The influence of aeration on the change in corrosiveness and aggressiveness of groundwater
Tadeusz Siwiec, Magdalena M. Michel, Lidia Reczek and Piotr Nowak

ABSTRACT
A high concentration of aggressive carbon dioxide disturbs many technological processes in water treatment. It also causes the development of corrosion in steel and concrete. De-acidification of groundwater by means of air bubbles alters pH and the concentration of aggressive carbon dioxide. This was investigated for the variables of air flow (\( Q = 20–50 \text{ L h}^{-1} \)) and height of water layer (\( H = 25–75 \text{ cm} \)) as well as aeriation time (\( t = 0–20 \text{ min} \)). The obtained three-parameter models showed good correlation with the experimental results, except in a few cases where \( r^2 \) was bigger than 0.9. Furthermore, they allow for prediction of an increase of pH and a decrease in concentration of aggressive carbon dioxide in aerated water. The effectiveness of de-acidification of groundwater was evaluated using indices of water stability (Langelier Saturation Index, Precipitation Index, Ryznar Stability Index, Aggressiveness Index and Index of Aggressiveness). Although as a result of aeriation an increase of pH over 7 was observed, the non-corrosive values of the indices were not reached. This was due to a very low alkalinity of water, which was 0.7 meq L\(^{-1}\).

Key words | aeration of water, aggressive carbon dioxide, de-acidification of water, water stability indices

INTRODUCTION
In groundwater dissolved carbon dioxide is almost always found (Satora 2008; Satora & Rutkowska 2008; Reczek et al. 2014), the concentration of which can decrease as a result of desorption to the ambient air, dissolution of carbonate rocks or the process of photosynthesis. Total carbon dioxide (\( \text{CO}_2^t \)) is present in water in the form of carbonate and bicarbonate alkalinity (\( \text{CO}_2^\text{alc} \)) as well as free carbon dioxide (\( \text{CO}_2^f \)), which is divided into affiliated (\( \text{CO}_2^\text{aff} \)) and aggressive carbon dioxide (\( \text{CO}_2^\text{agr} \)). Affiliated carbon dioxide is in equilibrium with bicarbonates. However, an excess of affiliated carbon dioxide in relation to the state of the calcium carbonate equilibrium is aggressive carbon dioxide which causes pH decrease and gives water corrosive qualities (Gomólkowie 1992; Buchta & Dąbrowski 1998; Pobierżnik et al. 2012). The symptom of high concentration of carbon dioxide is a low pH; this agrees with Langelier’s theory and is presented by Equation (1) (Gomólkowie 1992; Plottu-Pecheux et al. 2001):

\[
\text{pH} = -\log K_1 + \log \text{HCO}_3^- - \log \text{CO}_2^f
\]  
(1)

where \( K_1 \) is the ionization constant, \( \text{HCO}_3^- \) is alkalinity (meq L\(^{-1}\)) and \( \text{CO}_2^f \) is acidity (meq L\(^{-1}\)). Affiliated carbon dioxide can be calculated from Equation (2) and aggressive carbon dioxide can be calculated from Equation (3) (Gomólkowie 1992):

\[
\text{CO}_2^\text{aff} = 44 \cdot k \cdot (\text{HCO}_3^-)^3
\]  
(2)

\[
\text{CO}_2^\text{agr} = \text{CO}_2^t - \text{CO}_2^\text{aff}
\]  
(3)

