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Simulation of Mechanistic Model for Soil Development in Masuleh West of Alborz-Iran

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Abstract: Mechanistic model of soil evolution incorporates the physical and chemical weathering of minerals and rock; are presented and developed for soil formation at the catena scale for different time scale. In this study, a rudimentary mass-balance is used to demonstrate a simulation for soil thickness in landscape. The model state the changes occurred in soil thickness over the time duration; it depends on physical weathering rate of rock, the losses may be due to chemical weathering and transport of soil through erosion. The mechanistic model numerically solved by application of finite difference approach and then applied to a digital elevation the model. Simulation of soil development was performed for the landscape in Masuleh area located in northern part of Alborz Mountain for different time span. The obtained results showed the soil thicknesses were highly related to profile curvature. The effects of climate, rock type and land management are presented by different combination of weathering rates and erosive diffusivity. The results showed promising progress in evaluation of the quantitative pedogenises. Finally, application of the simulated mechanistic model in the selected field area for soil erosion can predicate the affect of land management practice on soil development.

Key words: Digital elevation · Landscape development · Mechanistic model · Quantitative Model · Rudimentary mass balance · Soil production

INTRODUCTION

Quantifying soil formation process has becomes an important topic in pedology, mainly as a response to increasing environmental problems Hoosbeek and Bryant [1]. Mechanistic pedology models consider weathering in a profile scale nearly at a landscape level. Meanwhile, the landscape model from geomorphology has made lots of progress in quantifying and modeling soil weathering and distribution in landscape. Minasny *et al*. [2] have allowed quantitative modeling to evaluate the long term impact of human activities and climate change on soil and landscapes. Furthermore, it allows us to gain a better understanding on soil-landscape relations.

The idea of mechanistic modeling was formalized by Jenny [3] who has described the soil as a function of several stated factors such as: Climate, organisms, relief, parent materials and time. He has formulated an equation to describe single factor as a function of soil properties. The stated 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].

The mass-balance models are based on a mechanistic approach. These models are in line with the "processes" approach. In general, attempts to formulate a continuity equation to count for the change of soil properties with respect to time. Pedogenesis process Modeling can be identified in two broad categories; the first category is modeling soil formation, started from bedrock, dealing with processes that can produce a soil with the related properties. The second category is modeling changes soil properties throughout the process.

Attempts have been made to formulate mechanistic models for the profile development at a particular location in landscape introduced by Kirkby [5]. This profile model coupled with a slope evolution processes forming an integrated model identified by Kirkby [6]. There are two

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main opinions in pedogenesis mechanistic model: the landscape evolution model and the soil profile model. The landscape evolution model mainly comes from geomorphology, where soil is modeled as a single layer of regolith. In addition, the main process is weathering which is mostly physical properties of materials transported in to landscape. The soil profile model from pedology and geochemistry points of view is mostly weathering as vertical transport of materials occurred within the profile; assuming a level landscape with minimum run off and lateral transport.

The knowledge on soil development is a major gap between rock weathering and slope formation. This knowledge can help our understating of how landforms evolve. Heimsath and his coworkers [7, 8] integrated a soil production function into their landscape evolution model. They were able to simulate soil evolution across a landscape and verify it with field data from the Tennessee valley. Slater [9] presented a framework for integrating soil-landscape and pedogenic models in a three-dimensional context. Minasny and McBratney [2, 10, 11] presented a basic mechanistic model that considered soil formation spatial at the catena to landscape. They have presented numerical studies and showed numerical application of the stated model. Salvador-Blanes *et al*. [12]. The presented a Mechanistic model deals with soil evolution, incorporating the physical and chemical weathering of minerals.

In this study, the correlation between pedogenetic and landscape with soil changes process throughout the time were investigated. The key points and questions were considered from this research work were:

- Is there any promising progress in quantitative evaluation of pedogenesis?
- Does the application of the mechanistic model can be helpful to predicate the affect of land management practice on soil development?

