

Article

An Empirical–Analytical Model of Mine Water Level Rebound

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Abstract

This paper aims to develop a robust empirical–analytical model using the statistics of mine water level rebound in abandoned mines and the basic physical principles of underground hydraulics. The data collected and treated included the time series of the mine water level for 35 closed and flooded mines from four European countries. Within the developed model, mine water level evolution is governed by an ordinary differential equation with one fitting parameter that depends on the floodable cavity volume in a mine and water inflow before flooding begins. The model assumes that rock properties and residual void distribution are homogeneous, and the mines being flooded are almost isolated hydraulically from the neighboring ones. The exponential formula, as the governing equation solution, was found to be the most suitable for fitting the measurements. The calculated exponential curves allow for excellent or very good fitting of the measured water levels for 17 of 35 mines, and acceptable fitting for 11 mines in terms of minimizing mean-square-root deviation. The proposed approach can be applied to preliminary assessments of mine water level rebound in developing and calibrating sophisticated numerical flow models.

Keywords: flooding the mines; mine water level rebound; differential equation; modeling; fitting



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1. Introduction

In recent decades, the use of coal in the energy sector of predominantly European countries has been significantly reduced. To be in line with the UN Paris Climate Agreement, European and OECD countries need to be coal-power free by 2030 at the latest [1]. Most European countries have already closed their mines and are in the transition to the post-mining period.

Even in countries with a developed coal industry that is currently actively operating, mine closures are part of the resource development cycle. In China, which is the leader in coal production of about half of the world's production, 477 mines were closed in Guizhou province in the southwest of the country by 2021 [2]. In India, which ranks second in world production, 37 unprofitable mines were planned to close in 2017 [3]. In the USA, more than several hundred coal mines have been closed from 2008 to 2020 [4]. In 2017, only 104 of 270 Ukrainian coal mines were active [5], and the closure has been ongoing in all coal mining areas of the country until now.

The closure of hundreds of mines around the globe requires thorough planning of the transition to the post-mining period and especially forecasting the mine water level rebound in underground mine workings to avoid negative after-effects such as water

quality deterioration, land subsidence, gas displacement, etc. [6]. Particularly, mine water level rebound plays an essential role in developing the land surface uphill, which may cause much damage to buildings and facilities in post-mining areas. Using soil mechanics relations, an analytical model based upon the principle of effective stress and mine water ponds was implemented with the support of satellite surveying data to estimate surface heave in response to measured groundwater level changes [7]. The same process was simulated numerically in [8] for both unconfined and confined hydraulic conditions, with the water level being the crucial boundary condition. So, mine water level (MWL) rebound should be appropriately studied and predicted to develop and apply necessary measures in a timely manner.

The models developed in recent decades to predict MWL rebound, often in combination with other processes, are based on analytical, semi-analytical, and numerical approaches. The concept outlined in [9] combined 3D pipe networks as major mine roadways with a variably saturated porous medium using equations of hydraulics and groundwater flow. The developed model, GRAM, assumed volumes of workings as ponds interconnected only at discrete overflow points. The results of this approach applied to mines in the UK were then reviewed in [10]. A similar approach with hydraulic calculations of underground volumes as interconnected ponds was demonstrated in the examples of two mines in South Korea using the developed software that enables 3D visualization of groundwater level rebound georeferenced to a topographic map, locations of underground workings, and borehole data [11]. Most comprehensively, this approach has been implemented in the BoxModel [12,13], widely applied to water management in the complex multi-mine systems in the Ruhr coal mining area of Germany.

The currently applied numerical models of MWL rebound include the finite element method [14–17] and the finite-difference method [18–20]. On the one hand, the FEM and FDM models are deemed to be the universal tools for mine water and groundwater flow applications, especially in affected rocks with complex internal geometry and hydraulic connections. On the other hand, these models calculate the groundwater head that differs from the MWL. In addition, the uncertainties in geological data may minimize the advantages of detailed gridding by numerical models. In contrast, the analytical model [21], although applicable to hydraulically isolated mines, calculates the MWL directly as the time-dependent boundary condition and was able to reproduce the MWL rebound in three closed German collieries with high accuracy.

The set of numerical and analytical models of mine water flow can be enhanced by a simple model based on primary geological and mining parameters, considering the behavior of MWL rebound recorded in various conditions. Such a model would be an easy-to-use tool for predictions that could improve the reliability of calculations being made by sophisticated numerical models.

The idea of this study is to develop a robust, relatively simple model with a statistically based fitting curve for the MWL data with a minimum number of fitting parameters, substantiated also by the basic principle of groundwater and mine water flow. Such a model can be employed in the process of developing complicated numerical models and for analyzing their accuracy.

2. Materials and Methods

2.1. Data on Mine Water Level Rebound

The process by which groundwater or mine water levels increase following the cessation of mining operations and aggressive dewatering (the pumping of water out of the mine) is known as “mine water level rebound”. Water is pumped out during busy mining to keep the workings dry. Rainfall and natural groundwater input progressively replenish

the mine voids. This rebound process typically goes through a few different phases, each of which is distinguished by unique hydrodynamic circumstances.