where \( k \) is the calcium carbonate equilibrium constant which depends on temperature. A high concentration of \( \text{CO}_2^\text{agr} \)
disturbs many technological processes in water treatment, such as coagulation, demanganization, nitrification and others. It also causes corrosion development in steel and concrete. Water corrosiveness is a significant problem in those countries which desalinate their water supply (Withers 2005; Shams El Din 2009). Water corrosiveness is also a concern in relation to the processes of reverse electrodialysis (Myint et al. 2013). Corrosiveness of water is problematic for the distribution network and causes an increase in iron content at low flow rates, especially when the water is soft (Berghult et al. 2001). To control the corrosive effect of soft water, which is characterized by low buffer capacity, chemical methods are commonly used. Remineralization is a more reliable and effective method than the adding of phosphate (Jaeger et al. 2006). De-acidification through remineralization is not always preferable because it can decrease the effectiveness of subsequent treatment processes (Zymon 2007). As well as this, chemical de-acidification can be preceded by aeration, which will reduce water demand for chemicals. Although dissolution of carbon dioxide is a dozen times higher than dissolution of oxygen (Kowal & Świderska-Bróż 2007), during water aeration, dissolution of oxygen and, partially, other gases in water takes place. As a result, carbon dioxide is displaced from the water and this decreases its aggressiveness and corrosiveness. The aim of the research was to analyse the effectiveness of de-acidification of soft groundwater by means of bubbling in order to change the parameters of the process, i.e. air flow rate and water layer height, which led to the determination of empirical models describing changes of water pH and aggressive carbon dioxide concentration. The values of pH and $\text{CO}_2^{eq}$ were used to determine temporary indices of aggressiveness and corrosiveness of water during the process of aeration.

**MATERIALS AND METHODS**

**Characteristics of the groundwater**

Water with specific properties, which comes from a deep well located on the territory of a water supply station in Seroczyn in the rural administrative district of Wodynie near Warsaw, was used in the research. A detailed description of the water supply station and characteristics of groundwater quality are given in works by Reczek et al. (2014, 2015). The most important properties of this water were: very low pH 6.0 and alkalinity 0.7 meq L$^{-1}$, low hardness 2.7 meq L$^{-1}$ and high acidity 4.0 meq L$^{-1}$, which resulted in a high concentration of aggressive carbon dioxide of 61.6 mg L$^{-1}$. The concentration of oxygen in water taken directly from the well was close to zero (it fluctuated in the range of 0–0.1 mg L$^{-1}$). The water was characterized by an increased turbidity, colour and concentration of iron, manganese and nickel (6.18 NTU, 14 mg Pt L$^{-1}$, 3.81 mg Fe L$^{-1}$, 118 μg Mn L$^{-1}$, 41 μg Ni L$^{-1}$). The water contained minimal quantities of organic compounds (chemical oxygen demand (COD)–KMnO$_4$ 1.72 mg O$_2$ L$^{-1}$). An increased concentration of sulphates in relation to chlorides (128.0 mg SO$_4^{2-}$ L$^{-1}$, 46.8 mg Cl$^-$ L$^{-1}$) was comparatively unusual for Polish conditions.

**Aeration experiment**

The research was based on aeration of water applying a bubbling method in an open transparent column with a 3-cm diameter. It also had a porous glass grid. The pore diameter was 16–40 μm. The column was filled with the tested water from the upper part and at the bottom it was connected to an air pump and a rotameter. The porous grid distributed the air, which in the form of bubbles flowed through the layer of water – a similar set-up was described by Mouza et al. (2005). The intensity of aeration was regulated with the help of a valve and a rotameter. The independent variables were: air flow rate $Q$ (20, 30, 40 and 50 L h$^{-1}$), water layer height $H$ (25, 50 and 75 cm) and time of aeration $t$ (0, 0.5, 1, 2, 3, 4, 5, 10, 15 and 20 min). After each mentioned time of aeration the pH, alkalinity and acidity of the water were measured. The parameter tests on the water were carried out using the following analytical methods: pH – electrometric method; total alkalinity and acidity – titration methods (APHA/AWWA/WEF 1998). Aggressive carbon dioxide concentration ($\text{CO}_2^{eq}$) was calculated with the help of Equations (1)–(3). In order to measure alkalinity/acidity, water samples of 0.1 L were withdrawn, which significantly reduced the amount of water left in the column and thus prevented further sampling. For that reason the samples of water were aerated separately in the range of $t_0$–$t_20$. Oxidizing compounds of iron caused colmatage of the grid. For this reason it
was cleared every time in acid and cleansed with distilled water until the acidic reaction disappeared.