The purpose of this study was to simulate the mechanistic model for soil production at the catena scale in the landscape of Masuleh area which is located in western part of Alborz mountain (Iran) and also to illustrate the application of the model in quantification of pedogenesis.

MATERIALS AND METHODS

Theory: Mechanistic model for soil formation in the landscape is based on investigations conducted by 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:

$$\frac{\partial h}{\partial t} + \frac{\rho r}{\rho s} \times \frac{\partial e}{\partial t} = -\nabla q \quad (1)$$

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

Ahnert and Heimsath *et al*. [13] suggested that the state of physical weathering of bedrock $\left(\frac{\partial e}{\partial t}\right)$ can be represented as an exponential decline with soil thickness:

$$\frac{\partial e}{\partial t} = -P_0 \exp(-k_1 h) \quad (2)$$

Where $P_0[m\ year^{-1}]$ the maximum weathering rate of bedrock and $K_1[year^{-1}]$ is an empirical constant. The reduction of weathering rate with thickening of soil is 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 the freely-drained soils. Therefore, the parameters P_0 and K_1 are related to the climate and type of parent materials.

The model for soil production in the study area considers a landscape with symbol e that refers to the interface between bedrock and soil, h is the thickness of soil layers, Z is elevation and q is flux of soil transport (Figure 1). Change in soil thickness with respect to time depends on the processes of formation of soil weathering of bedrock, the loss of materials by chemical weathering and transport of soil by erosion.

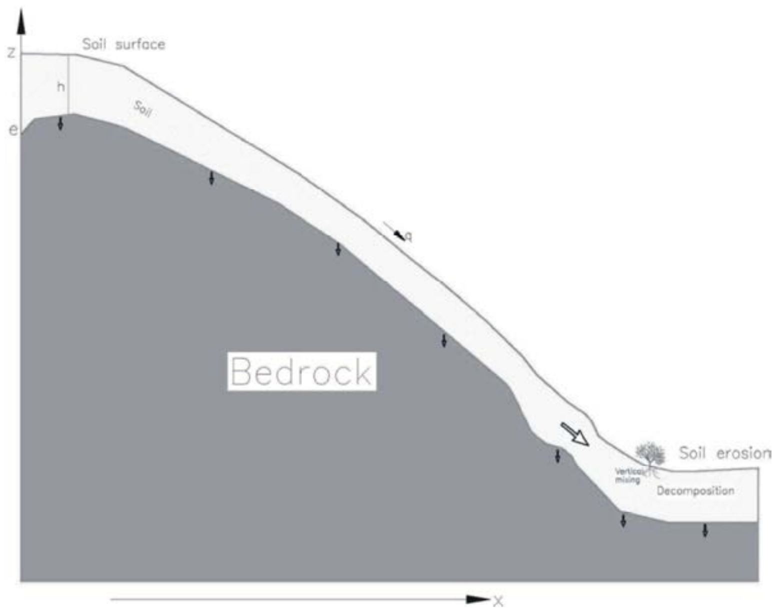

Fig. 1: Model for soil formation in Masuleh area

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:

$$\frac{\partial e}{\partial t} = \begin{cases} For h \le hcP_0(1+K_1\frac{h}{he}-\frac{h^2}{h_t^2}) \\ For\ h > P_0K_1\exp(hc-h) \end{cases} \qquad (3)$$

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.

$$\frac{\partial e}{\partial t} = -(P_0[\exp(-K_1h)-\exp(-K_2h)]+P_a) \qquad (4)$$

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 $h \le h_c$ and P_a is the weathering rate at steady-state condition [m year^{-1}] for the condition $K_1 < K_2$. The critical thickness where weathering is optimized is given by the following relation:

$$h_c = \frac{Ln(\frac{K_2}{K_1})}{K_2-K_1} \qquad (5)$$

Methods: Field investigation and geographic location of 1000 sample points were recorded by GPS. Thereafter, by integrating the soil, geologic and topographic maps, have resulted in 50 topography units in the study area. Simulation is performed for a landscape in the Masuleh area which is located in the western part of Alborz, a major mountain range in northern part of Iran between 36°58'25" and 37°10'33" E longitude and 49°9'20" and 49°12'30"N latitude (Figure 2).

