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SIMULATION OF MINE WATER INFLOW: CASE STUDY OF THE ŠTAVALJ COAL MINE (SOUTHWESTERN SERBIA)

SYMULACJA WPŁYWU WÓD KOPALNIACH DO WYROBISKA. STUDIUM PRZYPADKU: KOPALNIA WĘGLA STAVALJ (POŁUDNIOWO-ZACHODNIA SERBIA)

The inflow of mine water to mining operations is often caused by random events such as precipitation. Consequently, the mine water inflow regime can be defined as a function of random events applying the theory of random processes.

Regression models of the multiple linear correlation type have been used to simulate the inflow of mine water into mining operations, produce short-range predictions and facilitate rapid response inside the mine. The significance of such models lies in the ability to simulate and predict the consequences (mine water inflow), caused by events of a random nature (meteorological parameters: precipitation and air temperature).

The presented prognostic models have been calibrated for mine water inflow to the Štavalj Coal Mine in southwestern Serbia. Mathematical dependencies were defined based on daily mine water inflow rates recorded during the period from 2003 to 2011, which can be used to generate short-range (1-7 day) predictions of mean daily mine water inflow rates to the Štavalj Coal Mine. A strong correlation (coefficient of correlation $r = 0.93$, Sig. = 0.00) was derived for the one-day forecast. The coefficients of correlation for predictions of mean daily mine water inflow rates related to time periods of two, three...seven days gradually declined to 0.63 (7-day mean daily inflow rate).

Keywords: mine water, coal, simulation, short-range prediction

Przedostawanie się wody do wyrobisk górniczych spowodowane jest czynnikami losowymi, na przykład opadami. Dlatego też dopływ wód kopalniach zdefiniować można jako funkcję czynników losowych, z zastosowaniem teorii procesów losowych.

Symulacje dopływu wód kopalniach do wyrobiska prowadzono z wykorzystaniem modelu regresji typu wielokrotnych korelacji liniowych, na tej podstawie opracowano prognozy krótkoterminowe, tym

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samym umożliwiając podjecie szybkich działań w kopalni. Znaczenie modeli takich polega na ich przydatności do symulacji i przewidywania skutków dopływu wód kopalnianych, spowodowanego czynnikami losowymi (parametry meteorologiczne: opady i temperatura powietrza).

Zaproponowany model skalibrowany został na przykładzie badanego dopływu wód kopalnianych do kopalni Stavalj w południowo-zachodniej Serbii. Matematyczne zależności zdefiniowano w oparciu o dobowe natężenia przepływu wód kopalniach zarejestrowane w okresie od 2003 do 2011 roku, które wykorzystać można do opracowania krótkoterminowych prognoz (obejmujących 1-7 dni) średniego natężenia przepływu wody do kopalni węgla Stavalj. Stwierdzono wysoki poziom korelacji dla prognozy jednodniowej (współczynnik korelacji r = 0.93). Wartości współczynnika korelacji otrzymywane dla kolejnych dni stopniowo malały, do 0.63 dla prognozy siedmiodniowej.

Słowa kluczowe: wody kopalniane, węgiel, symulacje, prognozy krótkoterminowe

1. Introduction

Assessments of the conditions leading to the hydration of hard and subbituminous (black lignite) coal deposits in Serbia suggest that mine water inflow to underground mining operations is an inherent characteristic of all natural and anthropogenic processes that take place at a coal mining site.

The main feature of these processes is their random nature in space and time, such that their outcome (mine water inflow) also has the characteristics of a random process. Given that the causes of mine water inflow are random events such as precipitation, the mine water inflow regime can be defined as a function of such a process applying the theory of random processes.

The present research specifically assesses mine water inflow to the Štavalj Coal Mine. The Štavalj Coal Mine is one of the most prospective underground black lignite mining sites in Serbia (Fig. 1). Geological reserves of 240 million tons have been detected over only 20% of its surface area. However, it is also the wettest coal mine in Serbia. It was flooded on a number of occasions and measured mine water inflow rates as high as 200 l/s at certain coal extraction stages (Luković, 1970).

Fig. 1. Satellite image of the Štavalj Coal Mine

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Correlation theories of random processes were used to simulate and produce short-range predictions of mine water inflow to this particular mine. Based on daily mine water inflow, precipitation and temperature data recorded during the period from 2003 to 2011, mathematical dependencies suitable for inflow rate estimation as a function of meteorological conditions were defined. Multiple linear correlation functions were used to establish the mathematical dependencies. A prognostic function defined in this way can be used for short-range predictions of mine water inflow to mining operations for time periods of one to seven days or more.

2. Mine water inflow simulation methods

Regression models were used to simulate mine water inflow to mining operations, particularly the multiple linear regression model.