Data analysis

The results of pH measurements and aggressive carbon dioxide calculation enabled the identification of mathematical dependences which could describe the variability of these parameters. Linear, power, exponential, logarithmic, S type, hyperbolic, double hyperbolic and root models were analyzed. The selection criterion of the model was the highest possible coefficient of determination $r^2$ attributed to every dependence; it was assumed that $r^2 > 0.8$. Dependences of pH = $f(t)$ and $CO_{2}^{agr} = f(t)$ were analyzed, they were generalized by pH = $f(t,V)$ and $CO_{2}^{agr} = f(t,V)$ to pH = $f(t,V,H)$ and $CO_{2}^{agr} = f(t,V,H)$, where V is air flow velocity. Although the measurements were carried out measuring the air flow Q, in order to increase a universality of the model, air flow rate was used which was calculated according to the conventional formula $V = Q/F$, where F is a cross-sectional area of the column. The calculations were carried out in an Excel spreadsheet. Changes of water aggressiveness and corrosiveness after the aeration process were estimated on the basis of the indices presented in Table 1. To calculate the Langelier Saturation Index (LSI) described by Equation (4) three methods (I–III) were used and the respective equations: (I) Equation (5); (II) Equations (6)–(10); (III) Equation (11). Precipitation Index (PSI) was calculated using Equations (12) and (6), Ryznar Stability Index (RSI) using Equations (13)–(17), Aggressiveness Index (AI) using Equation (18), Index of Aggressiveness (IA) using Equation (19).

RESULTS AND DISCUSSION

Exemplary results of measurements of pH variation and aggressive carbon dioxide in water as a function of time are shown in Figure 1(a) and 1(b). The initial concentration of $CO_{2}^{agr}$ was high at about 65 mg L$^{-1}$. This value influenced the water’s pH so much that it was 6.0, which is not acceptable for water consumed by people (WHO 2011). As the aeration time passed the quality of the water improved, which is shown by a systematic increase in pH to the value of about 7.0–7.6 (Figure 1(a)) and a decrease of $CO_{2}^{agr}$ concentration to a value below 10 mg L$^{-1}$ (Figure 1(b)). All series were characterized by the same shape, except the series for $Q = 20$ L h$^{-1}$ and $H = 25$ cm. This was associated with small values of the control parameters, whose setting was not easy, and generated more errors. In each research series the highest decrease of $CO_{2}^{agr}$ concentration was observed in the first seconds of aeration, as after 0.5 min it dropped by about 50%. Further, $CO_{2}^{agr}$ concentrations decreased with less intensity in the time range of 0.5–5 min. After 5 min changes of concentration were not enough to be observable. The rapid decline in $CO_{2}^{agr}$ concentrations (strong nonlinearity), especially in the initial phase of aeration, may be due to the fact that the water drawn from the aquifer was at an elevated pressure, which promotes the saturation of CO$_2$. During the first several seconds in experimental conditions (ambient pressure) a rapid displacement of $CO_{2}^{agr}$ occurred by dissolving oxygen. After this, the process slowed and $CO_{2}^{agr}$ concentration decreased less rapidly. The pH value did not show irregular changes as it is a logarithmic dependence. During the first 5 min the intensity of changes was the highest, and pH was close to the value of 7.0. The increase of Q of the air, i.e. the quantity of bubbles flowing through the layer of water and total area of contact of the water with the air, had a greater influence on pH increase than on $CO_{2}^{agr}$ decrease. The increase of height of the water layer (H) led to an increase of pH and a decrease of $CO_{2}^{agr}$ concentration. This was caused by a prolongation of the contact time of the air bubbles with the water and intensification of the processes of diffusion of oxygen to the water and desorption of $CO_{2}^{agr}$. The influence of the height of the water layer on the effect of de-acidification was not as strong as the influence of air flow rate. However, it is rather noticeable as there were distinct differences between the measuring points assigned to certain measuring series. It is worth noting that, when the diameter of the column is constant, the increase of H of water translates to its larger volume; thus, in a given measuring series, when an intensity of aeration is constant and heights of the water layer are different, there is a different air volume to water volume ratio.