The elevation is from 300 to 1800 m above the mean sea level, ranging from hills to mountains. The mean annual precipitation and temperature regimes are Udic and Mesic, respectively. The geology is diverse and dominated by Precambrian and Paleozoic metamorphic and mafic rocks, covered by Jurassic and Cretaceous shale and limestone.

The present investigation started the simulation with an initial 20 cm soil thickness since there was no information available on initial soil condition. Therefore, investigation started with an initial thickness that corresponds to liner function of slope curvature. It is a fact that there is a relationship between topography and soil thickness that should be considered. Thus, starting with uniform soil thickness, bear the weakness of our assumption. The values for model parameters were obtained from the literature and used for calculation. The summary of calculation and implemented data for the simulation is shown in Table 1. The density of soil and rock (ρs, ρr) and diffusivity D is assumed to be spatially

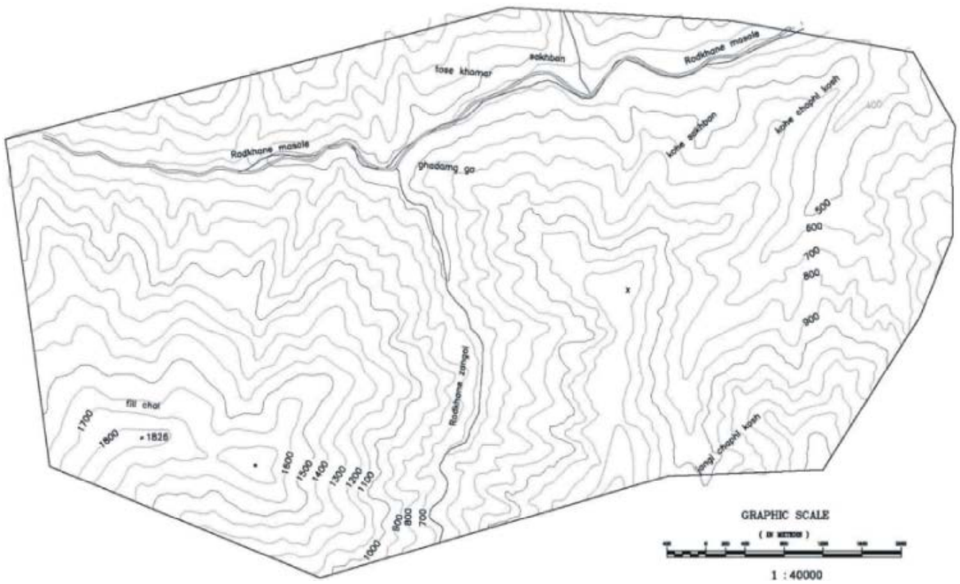

Fig. 2: Topography map of study area

Table 1: Parameters for the model used in present study

Parameters	Values
D (m2 year^{-1})	0.0003
P_0 (mm year^{-1})	0.25
P_a (mm year^{-1})	0.05
k1 (m^{-1})	4
k2 (m^{-1})	6
ρ_r (Kg m^{-3})	2600
ρ_s (Kg m^{-3})	1300

and temporally constant. The time-step used were 1000, 5000, 10,000, 15,000, 20,000, 30,000 years. The calculation was implemented with a commercial spread-sheet program (MS Excel). Using rows and columns as time and space grids in the explicit finite-difference approach. Also, AutoCAD civil 3D 2010, surfer 8 and Arc View GIS were used.

Some values of Table 1 were based on field survey investigation in the studied area and experimental result of laboratory finding of collected samples and then trials to the model to take realistic value. The simulation assumed to be a closed system, where materials cannot be moved outside the system; while considered that the area has a uniform parent material, climate and influence of organisms. The model simulates the distribution of soil thickness in a landscape. Topography and time are the most important variable factors. Also, topography conducts the most important soil redistribution in this landscape.