The multiple linear regression model is commonly used to simulate or predict certain variables (Krešić, 2010). If an event is a function of two or more independent occurrences, then we speak of multiple linear regression. If the regression analysis is aimed to test multiple correlations, the number of observations N should be $N > 50 + 8$ m, where N – number of observations and m – number of independent variables (Tabachnick et al., 2007; Soldić-Aleksić, 2011). The significance of this type of model lies in the ability to predict the outcome of an event based on our knowledge about other occurrences. A correlation is in fact established between the dependent variable Y and independent variables X_1, X_2, ... X_k, to simulate or predict the independent variable over a certain time period (Prohaska, 2006). This dependency is expressed by the following regression model:

$$Y_i = \beta_o + \beta_1 \cdot x_{1,i} + \beta_2 \cdot x_{2,i} + \ldots + \beta_n \cdot x_{n,i} + e_i \quad (1)$$

where:

Y_i — dependent variable of the i-th order;
x_i — independent variable of the i-th order;
β_i — unknown coefficients of multiple regression and
e_i — random error.

Applying the least square method, the unknown coefficients of multiple regression were computed and Equation (1) became:

$$\tilde{y} = a + b_1 \cdot x_1 + b_2 \cdot x_2 + \ldots + b_n \cdot x_n$$

where:

$\tilde{y}$ — analytical value of dependent variable;
$a, b_1, b_2, \ldots, b_n$ — computed numerical values of multiple regression coefficients.

3. Analysis of mine water inflow regime

Opening of the mine and the initial stages of mining at the Štavalj Coal Mine caused intensive drainage of groundwater from a fractured aquifer formed in Miocene sediments overlying the coal seam (Fig. 2). Mine water inflow to the mining operations largely came from the faults intersected by mining (Marković et al., 1996).

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Large surfaces excavated over time and caving of the coal seam roof enhanced surface water infiltration and enabled hydraulic linking of groundwaters from various faults (Zeremski et al., 1975).

While coal was being extracted from a relatively shallow section of the mine, mine water inflow fluctuated to a large extent during the year, depending on the precipitation regime (Luković, 1970). The ratio of minimum to maximum mean monthly mine water inflow rates was 1:3.

Under present mining conditions, where mining operations have reached a depth of 260 m from the ground surface, the mine water inflow rates are more uniform (Q = 51-77 l/s), but they still depend on the precipitation regime (Bukumirović, 2002). The inflow interferes with coal extraction and necessitates considerable expenditures for ongoing maintenance of the drainage system. The pumping capacity has been designed for the current inflow rates. Inflow predictions are extremely important for safety reasons, to ensure appropriate sizing of the mine drains and handling of the maximum expected inflow rates.

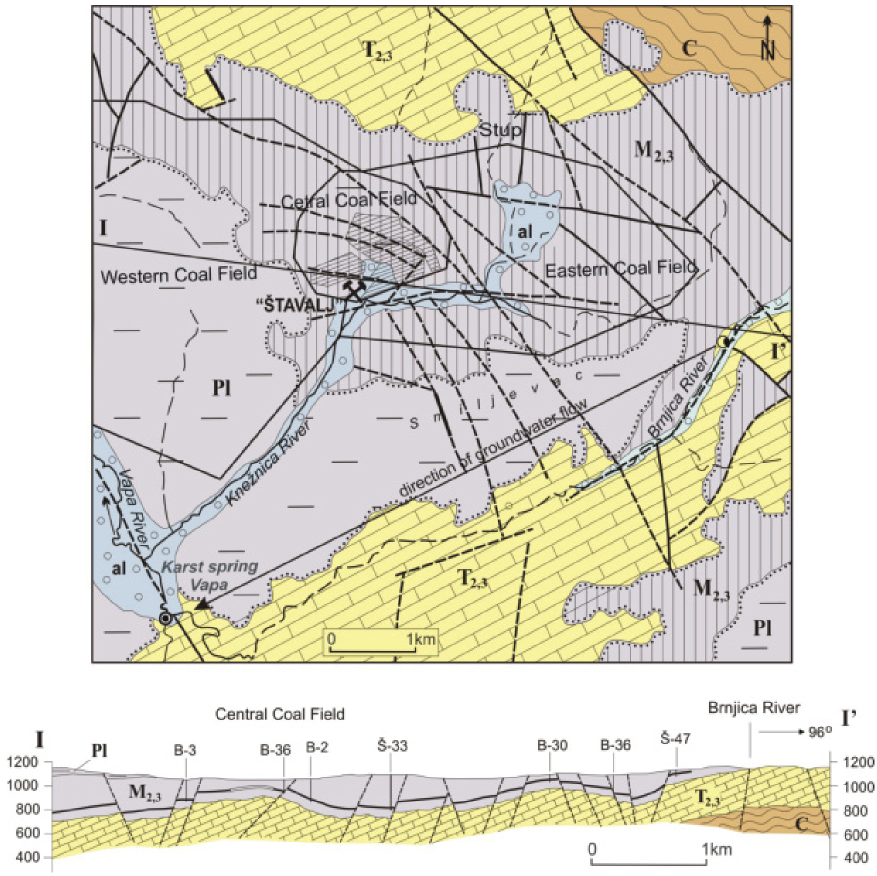

Fig. 2. Hydrogeological map of the extended area of the Štavalj Coal Mine, including characteristic section I-I' al – alluvium, intergranular aquifer; Pl – Pliocene gravel, sand and clay, hydrogeological complex; $M_{2,3}$ – Miocene marl, marly limestone, clay and coal, hydrogeological complex; $T_{2,3}$ – Middle and Upper Triassic limestones, karst aquifer; C – Carboniferous schists, non hydrated rocks

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The duration of minimal inflow rates is also very significant for coal mines. Such intervals are suitable for brief shutdowns of the drainage system to service electrical installations and piping, undertake pump maintenance or replacement, connect new drains, clean pipes from sediments that reduce their conveyance capacity, and the like.