The analysis made in [22] revealed three phases of MWL rebound in the general case. MWL rebound typically progresses through the stages of a quick increase at the beginning, a gradual stabilization period in the middle, and a long-term equilibrium phase at the end.

During the initial stage, the MWL rises relatively fast due to a usually smaller floodable void volume at lower levels of mining and larger hydraulic gradients. The low water column of the mine causes little hydrostatic pressure at inflow sites just after dewatering stops. As a result, deep groundwater influx rates are high, which causes water levels to rise quickly. Depending on the geometry of the local mine, rebound velocities during this period might reach several hundred meters annually [23].

In the intermediate stage, the MWL rebound rate slows down as the hydraulic head difference decreases and the floodable volume is successively filled with groundwater. Small inflows and a slow rise in the stabilizing water level in the shaft characterize the final stage of MWL rebound. Hydrostatic pressure rises as the mine fills, lowering input rates. Although at a reduced rate, typically less than 100 m annually, water levels are still rising. The slow approach to equilibrium characterizes this period [24].

In the final phase, the water level reaches a steady-state position when decreasing inflow and outflow are balanced. Rebound velocities drop to 1–2 m per month during this phase, and the system becomes closer to long-term stability [25].

The primary sources of input include vertical infiltration of surface or groundwater, deep groundwater influx, and inflows from lateral connections to nearby mines. Instead of happening at specific locations, these inflows often happen diffusely throughout mine roofs and the adjacent strata. Rebound curves and the volume of floodable voids are usually used to estimate inflow rates once dewatering is complete, as direct inflow measurement is only practical during active mining [26,27]. Natural groundwater recharge may be approximated by vertical inflow in regions with no protective overburden. Furthermore, as the Barredo and Figaredo mines showed, inflow may be significantly influenced by leakage from surface water sources like rivers or streams [28]. Early tracer studies also confirmed hydraulic connections between surface water and mine workings [28].

As part of the “Evaluation of Mine Water Rebound Processes” [22] project, experience in dealing with mine water management was gathered from a large number of European coal mining areas (Table 1). Measurement data on MWL rebound were compiled, analyzed, and evaluated. The measurement data were either provided directly by the mine water management operator or taken from publications, with curves on MWL rebound being digitized using computer software. The evaluation in this study focused on MWL rebounds recorded at the mines in four European countries.

A comparative presentation shows the significant variability in the rates of rise in the MWL in underground mine workings (Figure 1). This variability is due to the geometrical complexity of underground workings and the pronounced heterogeneity of the deposit and the overburden.

This general non-linear pattern with the fading MWL rebound rate can change in many sites due to uneven vertical distribution of floodable voids and heterogeneity of flow properties of rocks, even if hydrogeological conditions are almost stable. However, the external similarity of MWL evolution curves in the studied mines gives grounds to suggest a non-linear formula suitable for the general case. Among the basic regression types (linear, polynomial, exponential, logarithmic), the exponential one with a negative power looks the most preferable as it more clearly allows the bounding of the fading MWL evolution with the basic parameters of this process: hydraulic head difference and floodable volume. At

the same time, other types of regression can be better applied in some specific cases or to some time-limited periods of flooding.

Table 1. Basic data on flooding the mines analyzed in this study.