RESULTS AND DISCUSSION

In this work, the model applied to the digital elevation model of Masuleh area, (Figure 3).

The area was selected because it has a complete DEM coverage with a wide range of Topographic relief from 300 m in the valleys to 1800m on the hills from the mean sea level. The gained results showed that the environmental factors such as climate and geology had sensible influence on soil production in the area. The effect of weathering rates on soil thickness is shown in Figure 4. The presented data demonstrated that the weathering rate decrease exponentially with an increase of soil thickness, correspond to exponential decrease of temperature amplitude. When the soil is thick, the long residence times of water would allow thermodynamic equilibrium with the minerals and weathering rates will be slower. There is an intermediate or critical thickness (h_c) where soil can hold enough water and the chemical weathering is the most effective parameter. Under thin soil or exposed bedrock water tends to runoff, reducing the chance of the decomposition of bedrock. Meanwhile, decreasing weathering rate with increasing soil thickness reinforces the stabilizing effect of the diffusion process. With the same weathering rate, soil from the hill will be transported down to the slope by the erosion process and accumulated in the valley. The obtained data are also showed that with an initially thin soil, the rate of production is very limited. That corresponds to the

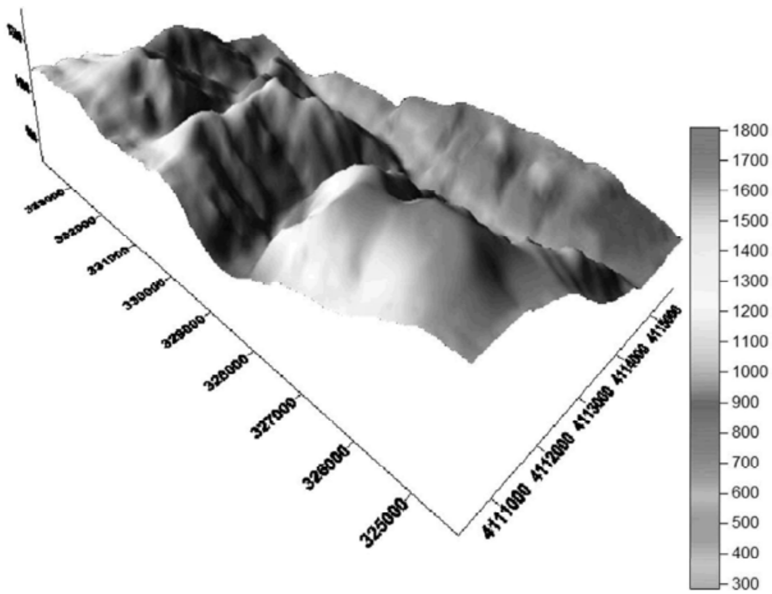

Fig. 3: Digital elevation model for the landscape of Masuleh plain, North of Iran

