Rad et al. (2012)

Quantifying soil formation process has become an important topic in pedology, mainly as a response to increasing environmental problems (Hoosbeek and Bryant, 1992). Quantitative modeling allows us to describe the soil as a function of state factors: climate, organisms, relief, parent materials and time. Hoosbeek and Bryant [3] have formulated an equation to describe single factor as a function of soil properties. The described factors are based on a theoretical manner and empirically may be solved by experimentation or field observation. The empirical correlation still is mostly employed today and soil formation can be defined by varying a single factor and keeping the other factors constant; this technique was proposed by Huggett [4].

Minasny and McBratney [2, 10-12]. The model is based on mass balance, where the change in soil thickness with respect to time depends on the processes of:

- Formation of soil from physical weathering of bedrock;
- Loss of material by chemical weathering and
- Transport of soil by erosion. Soil formation depends on the rate of breakdown or weathering of the underlying parent materials under physical, chemical and biological processes. The continuity equation for the soil development with respect to time is formulated as: the change in soil elevation (soil thickness + bedrock weathering − soil weathering) with respect to time is equal to the transport of soil:

$$\frac{\partial h}{\partial t} + \frac{\rho r}{\rho s} \frac{\partial e}{\partial t} = -\nabla q$$

(1)

Where $h$ is the thickness of soil, $\frac{\partial e}{\partial t}$ is the rate of bedrock weathering, $\nabla$ = partial derivative vector $(\frac{\partial}{\partial x}, \frac{\partial}{\partial y})$, $q$ is the flux density (transport of soil material), $\rho_s$ is the density of soil and $\rho_b$ is the density of rock. The main processes drive the soil formation are weathering of bedrock and transport processes.


1. Introduction

Quantifying soil formation processes has become an important topic in pedology, mainly as a response to increasing environmental problems (Hoosbeek and Bryant, 1992). Quantitative modeling allows us to describe the soil as a function of state factors: climate, organisms, relief, parent materials and time. Hoosbeek and Bryant [3] have formulated an equation to describe single factor as a function of soil properties. He then pointed out that there are two principal methods that the state equation may be solved: first in a theoretical or conceptual manner by logical deductions from certain premises and second empirically by experimentation or field observation. The empirical method is still mostly...
Ahnert and Heimsath et al. [13] suggested that the state of physical weathering of bedrock \((\partial e/\partial t)\) can be represented as an exponential decline with soil thickness:

\[
\frac{\partial e}{\partial t} = -P_0 \exp(-k_1 h)
\]

Where \(P_0\) [m year\(^{-1}\)] is the maximum weathering rate of bedrock and \(K_1\) [year\(^{-1}\)] is an empirical constant. The reduction of weathering rate with thickening of soil related to the exponential decrease in temperature amplitude with increasing depth below the soil surface. Also, the exponent may decrease in average water penetration for freely-drained soils. Therefore, the parameters \(P_0\) and \(K_1\) are related to the climate and type of parent materials.

There is an intermediate or critical thickness \((h_c)\) where soil can hold enough water and the chemical weathering is the most effective parameter in the correlation. A number of landscape evolution models have adopted that is so-called “humped” model. Ahnert [13] described the humped model as a piecewise function:

\[
\frac{\partial e}{\partial t} = \begin{cases} 
& \text{For } h \leq h_c \left(1 + K_1 \frac{h}{h_0} - \frac{h^2}{h_0^2} \right) \\
& \text{For } h > h_c K_1 \exp(h_c - h) 
\end{cases}
\]

(3)

where \(h_c\) is defined as critical thickness, \(K_1\) is weathering constant which determines the relative magnitude of weathering when greater than \(h_c\) compared to base rock. As an alternative, Salvador et al. [12] presented a double exponential model which describes this weathering process:

\[
\frac{\partial e}{\partial t} = -(R_0[\exp(-K_1 h) - \exp(-K_2 h)] + P_e)
\]

(4)

Where \(K_1\) is the weathering rate of mechanical breakdown of rock materials and it is constant when and \(K_2\) is the rate of chemical weathering, when \(h \leq h_c\) and \(P_e\) is the weathering rate at steady-state condition [m year\(^{-1}\)] for condition \(K_1 = K_2\). The critical thickness where weathering is optimized is given by the following relation:

\[
h_c = \frac{\ln(K_2/K_1)}{K_1 - K_2}
\]

(5)
The mean value of soil thickness for the whole area shows a slow increase in the soil thickness at the initial stage, due to the weathering model which requires a critical thickness of 20 cm. After 20,000 years the rate of soil formation starts to reach steady state. It is also interesting to note that the standard deviation of the soil thickness increases with respect to time.


diffusivity coefficient (D) as constant parameter in landscape from the point of view of place and time. In fact, it was independent of slope and curvature. Nonlinear diffusivity has been found and a nonlinear relationship between sediment flux and gradient had been demonstrated. As the soil develops, the gradient and curvature will also change and consequently D (which is assumed to be constant) would change.

The evolution of soil thickness with time is presented in Fig. 4. The mean of the soil thickness for the whole area shows a slow increase in the soil thickness at the initial stage, due to the weathering model which requires a critical thickness around 20 cm. After 20,000 years the rate of soil formation starts to decrease. It is also interesting to note that the standard deviation of the soil thickness increases with time. Fig. 5 shows the

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( D ) (m² year⁻¹)</td>
<td>0.0003</td>
</tr>
<tr>
<td>( K ) (m year⁻¹)</td>
<td>0.1</td>
</tr>
<tr>
<td>( v ) (m year⁻¹)</td>
<td>0.0025</td>
</tr>
<tr>
<td>( n )</td>
<td>1.0</td>
</tr>
<tr>
<td>( m )</td>
<td>0.7</td>
</tr>
<tr>
<td>( P_0 ) (mm year⁻¹)</td>
<td>0.25</td>
</tr>
<tr>
<td>( P_s ) (mm year⁻¹)</td>
<td>0.05</td>
</tr>
<tr>
<td>( k_1 ) (m⁻¹)</td>
<td>4</td>
</tr>
<tr>
<td>( k_2 ) (m⁻¹)</td>
<td>6</td>
</tr>
<tr>
<td>( \rho_s ) (kg m⁻³)</td>
<td>2600</td>
</tr>
<tr>
<td>( \rho_a ) (kg m⁻³)</td>
<td>1500</td>
</tr>
</tbody>
</table>

The erosive diffusivity coefficient \( D \) is always assumed to be spatially constant in a landscape and to be independent of slope or curvature. Nonlinear diffusivity transport has been found and a nonlinear relationship between sediment flux and gradient has also been demonstrated (Roerin 1999). This kind of formulation needs to be incorporated into the model.