To assess the groundwater regime and simulate groundwater inflow (Ristić-Vakanjac et al., 2012), it was necessary to first define the surface area of the terrain where inflow to the mining operations was formed directly from precipitation or indirectly by infiltration of a portion of the precipitation (Ristić, 2007; Ristić-Vakanjac et al., 2013). Based on available data (Čokorilo et al., 2011; Čokorilo, 2012), the mean annual evaporation rate (E) in the extended area of the Štavalj Coal Mine from 2003 to 2011 was 450 mm.

In the same area, the mean long-term precipitation total (P) from 2003 to 2011 was 807.6 mm. Based on these data, the runoff layer (h) was:

$$h = P - E = 807.6 - 450 = 357.6 \text{ mm}$$

The size of the drainage area (F) can be computed from the runoff layer (h) and mean annual groundwater inflow to the mining operations (Q), using the equation:

$$h = \frac{Q \cdot t}{F} \tag{2}$$

where t is the time period in seconds.

It follows from Equation (2) that the drainage area is:

$$F = \frac{Q \cdot t}{h} = \frac{0.069\,\text{m}^3/\text{s} \cdot 31.536 \cdot 10^6\,\text{s}}{0.357\,\text{m}} = 6.0951 \cdot 10^6\ \text{m}^2 = 6.1\ \text{km}^2$$

Table 1 shows the water balance parameters, where F is the size of the drainage area, P is the mean annual precipitation total, E is the mean annual evaporation rate, h is the runoff layer, Q_{av} is the average annual groundwater inflow rate to the mine, q is the specific runoff, W is the water volume and j is the runoff coefficient.

TABLE 1

Summary of groundwater balance parameters of the aquifer that discharges into the pit of the Štavalj Coal Mine

F (km^2)	P (mm)	E (mm)	h (mm)	Q_{av} (m^3/s)	q (l/s/km^2)	W (10^6 m^3)	φ
6.1	807.6	450	357.6	0.069	11.3	2.18	0.442

4. Multiple linear regression results

For multiple linear regression purposes, first an auto-correlation analysis of groundwater inflow to the mining operations (Fig. 3) and a cross-correlation analysis of precipitation and water inflow were undertaken for a time step of up to 100 days (Krešić, 2010), Figure 4.

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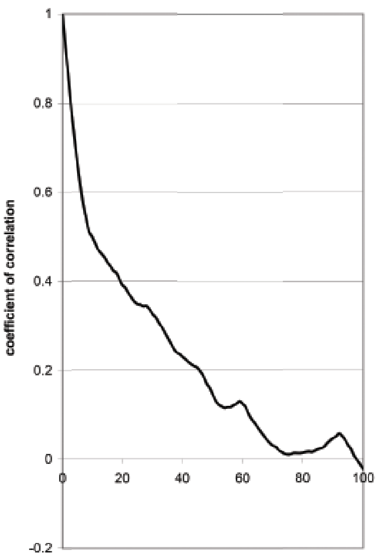

Fig. 3. Auto-correlation analysis of mine water inflow to the mining operations

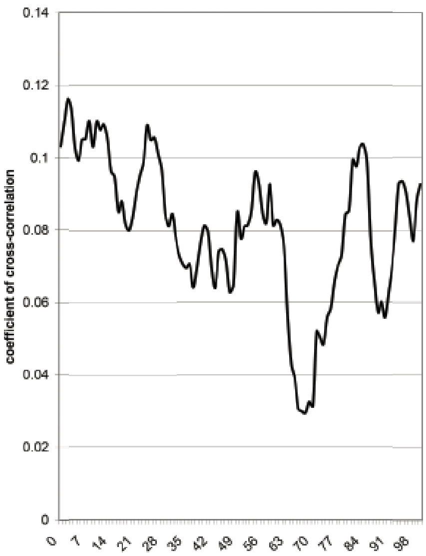

Fig. 4. Cross-correlation function of precipitation in the drainage area and mine water inflow to mining operations

Figure 3 suggests that the effect of the groundwater inflow rate rapidly decreased with time-step increase. The auto-correlation coefficient stagnated for time steps of 25 to 28 days, while the correlation coefficients increased after 69 and 93 days (two peaks in the auto-correlogram), as a result of snowmelt following a long and cold winter (after 2-3 months). This was corroborated by the cross-correlogram. Even though the coefficients of correlation between daily precipitation and daily groundwater inflow to the mine were low for different time steps (up to 100 days), the cross-correlogram exhibited distinct peaks after 1, 24, 56 and 84 days, indicating higher groundwater inflow rates caused by snowmelt.