Name of Mine	Country	Flooding Duration, Month ¹	Number of Measurements	Increase in the MWL, m	Range of Flooding, m a.s.l.	Inflow Before Flooding, m ³ /a	Sources in Reference List
Königsborn	Germany	230	230	918.54	−894.52...24.02	n. a. ²	[24]
Westfalen	Germany	195	60	746.92	−1178.20...−431.28	n. a.	RAG data
Westfeld Ibbenbüren	Germany	32	32	560.88	−493.06...67.82	n. a.	[24]
Witten	Germany	29	29	509.38	−431.17...78.21	n. a.	RAG data
Warndt	Germany	95	95	966.66	−850.88...115.78	n. a.	[29]
Houve	France	78	78	772.96	−575.50...197.46	n. a.	[30]
Vouters	France	116	116	1158.98	−1033.19...125.79	n. a.	[31,32]
Simon 5	France	113	113	893.92	−768.19...125.73	n. a.	[31,32]
Barredo	Spain	10	10	277.23	−134.40...142.83	n. a.	[33]
Figaredo	Spain	10	10	335.05	−185.83...149.22	n. a.	[33]
Fishburn	The U.K.	154	54	210.02	−142.96...67.06	15,056	[34,35]
Michael	The U.K.	90	84	252	−298.95...−46.95	23,000	[36,37]
Barnsley Main	The U.K.	240	240	370.76	−328.91...41.85	n. a.	[37–39]
Wellesley	The U.K.	269	113	322.78	−525.78...−203.00	n. a.	[36]
Horden	The U.K.	127	127	250.55	−258.80...−8.25	40,800	[6,34,39]
Dawdon	The U.K.	126	126	253.28	−260.25...−6.97	1680	[34,37,39]
Easington	The U.K.	154	154	406.80	−415.80...−8.99	9840	[34,37,39]
Hawthorn	The U.K.	124	124	265.88	−267.45...−1.57	n. a.	[34,39]
Wheal Jane No.2	The U.K.	8	8	368.05	−358.73...9.32	60,000	[26]
Sherburn Hill	The U.K.	126	126	69.54	−45.01...24.53	6240	[34,37]
Nicholsons	The U.K.	126	126	73.56	−75.83...−2.27	3120	[34]
Lumley 6th	The U.K.	126	126	86.06	−95.20...−4.14	2880	[34]
Mainsforth	The U.K.	235	235	247.36	−175.42...71.94	16,400	[34,40]
Bates	The U.K.	183	183	49.49	−46.26...3.23	280	[6]
Bedlington	The U.K.	220	220	93.33	−90.03...3.30	n. a.	[6]
New Delaval	The U.K.	220	220	78.40	−78.88...−0.48	n. a.	[6]
Ladysmith	The U.K.	240	240	40.49	68.54...109.03	9820	[35]
Woodhouses	The U.K.	240	240	40.53	67.39...107.92	n. a.	[35]
Thurcroft	The U.K.	236	64	636.60	−724.10...−87.50	960	[41–44]
Kilnhurst	The U.K.	240	154	528.43	−486.58...41.85	2000	[38,43]
Oxcroft	The U.K.	104	104	124.48	−109.31...15.17	n. a.	[6]
Langton	The U.K.	82	82	164.71	−177.66...−12.95	n. a.	[6]
Lochhead	The U.K.	77	76	233.66	−276.55...−42.89	9029	[36,37]
Frances	The U.K.	185	185	216.48	−218.51...−2.03	6.135	[6,36]
Markham Main	The U.K.	58	58	102.80	−167.08...−64.28	n. a.	[45]

¹ measurements are converted to one per month; ² n. a. means not available.

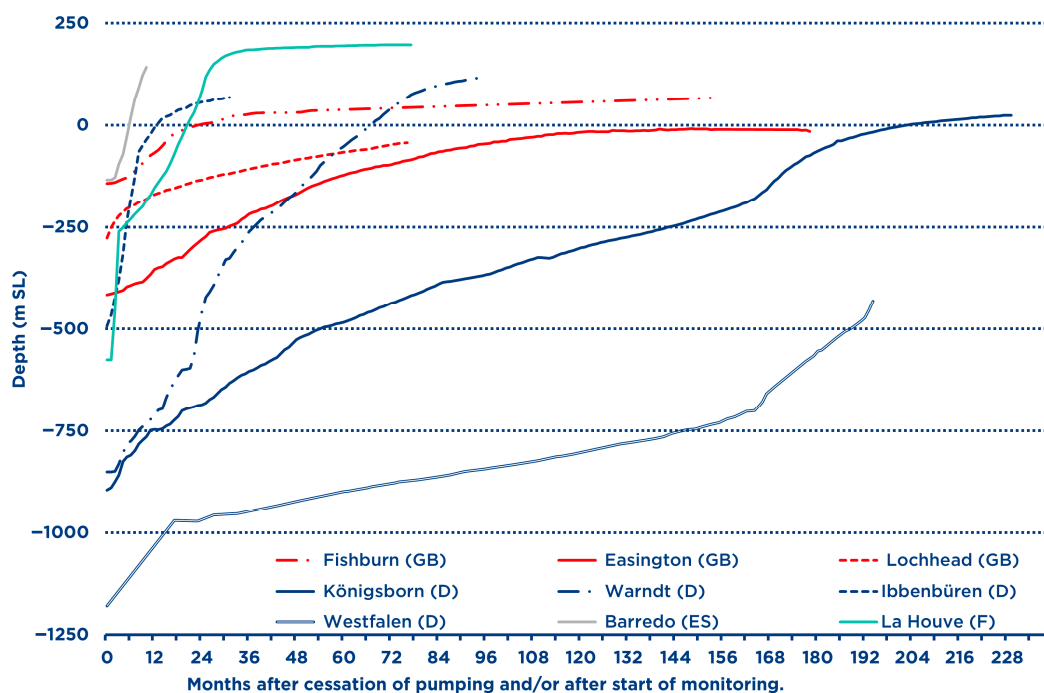


Figure 1. MWL rebounds in European hard-coal mining regions [22].

Generative artificial intelligence (GenAI) has not been used in this study.

2.2. Assumptions and Equations

In the proposed model, we assume the following:

- (1) The mine is hydraulically isolated;
- (2) Homogeneous rock properties within the area are affected by mining and remaining cavity volumes;
- (3) Inflow to the mine is driven by the difference between the almost static groundwater head on the outer boundary and the MWL;
- (4) The inflow rate to the mine is proportional to the rate of water exchange before the MWL rebound in the quasi-steady state as the integral indicator of the flow property of the entire mine;
- (5) Mine drainage is inactive during the period of flooding.

