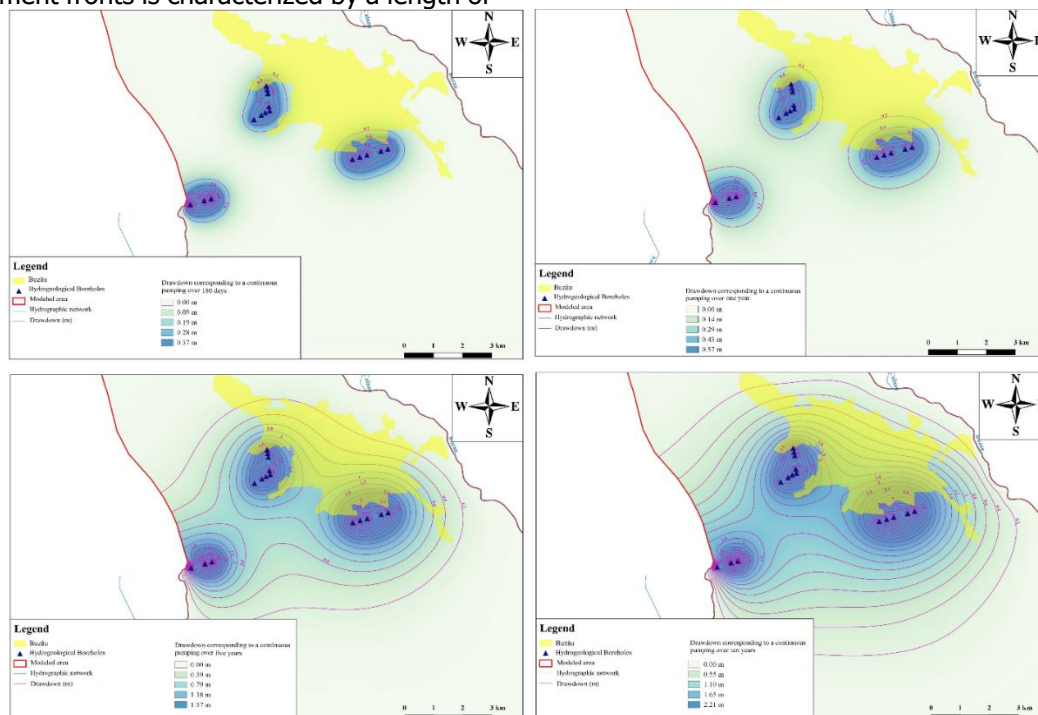


Fig. 5: Depression cones following exploitation over a period of 180 days, one year, five years, and ten years

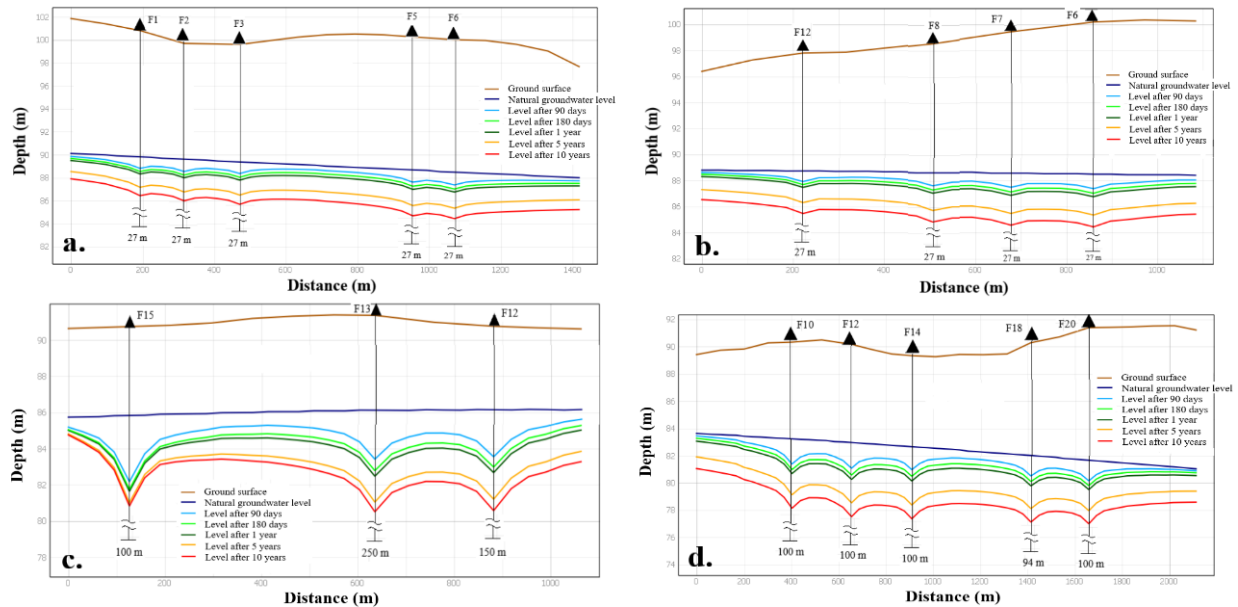


Fig. 6: Groundwater level variations in the Buzău catchment fronts, a. Crâng catchment front, the wells located perpendicular to the flow direction, b. Crâng catchment front, the wells located on the flow direction, c. Zahăr I catchment front, d. Sud catchment front

The depression cones of the Sud and Zahăr I catchment fronts have merged in less than five years (Figure 7). Thus, between the two catchments, the groundwater level decreased by 0.59 m in five years,

respectively 1.26 m in ten years. This change in the depth of the groundwater level can lead to the drying of wells or boreholes in private households.