Keeping this in mind and for the purpose of simulating mine water inflow using daily precipitation totals and mean daily temperatures, the predicted mean daily inflow to the Štavalj Coal Mine was derived applying multiple linear regression as follows:

$$Q_{in\ flow,i} = a + b_1 \cdot P_{i-1} + b_2 \cdot P_{i-24} + b_3 \cdot P_{i-56} + b_4 \cdot P_{i-84} + b_5 \cdot T_i \tag{3}$$

where:

$Q_{in\ flow}$ — mean daily water inflow to the Štavalj Coal Mine on the *i*-th day;
P — daily precipitation totals on days i–1, i–24, i–56 and i–84;
T — mean daily air temperature on day i–1;
$a, b_1, b_2, b_3, b_4, b_5$ — dimensionless parameters defined by the least square method.

The dimensionless parameters were obtained applying multiple linear regression and their values were:

$$Q_{in\ flow,i} = 66.766 + 0.0354 \cdot P_{i-1} - 0.0094 \cdot P_{i-24} - 0.0172 \cdot P_{i-56} + \\ + 0.0025 \cdot P_{i-84} + 0.271 \cdot T_{i-1} \tag{4}$$

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Analysis of the impact of predictor (Equation 4) on the variable (mine water inflow), are shown in Table 2.

TABLE 2

Analysis of the impact of predictor (Equation 4) on the variable (mine water inflow)

Dependent variable	**Independent variable**	**Standardized Coefficients** ***β***	**Sig.**
Mine water inflow at the moment *i*	Precipitation at the moment i–1	0.019	***0.039***
	Precipitation at th moment i–24	–0.011	0.492
	Precipitatin at the moment i–56	–0.019	0.211
	Precipitation at themoment i–84	0.003	0.855
	Air temperature at the momentu i	0.491	***0.000***

F = 202.20; Sig. = 0.00; r = 0.49; Sig. = 0.00; Adjusted R^2 = 0.23

There is explained 23% of the variance in the dependent variable (R^2 = 0.23) by the regression model. The coefficient of correlation is r = 0.49; Sig. = 0.00. The model is statistically significant (F = 202.20; Sig. = 0.00). Precipitation at the moment i–1 (β = 0.019; Sig. = 0.039) and the air temperature at the moment i–1 (β = 0.491; Sig. = 0.000), impact on the mine water inflow at the moment i (Table 2).

Figure 5 shows recorded groundwater inflow rates to the Štavalj Coal Mine and those computed from Equation (4).

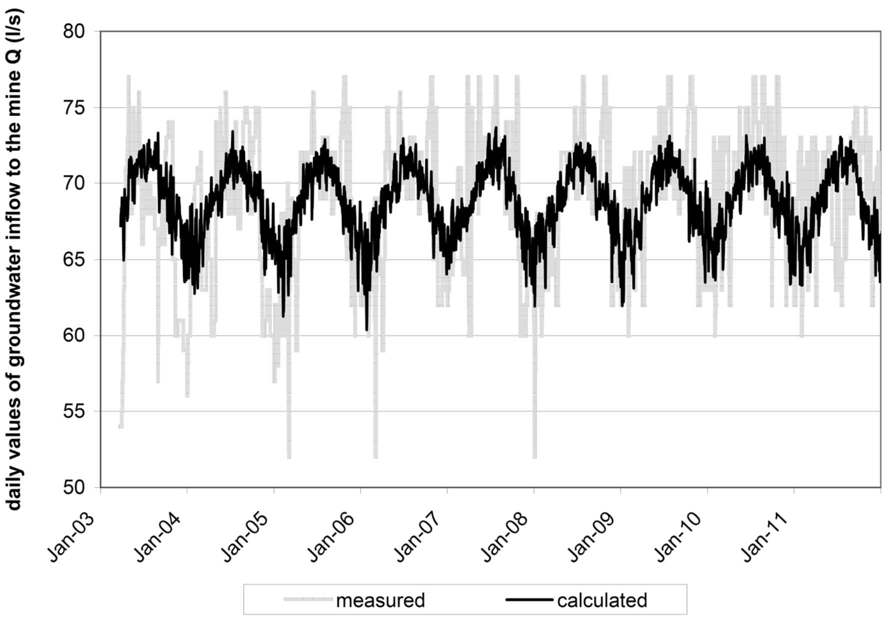

Fig. 5. Real and computed groundwater inflow rates to the Štavalj Coal Mine applying multiple linear correlation (Equation 4)

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A new dependency was established in order to ensure the best possible simulation of daily groundwater inflow rates. In addition to precipitation and temperature, an independent variable – groundwater inflow for a one-day time step – was introduced as:

$$Q_{in\ flow,i} = a + b_1 \cdot Q_{in\ flow,i-1} + b_2 \cdot P_{i-1} + b_3 \cdot P_{i-24} + \\ + b_4 \cdot P_{i-56} + b_5 \cdot P_{i-84} + b_6 \cdot T_{i-1} \qquad (5)$$

where:

$Q_{in\ flow}$ — mean daily water inflow to the Štavalj Coal Mine on days i and i–1;
P — daily precipitation totals on days i–1, i–24, i–56 and i–84;
T — mean daily air temperature on the i-th day;
$a, b_1, b_2, b_3, b_4, b_5, b_6$ — dimensionless parameters defined by the least square method.