A change in the MWL h_{mw} can be governed by an ordinary differential equation that relates the rate of MWL rebound to the difference between h_{mw} and the static groundwater head on the remote boundary h_{max} as follows:

$$\frac{dh_{mw}}{dt} = -\beta \cdot (h_{max} - h_{mw}) \quad (1)$$

where $h_{mw}(0) = h_{min}$, h_{min} is the MWL at the beginning of flooding, and t is time.

Replacing $\Delta h(t) = h_{max} - h_{mw}(t)$ yields

$$\frac{d\Delta h_{mw}}{dt} = -\beta \cdot \Delta h_{mw} \quad (2)$$

with $\Delta h_{mw}(0) = h_{max} - h_{min}$.

By solving Equation (2), we obtain

$$h_{mw}(t) = h_{min} + (h_{max} - h_{min}) \cdot [1 - \exp(-\beta \cdot t)] \quad (3)$$

In terms of physical sense, β quantifies the intensity of water exchange in rocks affected in the mining field. Approximately, it can be evaluated as

$$\beta = \frac{\dot{V}_0}{V_{fld}} \quad (4)$$

where $\dot{V}_0$ is the inflow to the mine before flooding, and V_{fld} is the floodable volume of rocks within the mining field borders.

The value of V_{fld} can be assessed either as the residual void volume above the MWL before flooding (if this data is available) or as the

$$V_{fld} = V_{f,0} \cdot p_{fl} \cdot n_t \quad (5)$$

where $V_{f,0}$ is the total volume of rocks and voids within the mining field borders and the flooded interval, p_{fl} is the non-saturated part of this volume above the virtual depression cone simulating the mine as the “big well”, and n_t is the total porosity of the affected rocks, including natural active porosity and the voids that appeared due to mining operations.

For example, for the mining area of 20 km², deepening to 800 m, $V_{fld} = 1.6 \times 10^{10}$ m³. If the inflow to the mine $\dot{V}_0 = 3200$ m³/d, and the total porosity $n_t = 0.01$, $p_{fl} = 0.05$, we evaluate β at 4.0×10^{-4} 1/d or 34.6 1/s.

Note that Equation (3) is applicable if the groundwater level at the far boundary h_{max} remains constant during the flooding.

The initial inflow $\dot{V}_0$ and floodable volume $V_{f,0}$ are crucial to evaluating the rate of flooding. Unfortunately, these parameters were often missing in reports and papers. If model assumptions are correct for a particular mine, it is possible to apply Equation (3) for fitting the measured time series a posteriori. Still, without credible ranges of $\dot{V}_0$ and $V_{f,0}$, it is impossible to make reliable predictions of MWL rebound.

2.3. Deviation Between Measured and Calculated Time Series

To evaluate how the measured MWL is fitted by Equation (3) for the period $[0, t_f]$, we used the mean-square-root deviation, calculated as

$$\Delta h_f = \sqrt{\frac{1}{t_f} \int_0^{t_f} [h_{mw,c}(\tau) - h_{mw,m}(\tau)]^2 d\tau} \quad (6)$$

where t_f is the duration of MWL rebound; $h_{mw,c}$ and $h_{mw,m}$ are calculated and measured MWLs, respectively, m a.s.l.

The Root Mean Square Deviation (RMSD) criterion allows for assessing how well the calculated time series captures the overall trend of MWL evolution. By reducing the impact of isolated significant deviations, RMSD offers a more robust assessment than maximum absolute deviation, which is susceptible to individual measurement mistakes. Particularly in cases when the data are noisy or diverse, as in the case of MWL rebound, RMSD offers a more dependable measure of model correctness than maximum or absolute deviations since it is comprehensive, resilient, and interpretable.

The quality of fitting is also quantified by the relative deviation $\Delta h_{f,r}$ defined as follows:

$$\Delta h_{f,r} = \frac{\Delta h_f}{h_{mw,max} - h_{mw,min}} \cdot 100\% \quad (7)$$

where $h_{mw,max}$ and $h_{mw,min}$ are the maximum and minimum measured MWL, m a.s.l.

To fairly compare MWL time series across mines of various sizes and vertical flooding intervals, the relative deviation (Equation (7)) offers a standardized measure of model fidelity. In contrast to absolute deviation (Equation (6)), it enables avoiding bias from higher water levels, demonstrating the model's appropriate accuracy, i.e., the quality of fitting of measured MWL time series in mines of different sizes with different vertical intervals of flooding.

The deviation calculated by Equations (6) and (7) depends on model parameters, particularly on the parameter β . By minimizing Δh_f , it is possible to fit the measured level time series in the best way. Regarding the usually low accuracy of geological data, the particular task was to evaluate not only the optimal value of β but also its plausible ranges and model response to the variation in β .