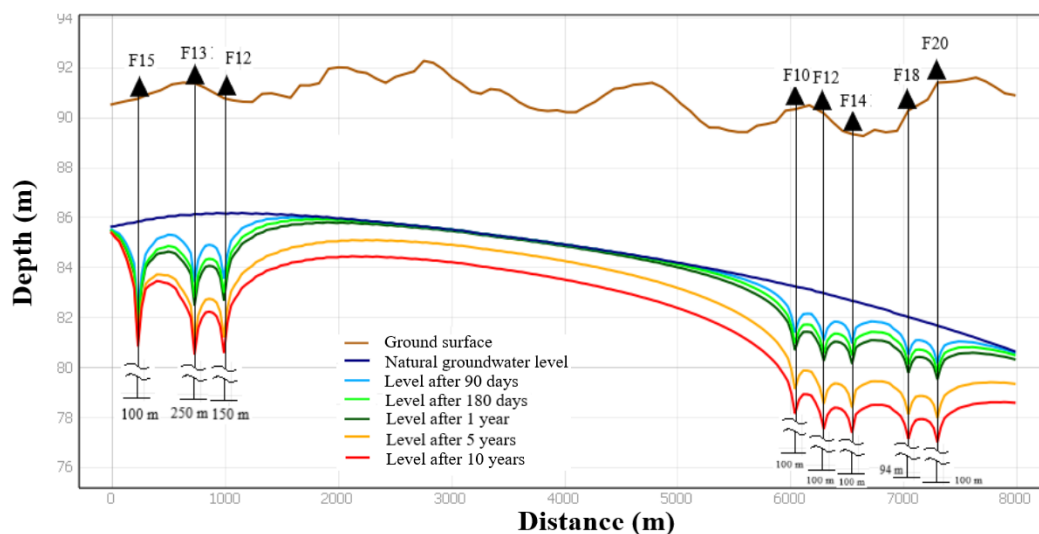


Fig. 7: Groundwater level variations in the Sud and Zahăr I catchment fronts

Conclusions

In this paper, the subject of overexploitation was approached using a mathematical model created for the phreatic aquifer from the Buzău river alluvial fan. A detailed flow model was created for the creation of an exploitation program at the level of the phreatic aquifer, to achieve a sustainable capitalization of this

resource, that does not affect the singular or industrial exploitations.

Using the mathematical model, the maximum allowable flows were defined for each hydrogeological borehole that exploits the phreatic aquifer. The results show that those from the Crâng catchment fronts can be utilized with flows varying between 4.0-4.5 l/s, while the maximum allowable output is equal to 19.0 l/s (F15) in a borehole from the Sud catchment front. This high value is due to the proximity of the Călmățui

river, which represents a continuous source of water for the aquifer when the natural regime is perturbed.

The simulation was performed for a maximum period of 10 years, with time steps that allowed an analysis of the depression cone extension and drawdown value after 90 days, 180 days, one year and five years of continuous pumping.

The depression cones for each catchment fronts had radii smaller than 830 m after 180 days of exploitation. In three years they reached one another, and in ten years of continuous exploitation, the resulting cone reached a diameter of 9.8 km.

The water level decreased in hydrogeological boreholes with a maximum value of 5.23 m for the Crâng catchment front, 8.06 m for the Zahăr I front and 5.77 m for the Sud front. The depression cone created by the exploitation led to a decrease up to 1.26 m of the groundwater level, between the hydrogeological boreholes of different fronts. These simulations were made in a transient regime. In the stationary simulation (which is not influenced by the time parameter) it was observed that pumping with the maximum allowable flows resulted in a drawdown that exceeds one-third of the water column, which indicates overexploitation. To avoid this situation, it is recommended not to exceed the maximum allowable flows and to put into operation alternative boreholes that capture the same aquifer.

Certainly, to carry out the complete management of the phreatic aquifer from the Buzău river alluvial fan, from a quantitative point of view, it is necessary to collect the information of all the hydrogeological boreholes and wells from this area. Depending on the degree of importance of each exploitation and the required flow, an operating program can be defined that does not affect the regeneration capacity of the aquifer and the consumers. A complex exploitation program can be created using a mathematical model, which can take into account the period in which the water is exploited (e.g., for irrigation a continuous flow is not required) and the variation of the flow over time (e.g., water demand: winter period vs summer period).

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