Table 2 presents determined models which describe pH and $CO_{2}^{agr}$ changes as a function of aeration time $t$, air flow velocity $V$ and water layer height $H$ for which $r^2 > 0.8$. The
models show good correlation with the experimental results. High values of determination coefficients were obtained. Except in a few cases $r^2$ is greater than 0.9, which confirms a very good agreement of the models with the experimental data. The applicability of the models’ ranges were specified for the scope of the studies. The graphs presented in Figure 2 prove this, the horizontal axis presents the values obtained from the measurements and the vertical axis shows the values calculated with the use of the models. The closer to the diagonal the points are, the better the matching of the model is to the measuring data, which are presented in graphs A and B for the two-parameter models. The points on graphs C and D are further from the diagonal, which is clear, because in the case of the models with a high

### Table 1 | Indices of aggressiveness and corrosiveness of water

<table>
<thead>
<tr>
<th>No.</th>
<th>Equations</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$LSI = pH_0 - pH_S$</td>
<td>$LSI &gt; 0$ calcium sediment precipitates and corrosive qualities of water are weakened</td>
<td>PN-72/C-04609 Woda i ścieki. (1987); APHA/AWWA/WEF (1998); Alvarez-Bastida et al. (2013); El Din (2009)</td>
</tr>
<tr>
<td>5</td>
<td>$pH_S = pK_2 - pK_s + pCa^{2+} + pHCO_3 + 5 \cdot pf_m$</td>
<td>$LSI = 0$ water does not have a tendency to precipitate or dissolve calcium carbonate and its corrosive qualities are also weakened</td>
<td>APHA/AWWA/WEF (1998); Plottu-Pechex et al. (2001); El Din (2009)</td>
</tr>
<tr>
<td>6</td>
<td>$pH_S = 9.3 + A + B - C - D$</td>
<td>$LSI &lt; 0$ water is capable of dissolving calcium compounds and its corrosive qualities are strengthened</td>
<td>PN-72/C-04609 Woda i ścieki. (1987); Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>7</td>
<td>$A = \log TDS - 10$</td>
<td>$PSI &lt; 0.5$ precipitation of calcium compound takes place</td>
<td>Marangou &amp; Savvides (2001)</td>
</tr>
<tr>
<td>8</td>
<td>$B = -13.12 \cdot \log (T + 273) + 34.55$</td>
<td>$PSI &lt; 1$ water is aggressive</td>
<td>Davil et al. (2009)</td>
</tr>
<tr>
<td>9</td>
<td>$C = \log Ca^{2+}$</td>
<td>$PSI &gt; 0.5-1$ medium sediment precipitation</td>
<td>Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>10</td>
<td>$D = \log HCO_3^-$</td>
<td>$PSI &gt; 0.5-1$ strong sediment precipitation</td>
<td>Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>11</td>
<td>$pH_S = 11.39 - 2 \cdot \log HCO_3^-$</td>
<td>$PSI &gt; 1$ very strong corrosion</td>
<td>Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>12</td>
<td>$PSI = 2 pH_S - pH_0$</td>
<td>$PSI &lt; 6.5$ precipitation of calcium compound takes place</td>
<td>Marangou &amp; Savvides (2001)</td>
</tr>
<tr>
<td>13</td>
<td>$RSI = 2 pH_{SR} - pH_0$</td>
<td>$RSI &gt; 6.5$ water is corrosive</td>
<td>Maragou &amp; Savvides (2001)</td>
</tr>
<tr>
<td>14</td>
<td>$pH_{SR} = pCa^{2+} + pAlc + CR$</td>
<td>$RSI &lt; 6$ medium sediment precipitation</td>
<td>Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>15</td>
<td>$pCa^{2+} = 4.9996 + 0.433 \cdot \ln HD$</td>
<td>$RSI &lt; 7$ weak sediment precipitation or early corrosion</td>
<td>Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>16</td>
<td>$pAlc = 4.7006 + 0.433 \cdot \ln HCO_3^-$</td>
<td>$RSI &gt; 7.5$ corrosion</td>
<td>Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>17</td>
<td>$CR = 2.4566 - 0.0189 \cdot T + 0.0363 \cdot \ln TDS$</td>
<td>$RSI &gt; 7.5$ corrosion</td>
<td>Alvarez-Bastida et al. (2013)</td>
</tr>
<tr>
<td>18</td>
<td>$AI = pH_0 + \log (HD \cdot HCO_3^-)$</td>
<td>$AI &lt; 10$ water is strongly corrosive</td>
<td>Davil et al. (2009)</td>
</tr>
<tr>
<td>19</td>
<td>$IA = \frac{(CO_{gr}^-)}{CO_{gr}^+}$</td>
<td>$IA &gt; 1$ water is aggressive</td>
<td>Gomólkowie (1992); Kowal &amp; Świderska-Bróż (2007)</td>
</tr>
</tbody>
</table>