Here, too, the dimensionless parameters were derived applying multiple linear regression and the values were:

$$Q_{in\ flow,i} = 6.319 + 0.9048 \cdot Q_{in\ flow,i-1} + 0.0087 \cdot P_{i-1} + 0.00156 \cdot P_{i-24} + \\ + 0.00175 \cdot P_{i-56} + 0.00527 \cdot P_{i-84} + 0.02648 \cdot T_{i-1} \qquad (6)$$

Analysis of the impact of the predictor (Equation 6) on the variable (mine water inflow), are shown in Table 3.

TABLE 3

Analysis of the impact of the predictor (Equation 6) on the variable (mine water inflow)

Dependent variable	**Independent variables**	**Standardized Coefficients** ***β***	**Sig.**
Mine water inflow at the moment i	Mine water inflow i–1	0.908	***0.000***
	Precipitation at the moment i–1	0.018	0.048
	Precipitation at the moment i–24	0.002	0.782
	Precipitation at the moment i–56	0.002	0.767
	Precipitation at the moment i–84	0.006	0.356
	Air temperature at the moment i	0.047	***0.000***

F = 353.4; Sig. = 0.00; r = 0.93; Sig. = 0.00; Adjusted R^2 = 0.86

There is explained 83% of the variance in the dependent variable (R^2 = 0.86) by the regression model. The coefficient of correlation is as high as r = 0.93; Sig. = 0.00. The model is statistically significant (F = 353.4; Sig. = 0.00). The mine water inflow at the moment i–1 (β = 0.908; Sig. = 0.000), the precipitation at the moment i–1 (β = 0.018; Sig. = 0.048) and the air temperature at the moment i (β = 0.047; Sig. = 0.000) impact the mine water inflow at the moment i (Table 3).

Figure 6 shows recorded groundwater inflow rates to the Štavalj Coal Mine and those computed applying Equation 6, for the entire study period.

In this way a strong correlation between computed and recorded groundwater flow rates was established. It can be used to predict in the short term (for the next day) the expected mine water inflow rate to the mining operations in the event of heavy rainfall.

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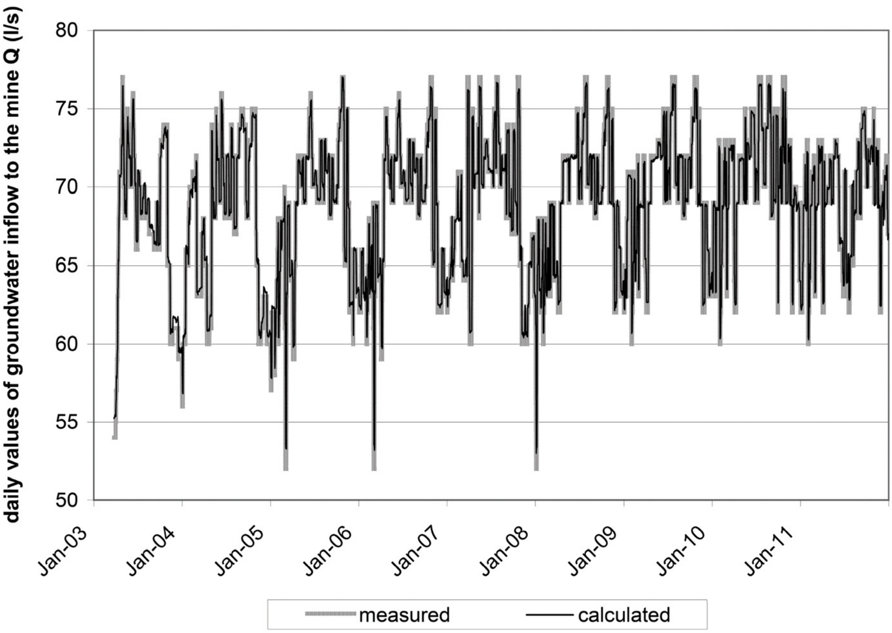

Fig. 6. Real and computed groundwater inflow rates to the Štavalj Coal Mine applying multiple linear correlation (Equation 6)

Multiple linear regression was also used to predict mean weekly inflow rates, as follows:

$$Q_{in\ flow,j} = a + b_1 \cdot Q_{in\ flow,j-1} + b_2 \cdot P_{j-1} + b_3 \cdot T_{j-1} \tag{7}$$

where:

- $Q_{in\ flow}$ — mean weekly inflow rate to the Štavalj Coal Mine, j-th week;
- P_{j-1} — weekly (7-day) precipitation total for week $j-1$;
- T_{j-1} — mean weekly air temperature for week $j-1$;
- a, b_1, b_2, b_3 — dimensionless parameters defined by the least square method.