The general criterion for fitting the measured MWL by Equation (6) is proposed as follows:

- $\Delta h_{f,r} < 3\%$ means for “excellent” fitting;
- $3\% < \Delta h_{f,r} < 5\%$ does “good” fitting;
- $5\% < \Delta h_{f,r} < 8\%$ does “acceptable” fitting;
- $8\% < \Delta h_{f,r} < 15\%$ does “poor” fitting;
- $h_{f,r} > 15\%$ does “unacceptable” fitting.

3. Results

All results of fitting the MWL by the exponential formula from Equation (3) (Table 2) can be subdivided into three groups following the criterion introduced in Section 3. Almost half of all cases (17 of 35) demonstrated a very low to small deviation $\Delta h_{f,r}$ below 5% between calculated and measured MWLs. In 11 of 35 cases, $\Delta h_{f,r}$ was from 5.3 to 7.6%, and for the remaining 7 cases, the deviation was from 8.7 to 14.4%, indicating poor fitting. The results for mines Königsborn, Sherburn Hill, and Kilnhurst in this score refer to the periods of best fitting (see remarks under Table 2). Generally, in most cases, the exponential formula proved to provide the best fit to the time series of MWL rebound.

Table 2. Results of fitting the measured MWL in 35 mines by Equation (3) with the parameter β .

Name of Mine	Δh_f , m	$\Delta h_{f,r}$, %	Rate of Exponential Fitting	Best Fit for β_{opt} , 1/d	Best Fitting Curve
Königsborn	52.45 25.30 ¹	5.71 3.54 ¹	Acceptable Good ¹	0.00033 0.000305 ¹	Exponential
Westfalen	72.88	9.76	Poor	0.000246	Linear, other
Westfeld Ibbenbüren	29.71	5.30	Acceptable	0.0048	Exponential
Witten	28.80	5.65	Acceptable	0.00396	Exponential
Warndt	71.05	7.35	Acceptable	0.00087	Exponential
Houve	38.67	5.00	Acceptable	0.00258	Other
Vouters	33.87	2.92	Excellent	0.00104	Exponential
Simon 5	47.87	5.36	Acceptable	0.001	Exponential
Barredo	39.10	14.10	Poor	0.0059	Linear
Figaredo	37.12	11.08	Poor	0.0057	Linear

Table 2. Cont.

Name of Mine	Δh_{fr} , m	Δh_{fr} , %	Rate of Exponential Fitting	Best Fit for β_{opt} , 1/d	Best Fitting Curve
Fishburn	11.3	5.38	Acceptable	0.00143	Exponential
Michael	7.07	2.81	Excellent	0.00099	Exponential
Barnsley Main	7.62	2.06	Excellent	0.00086	Exponential
Wellesley	2.28	0.71	Excellent	0.00063	Exponential
Horden	9.55	3.81	Good	0.00092	Exponential
Dawdon	10.70	4.22	Good	0.00079	Exponential
Easington	20.08	4.94	Good	0.00069	Exponential
Hawthorn	11.46	4.31	Good	0.00072	Exponential
Wheal Jane No.2	7.27	1.97	Excellent	0.0193	Exponential
Sherburn Hill	2.96 ² 5.19 ³	5.690 ² 10.90 ³	Good ² Poor ³	0.0024 ² 0.0007 ³	Exponential
Nicholsons	9.44	12.83	Poor	0.00042	Linear
Lumley 6th	10.73	12.47	Poor	0.00038	Linear
Mainsforth	9.82	3.97	Good	0.00075	Exponential
Bates	2.65	5.36	Acceptable	0.00055	Exponential
Bedlington	3.45	3.69	Good	0.00053	Exponential
New Delaval	4.80	6.12	Acceptable	0.00047	Exponential, linear
Ladysmith	2.79	6.90	Acceptable	0.00082	Exponential
Woodhouses	2.48	6.12	Acceptable	0.00082	Exponential
Thurcroft	5.92	0.93	Excellent	0.0005	Exponential
Kilnhurst	30.78 9.66 ⁴	5.83 2.94 ⁴	Acceptable Excellent ⁴	0.00049 0.00091 ⁴	Exponential
Oxcroft	17.87	14.36	Poor	0.00106	Other
Langton	9.73	5.91	Acceptable	0.00072	Linear
Lochhead	11.44	4.90	Good	0.00133	Exponential
Frances	1.83	0.85	Excellent	0.00075	Exponential
Markham Main	9.55	9.29	Poor	0.00106	Linear

¹ For the first period to 5050 days; ² for the first period from 730 to 1400 days; ³ for the second period from 1520 to 3833 days; ⁴ for the first period to 4563 days.

The typical examples of best fitting by Equation (3) (Figure 2) show a very high coincidence of the fitting curve with the measured time series. During the periods of MWL rebound, there could be single outranged measurements (mine Barnsley, the beginning of measurements), which, however, did not affect the quality of fitting in the whole and the ability of Equation (3) to predict the behavior of MWL rebound correctly.

The range of $\pm 20\%$ of the parameter β allows for predicting the range of MWL fluctuations during the period of flooding, even for the cases of worse fitting (Figure 3). The assessment of such a range for β looks realistic regarding geodata accuracy.