$\text{pH}_0$: measured pH; $\text{pH}_S$: pH of the water in equilibrium with CaCO$_3$; $K_2$: second dissociation constant for carbonic acid; $K_s$: solubility product constant for CaCO$_3$. $K_2$ and $K_s$ values taken from (APHA/AWWA/WEF 1998); $Ca^{2+}$: calcium ion concentration in Equation (5) (mole L$^{-1}$), in Equation (9) (mgCaCO$_3$ L$^{-1}$); $HCO_3^-$: alkalinity in Equation (5) (meq L$^{-1}$), in Equations (10), (16), (18) (mgCaCO$_3$ L$^{-1}$); in Equation (11) (mgCO$_2$ L$^{-1}$); $f_{ac}$: activity coefficient for monovalent species; $p$: $-\log$ of variable; $TDS$: total dissolved solids (mg L$^{-1}$); $T$: temperature ($^\circ$C); $HD$: water hardness (mgCaCO$_3$ L$^{-1}$); $CO_{gr}^+$ and $CO_{gr}^-$: (mgCO$_2$ L$^{-1}$) $\text{pH}_0$ in Equation (12) calculated from Equation (6).
Table 2 | Models describing changes of pH and CO\textsubscript{2} as a function of aeration time \(t\), air flow velocity \(V\) and height of aerated water layer \(H\)

<table>
<thead>
<tr>
<th>Model type</th>
<th>No.</th>
<th>Model</th>
<th>Scope of application</th>
<th>(r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH = (f(V,t)) (a \cdot x^b)</td>
<td>20</td>
<td>(\ln pH = (0.01316 \cdot V + 0.01637) \ln t + (0.0576 \cdot V + 1.8057))</td>
<td>(20 &lt; Q &lt; 50) (L h(^{-1}))</td>
<td>0.81–0.97</td>
</tr>
<tr>
<td>pH = (f(V,t)) (a + b \ln x)</td>
<td>21</td>
<td>(pH = (0.09914 \cdot V + 0.09605) \ln t + (0.3958 \cdot V + 6.0575))</td>
<td>(20 &lt; Q &lt; 50) (L h(^{-1}))</td>
<td>0.92–0.97</td>
</tr>
<tr>
<td>(\text{CO}_2) = (f(V,t)) (a \cdot x^b)</td>
<td>22</td>
<td>(\ln \text{CO}_2 = (-0.23736 \cdot V + 0.21547) \ln t + (-0.9254 \cdot V + 4.17589))</td>
<td>(20 &lt; Q &lt; 50) (L h(^{-1}))</td>
<td>0.80–0.97</td>
</tr>
<tr>
<td>pH = (f(H,t)) (a + b \sqrt{H})</td>
<td>23</td>
<td>(pH = (0.00175 \cdot H + 0.17549) \sqrt{H} + (-0.0006 \cdot H + 6.1639))</td>
<td>(25 &lt; \text{H} &lt; 75) (cm)</td>
<td>0.94–0.97</td>
</tr>
<tr>
<td>(\text{CO}_2) = (f(H,t)) (a + b \ln x)</td>
<td>24</td>
<td>(\ln \text{CO}_2 = (-0.01133 \cdot H - 9.28819) \ln t + (-0.056 \cdot V + 32.5772))</td>
<td>(25 &lt; \text{H} &lt; 75) (cm)</td>
<td>0.96–0.98</td>
</tr>
<tr>
<td>pH = (f(V,H,t)) (a \cdot x^b)</td>
<td>25</td>
<td>(\ln pH = (-0.0005248 \cdot H + 0.02628) \cdot V + (0.000458 \cdot H + 0.00493) \ln t + ((-0.00224 \cdot H + 0.113) \cdot V + (0.00145 \cdot H + 1.7693)))</td>
<td>(20 &lt; Q &lt; 50) (L h(^{-1}))</td>
<td>0.83–0.96</td>
</tr>
<tr>
<td>(\text{CO}_2) = (f(V,H,t)) (a \cdot x^b)</td>
<td>26</td>
<td>(\ln \text{CO}_2 = ((0.0076896 \cdot H - 0.040237) \cdot V + (-0.00575 \cdot H - 0.1374) \ln t + ((0.021752 \cdot H - 1.45326) \cdot V + (-0.022554 \cdot H + 4.70129)))</td>
<td>(20 &lt; Q &lt; 50) (L h(^{-1}))</td>
<td>0.80–0.94</td>
</tr>
</tbody>
</table>
degree of universalism with three independent variables, it is
difficult to obtain a good correlation. However, the use of
these models allows for an estimation of the change of pH
and $CO_{2\text{agr}}$ during aeration of aggressive groundwaters. The
three-parameter model (Figure 2(d)) systematically overesti-
mates the concentration of $CO_{2\text{agr}}$ for small times of aeration.
This follows from rapid $CO_{2\text{agr}}$ desorption during the first
seconds of aeration of the water, which was highly saturated
with $CO_{2\text{agr}}$. Experimental uncertainty was estimated as fol-
lowing: for the pH-meter it was 0.01 and for the buffer it
was 0.02 (in sum $\text{pH} = \pm 0.03$). As a consequence the error
was 0.4%; for height of the water layer it was 2 mm and
0.8% for $H = 25 \text{ cm}$; for air flow rotameter 2.5%. In accord-
ance with the rule of propagation the uncertainty of the
experimental setup was 3.5%. The deviations between
models and measurements of pH were low and averaged
1.7%. However, measurement uncertainty of alkalinity and
acidity is difficult to estimate (APHA/AWWA/WEF 1998),
which probably increased the deviations between models
and measurements of $CO_{2\text{agr}}$ (on average 46%). Additionally