After the dimensionless parameters were computed, Equation (7) became:

$$Q_{in\ flow,j} = 27.798 + 0.5828 \cdot Q_{in\ flow,j-1} + 0.0041 \cdot P_{j-1} + 0.1171 \cdot T_{j-1} \tag{8}$$

Analysis of the impact of the predictor (Equation 8) on the variable (mean weekly mine water inflow), are shown in Table 4.

There is explained 54% of the variance in the dependent variable ($R^2 = 0.54$) by the regression model. The coefficient of correlation is $r = 0.73$; Sig. = 0.00. The model is statistically significant ($F = 179.1$; Sig. = 0.00). The mean weekly mine water inflow related to the previous week $j-1$ ($\beta = 0.590$; Sig. = 0.000) and mean weekly temperatures of the previous week ($\beta = 0.219$; Sig. = 0.000) affect the mean weekly mine water inflow (Table 4). Statistical significance for both variables is at the 0.01 level. Likewise, total precipitation for the previous week affects

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the mean weekly mine water inflow (β = 0.180; Sig. = 0.049) (Table 4). This significance is at the very threshold limit value of statistical significance (0.05), but it also exceeds it, thus the impact has been confirmed.

TABLE 4

Analysis of the impact of the predictor (Equation 8) on the variable
(mean weekly mine water inflow)

Dependent variable	Independent variables	Standardized Coefficients β	Sig.
Mean weekly (7 days) mine water inflow	Mean weekly, but related to the previous week (j–1), mine water inflow	0.590	***0.000***
	Total precipitation for the previous week (j–1)	0.180	***0.049***
	Mean weekly temperatures of the previous week (j–1)	0.219	***0.000***

F = 179.1; Sig. = 0.00; r = 0.73; Sig. = 0.00; Adjusted R^2 = 0.54

Figure 7 shows recorded mean weekly groundwater inflow rates to the Štavalj Coal Mine and those calculated from Equation (8), for the entire study period.

Equation (8) can be used to predict mean weekly inflow rates to the Štavalj Coal Mine, or to predict in the short term (7 days) the expected average mine water inflow to the mining operations in the event of heavy rainfall.

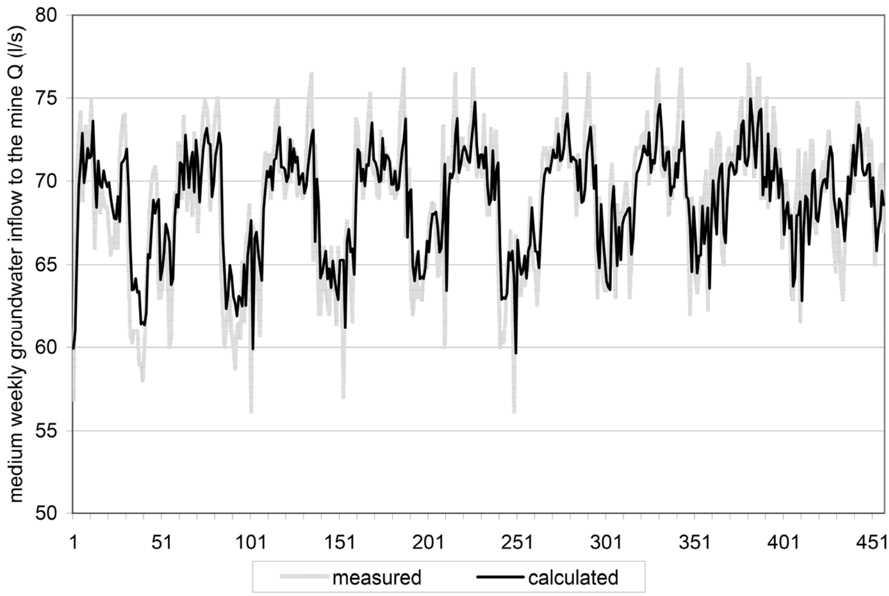

Fig. 7. Real and computed mean weekly groundwater inflow rates to the Štavalj Coal Mine applying multiple linear correlation (Equations 8)

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5. Discussion

The application of proposed multiple regression models required for the simulation of daily rates of mine water inflow (Equations 4 and 6) as well as the statistical analysis of the impact of the predictor on the analysed variable (Tables 2 and 3) have indicated that precipitation, temperatures and mine water inflows recorded for previous days justify statistically the formation of the proposed regression equation. However , it is statistically proved that previous precipitation recorded for 24, 56, and 84 days is not statistically justified to be used in the contemplated regression equations (Tables 2 and 3). In this case, for the above reasaons, the following regression dependence was used for simulation requirements of mine water inflow daily rates of the Štavalj Mine:

$$Q_{in\ flow,i} = a + b_1 \cdot Q_{in\ flow,i-1} + b_2 \cdot P_{i-1} + b_3 \cdot T_{i-1} \tag{9}$$

where:

$Q_{in\ flow}$ — mean daily water inflow to the Štavalj Coal Mine on days i and i–1;
P — daily precipitation totals on days i–1;
T — mean daily air temperature on the i-th day;
a, b_1, b_2, b_3 — dimensionless parameters defined by the least square method.