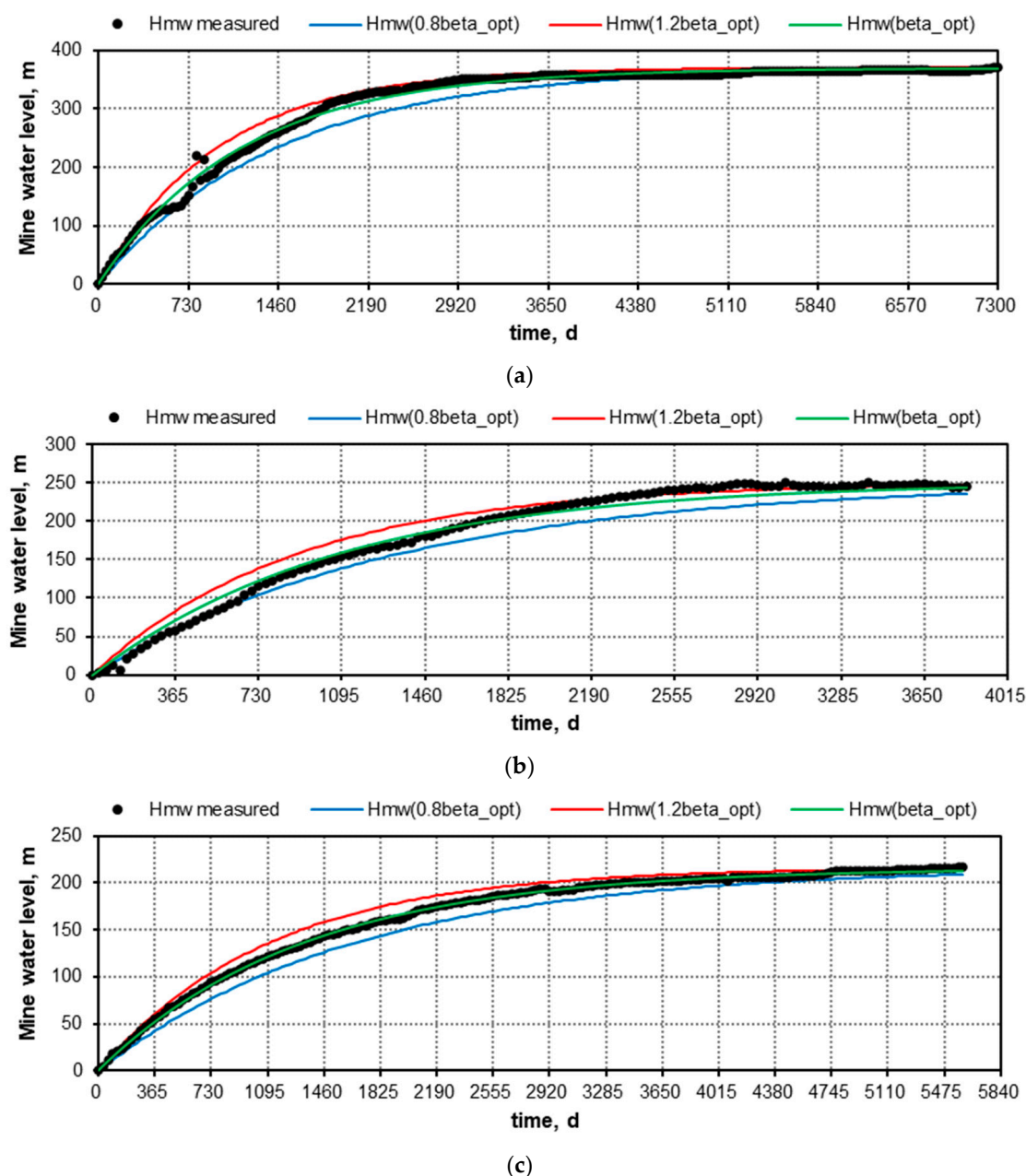


Figure 2. Fitting of MWL rebound with the minimum deviation by Equation (3) for the mines of Barnsley (a), Horden (b), and Frances (c) above the initial MWL position set to be 0 m. Points denote the measured MWL, the green line shows the fitting curve with the minimum deviation at β_{opt} , and the blue and red lines show the fitting curves calculated at $0.8\beta_{opt}$ and $1.2\beta_{opt}$.

The deviations of the measured MWL from the fitting curve may be caused by the heterogeneity of hydraulic conductivity, which demonstrates the case of the Königsborn mine (Figure 3b). After approximately 5000 days, as flooding began, the MWL reached low-permeable rocks with minor porosity, which accelerated MWL rebound. In the case of the Barredo mine (Figure 3c), the possible cause of poor fitting can be the unfinished flooding for the considered time range. The other likely causes of poor fitting could be the heterogeneous distribution of voids across the mining area, hydraulic connections with neighboring mines, and periodical impacts of mine drainage, which are often not documented adequately in available open sources.