Figure 2 | Comparison of calculated and measured pH and $CO_{2\text{agr}}$ values as a function of aeration time $t$, height of water layer $H$, air flow velocity $V$. (a) related to Equations (21) and (23); (b) related to Equations (22) and (24); (c) related to Equation (25); (d) related to Equation (26).
the composition of water was atypical for Langelier’s equation, which was used to calculate $CO_{agr}^{2ff}$.

Figure 3 presents values of aggressiveness and corrosiveness indices of water for boundary research series for which the least and the most favourable de-acidification effects were obtained. These were $Q = 20$ L h$^{-1}$ and $Q = 50$ L h$^{-1}$ at $H = 25$ cm, respectively. The LSI values calculated by methods I and II give values which differ by only 0.01 and it can be assumed that they are identical. The LSI calculated using method III reduced values by 0.56; however, their dependence on the time and conditions of aeration is the same. As for the rest of the indices, the decrease of aggressive and corrosive qualities of the water was noticed during its aeration, which caused a decrease in water acidity caused by the presence of aggressive carbon dioxide. Although aeration allowed de-acidification of water and an increase of its pH over 7, the values of the indices at which the properties are considered to be non-corrosive were not reached. This was caused by the very low alkalinity of the water, which was 0.7 meq L$^{-1}$. Alkalinity does not change as a result of aeration of water, which is why the only possibility to improve the properties of de-acidified water would be an increase of alkalinity due to alkalinization. Alkalization is carried out by adding alkali (Ca(OH)$_2$, Na$_2$CO$_3$, NaOH) to water or by filtration of water through de-acidifying deposits containing CaCO$_3$, MgCO$_3$ or MgO.

**CONCLUSIONS**

Aeration of water favours the removal of an excess of $CO_{agr}^{2ff}$, which causes de-acidification of water and an increase of pH above the value of 7.0. It has an influence on the decrease of corrosiveness and aggressiveness of water, which was shown in the analysis of changes in the values of the LSI, RSI, PSI, IA and AI indices. With regards to very low alkalinity, groundwater after aeration does not lose its corrosive and aggressive qualities completely in relation to concrete. Bubbling with air enables removal of $CO_{agr}^{2ff}$ only; however, $CO_{aff}^{2ff}$ does not change. The increase in $Q$ of the air, i.e. the quantity of bubbles flowing through the layer of water (so-called total area of air and water contact) has more influence on water de-acidification effectiveness than an increase in $H$ of a water layer, which causes the prolongation of the time that air bubbles are contact with the water. Three-parameter models describe the changes of pH and $CO_{agr}^{2ff}$ well and allow for an estimation of the values of these parameters during aeration of aggressive groundwater with low alkalinity.

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