After the dimensionless parameters were computed, Equations (9) became:

$$Q_{in\ flow,i} = 6.20522 + 0.90681 \cdot Q_{in\ flow,i-1} + 0.00736 \cdot P_{i-1} + 0.02617 \cdot T_{i-1} \tag{10}$$

Analysis of the impact of the predictor (Equation 10) on the variable (mean daily mine water inflow), are shown in Table 5.

TABLE 5

Analysis of the impact of the predictor (Equation 10) on the variable
(mean daily mine water inflow)

Dependent variable	**Independent variables**	**Standardized Coefficients β**	**Sig.**
Mine water in flow at the moment i	Mine water inflow at the moment i–1	0.909	***0.000***
	Precipitation at the moment i–1	0.018	***0.048***
	Air temperature at the moment i–1	0.047	***0.000***

F = 10615.4; Sig. = 0.00; r = 0.93; Sig. = 0.00; Adjusted R^2 = 0.86

The regression model explains 86% of the variance in the dependent variable (R^2 = 0.86). The coefficient of correlation is as high as r = 0.93; Sig. = 0.00. The model is statistically significant (F = 10615.4; Sig. = 0.00). The mine water inflow at the moment i–1 (β = 0.909; Sig. = 0.000), the precipitation at the moment i–1 (β = 0.018; Sig. = 0.048) and the air temperature at the moment i (β = 0.047; Sig. = 0.000) affect the mine water inflow at the moment i (Table 5).

To determine mean daily inflow rates that can be expected in the next two, three, four,... seven days, correlations were established like in Equation (9), where the series of independent variables (precipitation, temperature and water inflow) reflected the time step for which the

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prediction was made (i–1, i–3, ... i–7). For example, a time step of two days was used for the independent variables to predict mean daily inflow rates, that is:

$$Q_{in\ flow,i} = a + b_1 \cdot Q_{in\ flow,i-2} + b_2 \cdot P_{i-2} + b_3 \cdot T_{i-2} \tag{11}$$

The same principle was applied to establish the correlations needed to predict mean daily inflow rates to the mining operations in the next 3, 4, 5, 6, and 7 days. The dimensionless parameters were determined applying the above-described procedure. The coefficients of correlation between recorded and computed daily inflow rates are shown in Table 6.

TABLE 6

Coefficients of correlation between computed and recorded daily inflow rates to the mining operations for different prognostic time intervals as well as anaysis of predictor impact on variable (mean daily mine water inflow)

Time interval	1 day	2 days	3 days	4 days	5 days	6 days	7 days
Adjusted R^2	0.86	0.75	0.64	0.56	0.49	0.44	0.39
F	10615.4**	4851.9**	2943.7**	2085.3**	1590.4**	1262.2**	1046.7**
Coefficient of correlation (r)	0.932**	0.867**	0.805**	0.753**	0.707**	0.665**	0.629**
Q_{i-n} (β)	0.909**	0.819**	0.728**	0.645**	0.573**	0.505**	0.450**
T_{i-n} (β)	0.047**	0.091**	0.139**	0.185**	0.220**	0.251**	0.273**
P_{i-n} (β)	0.019*	0.025**	0.017*	0.014	0.012	0.011	/

* Statistical significance at the level of 0.05
** Statistical significance at the level of 0.01

The multiple linear correlation method applied to simulate and generate short-range (one to seven day) predictions of mine water inflow rates to the Štavalj Coal Mine yielded good results. Analyses presented in Table 6 indicate that mine water inflows, precipitation and temperatures registered in time intervals of one, two or three days can be used for the prognosis of the mine water inflow up to 3 days in advance. After the third day precipitation loses statistical significance thus for the requirements of the simulation of mine water inflow for time intervals (4, 5, 6, and 7 days) only mine water inflows and temperatures can be used. The coefficients of correlation were from 0.63 to 0.93 (Equation 9 and 10 and Table 6). A common feature of the simulations and derived prognostic equations was that the computed values were generally higher than recorded values in the winter months, and vice-versa in the summer months (Figure 8).

The apparent differences were a result of snowfall and the temperature regime in the Štavalj Coal Mine area (alt. 1040 m), where the long-term mean air temperature was 6.4°C (1960-2011), and the mean monthly temperatures in December, January and February were almost always sub-zero. For this period, the model considered snowfall at the time of occurrence, and not from the time snowmelt and infiltration into the underground began.

For the duration of snow cover on frigid days, the computed inflow rates were higher than recorded rates, by up to 18% (Figure 8, black circles). When there was infiltration due to snowmelt, the computed inflow rates were up to 15% lower (Figure 8, red circle), compared to measured rates. These differences are numerically represented in Table 7.