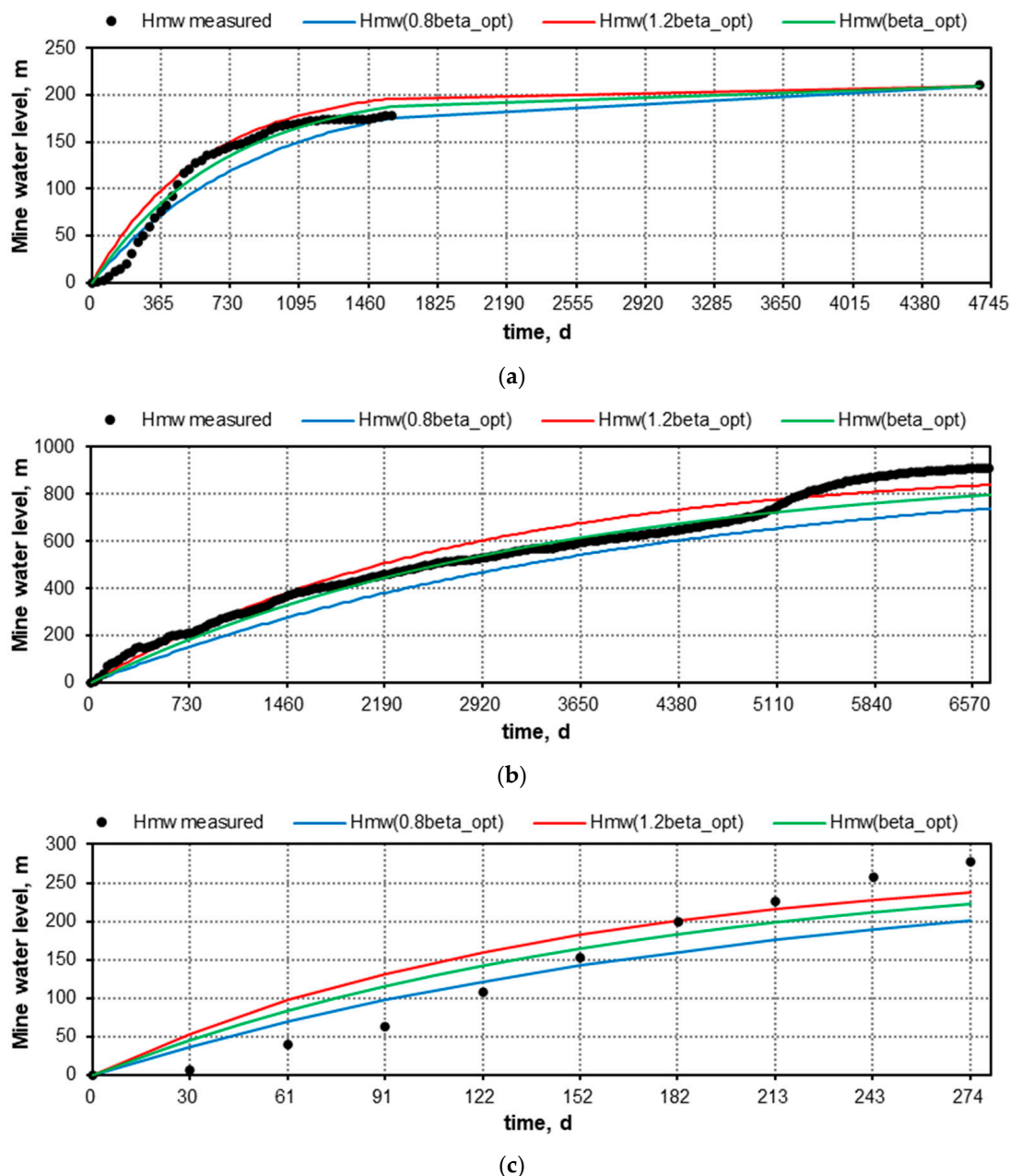


Figure 3. Fitting of MWL rebound with the minimum deviation by Equation (3) for the mines of Fishburn (a), Königsborn (b), and Barredo (c) above the initial MWL position set to be 0 m. Points denote the measured MWL, the green line shows the fitting curve with the minimum deviation at β_{opt} , and the blue and red lines show the fitting curves calculated at $0.8\beta_{opt}$ and $1.2\beta_{opt}$.

4. Discussion

Among the examined time series of MWL rebound brought together in Table 2, 26 of 35 fitting results (74%) have a relative deviation from 1.0% to 6.4% (Figure 4), which can be classified as “excellent” to “good” and quite “acceptable”. Most of the significant deviations with poor fitting were caused by the heterogeneity of rocks, the unfinished stage of MWL rebound, and the uneven distribution of voids in depth.

The exponential formula proved to fit the mode of MWL rebound for 26 cases the best. In contrast, linear regression showed better fitting in some time intervals, especially in cases where the data range refers to the unfinished MWL rebound (mines “Westfalen”, “Barredo”, and “Figaredo”).

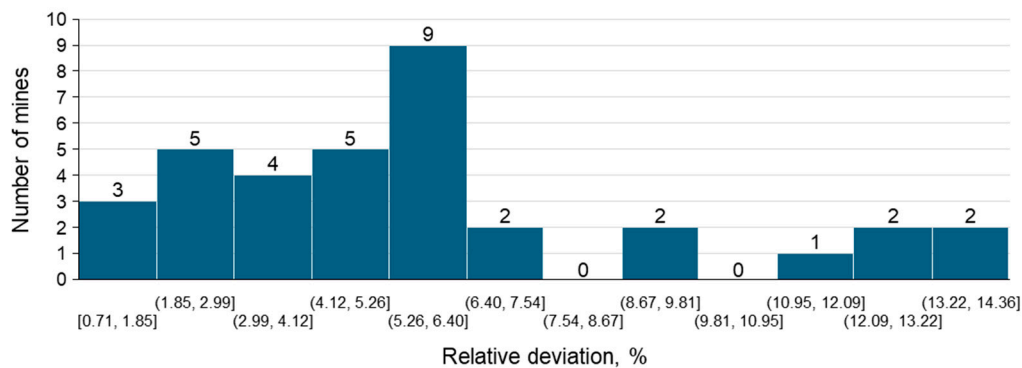


Figure 4. Distribution of fitting results (best fit for each mine is taken from Table 2).

In some cases, the MWL demonstrated essential fluctuations with temporary sinking of several meters, which was quite significant for the mines with a relatively small range of flooding of up to 40–50 m (mines “Ladysmith”, “Woodhouses”, and “Bates”). This could be the result of time-dependent recharge (infiltration), temporal drainage, or hydraulic connections to neighboring mines. In the case of mine “Sherburn Hill”, two periods of MWL rebound can be identified, with fast sinking in the middle of the observation period due to likely temporary mine dewatering. However, exponential fitting was good to acceptable if applied separately to both periods of MWL measurements in this mine.

The rate of MWL rebound depends on the parameter β that can be preliminarily evaluated by the mining data, following Equations (4) and (5). Regarding many uncertainties due to heterogeneities and multiple hydraulic connections inside and between the mines, this approach is likely not very exact. However, it can provide a first approximation for the range of β that can be refined afterwards. As an example, we compared the assessments of this parameter obtained by Equations (4) and (5) with the results of fitting by criteria in Equations (6) and (7) for three mines in Germany with known data on volume, the residual void volume, and the inflow before MWL rebound [21] (Table 3). In the following, the proposed assessments of the parameter β need to be refined.

Table 3. Results of fitting the measured MWL in three mines with known cavity volume by Equation (3) with the parameter β .

Name of the Mine	The Parameter β , 1/d, Assessed by		
	Equation (4) based on the data on residual volume	Equation (5) with calculations of floodable volume	Fitting of experimental curve by Equations (6) and (7)
Königsborn	0.00083	0.00051	0.000305...0.00033
Westfalen	0.00035	0.00007	0.000246
Westfeld Ibbenbüren	0.00215	0.00187	0.0048

5. Conclusions

In this study, we analyzed the behaviors of MWL rebound measured in 35 abandoned mines in four European countries using the developed empirical–analytical model. Based on empirical data analysis, an ordinary differential equation was proposed to govern MWL rebound in a single mine driven by the difference between the MWL on the outer boundary contour and the MWL in the shaft. The model fitting parameter of the rebound rate can be assessed by the floodable cavity volume in a mine and the mine water inflow before the MWL rebound begins. The model is applicable under a stable groundwater level on the

outer boundary, no drainage during flooding, and quasi-homogeneity of rocks affected by mining operations.

The governing equation solution obtained as the exponential formula was found to be the most suitable for fitting most of the measured time series. In case model assumptions do not meet geological and hydrogeological conditions fully, linear or another kind of regression can provide a better fit.

As the criterion of proximity of the calculated curve, we applied mean-square-root deviation and introduced the semi-quantitative scale of assessment, relating the absolute deviation to the flooded interval length. The calculated exponential curves allow for excellent (a deviation below 3%) or very good (a deviation of 3 to 5%) fitting of the measured MWL for 17 of 35 mines, and acceptable (a deviation of 5 to 8%) fitting for 11 mines. Obviously, the geological and hydrogeological settings of the examined mines do not fully match the model assumptions. But even under such conditions, the model demonstrated acceptable to excellent accuracy of fitting the measured time series in about 80% of cases.

The proposed approach allows for preliminary assessments of MWL rebound with a minimum number of known data, which is helpful at the stage of conceptualization, development, and calibration of sophisticated numerical flow models. Follow-up studies may include more exhaustive testing of the model on numerous cases around the world, a more accurate evaluation of model parameters using various methods, particularly selected indexes, and a comparison with the results of numerical modeling of mine flooding.

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Abbreviations

The following abbreviations are used in this manuscript:

a.s.l.	Above Sea Level
MWL	Mine Water Level
RMSE	Root Mean Square Deviation

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