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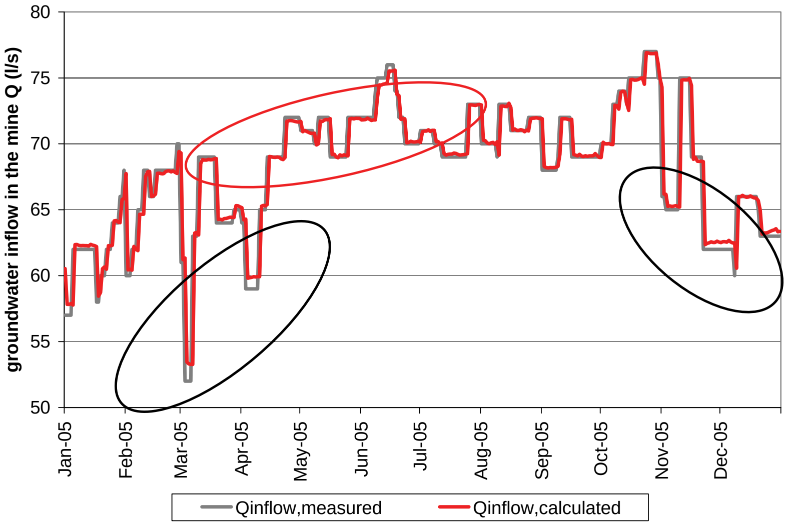

Fig. 8. Real and computed groundwater inflow rates to the Štavalj Coal Mine applying multiple linear correlation (Equation 10), year 2005

Due to a lack of data, the model did not take into account the temporal redistribution of precipitation occurring in the form of snow and remaining on the ground surface as snow cover.

TABLE 7

Mean monthly and absolute maximum and minimum monthly departures from computed inflow rates, relative to recorded rates (%), derived for the year 2005 using Equation (10)

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Av	–0.2	0.2	–0.8	0.0	0.1	0.2	0.0	–0.1	–0.3	0.5	–0.9	–0.4
Max	6.8	4.9	15.5	7.8	4.0	3.0	5.1	5.3	3.9	4.2	3.1	8.2
Min	–7.3	–12.9	–18.0	–9.0	–4.2	–2.7	–1.6	–4.2	–5.7	–1.4	–12.6	–4.1

Distinct differences between seasonal inflow rates to the mine (Fig. 9) corroborated the above findings. These differences were more pronounced in the coldest years, like 2003, 2005 and 2008 (Fig. 9). In 2011, which was the warmest year with very little snow, the differences between seasonal inflow rates were virtually negligible as the groundwater inflow to the Štavalj Coal Mine was rather uniform throughout the year (Fig. 9).

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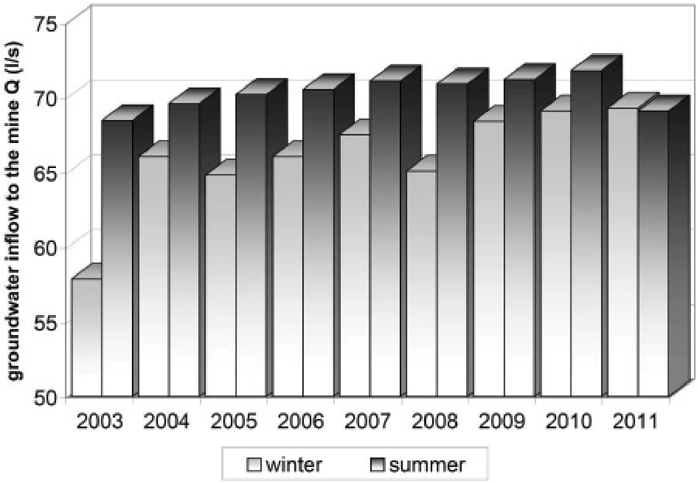

Fig. 9. Mean seasonal mine water inflow rates to the Štavalj Coal Mine

6. Conclusion

Regression models are commonly used to simulate or predict dependent variables. Multiple linear regression was applied in the present research to simulate and produce short-range predictions of groundwater inflow rates to the Štavalj Coal Mine. To establish correlations, the independent variables used included daily precipitation totals, temperatures and daily groundwater inflows for time steps of $i = 1, 2, 3...$, or for the time periods for which the mine water inflow prediction was generated. For short-range predictions of one day ($i = 1$), applying the theory of multiple linear regression, the equation

$$Q_{in\ flow,i} = 6.20522 + 0.90681 \cdot Q_{in\ flow,i-1} + 0.00736 \cdot P_{i-1} + 0.02617 \cdot T_{i-1}$$

produced very good results; the coefficient of correlation between recorded and computed inflow rates was 0.93. The same principle was applied to derive the dependencies needed to predict inflow rates to the mining operations in the next 2, 3, ... 7 days. As the prognostic time interval grew, the coefficient of correlation between computed and recorded values decreased, such that for the prognostic time interval of 7 days r = 0.63, which was still a strong enough correlation. However, although the correlation coefficients are satisfactory, the impact of precipitation loses statistical significance for short-range predictions exceeding three days ,thus, for these prognoses, there may be used only mine water inflows and mean daily temperatures with lengthening of time interval, for which short range predictions (4, 5, 6, and 7 days) are made.

It should be noted in closing that had snow data been available, the coefficients of correlation would have been much higher (i.e. the derived dependencies would have simulated groundwater inflow rates to the mining operations much better). In fact, the applied models did not take into account the time interval during which water was stored in the snow cover on the ground surface, or the period of snowmelt following an air temperature increase.

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