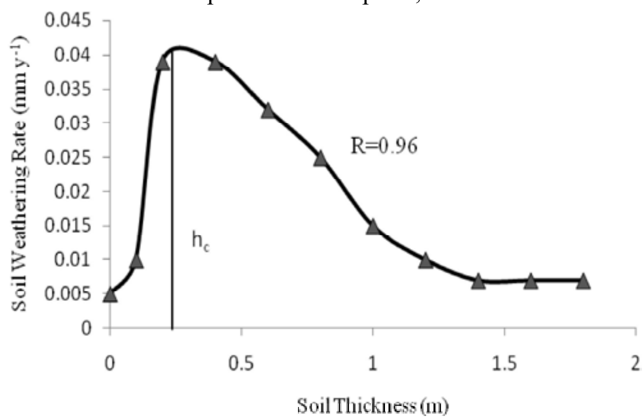

Fig. 4: A model for the soil weathering function

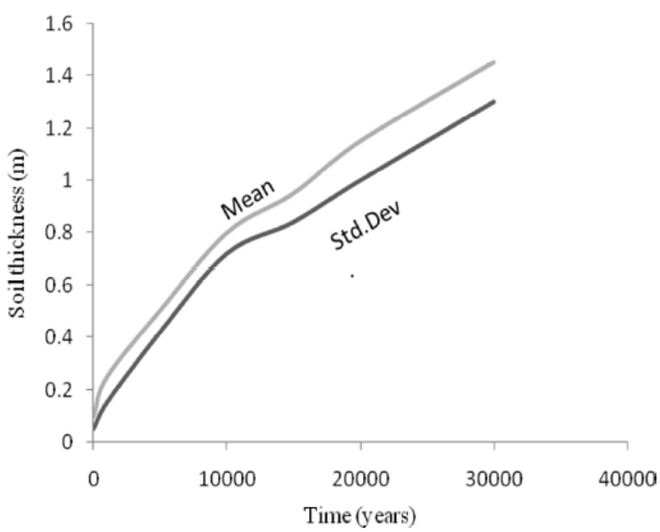

Fig. 5: Mean and standard deviation of the simulated soil thickness with respect to time

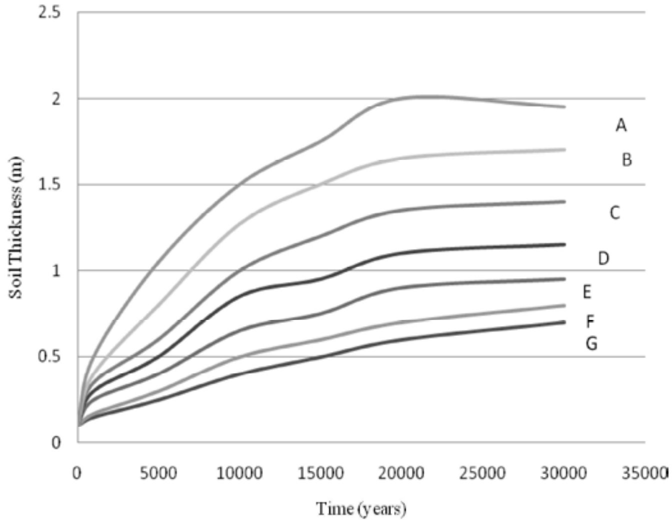

Fig. 6: Soil thickness as a function of time for the selected points in the landscape

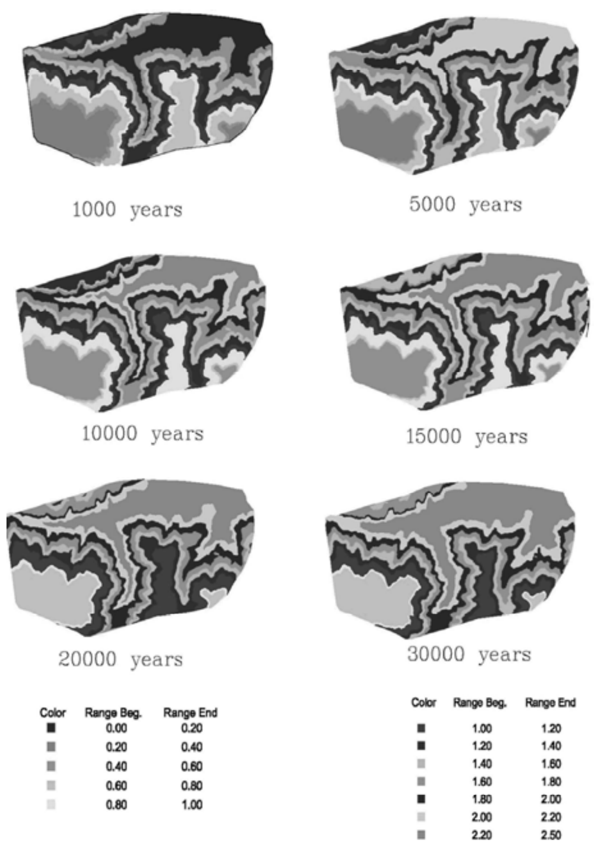

Fig. 7: The evolution of soil thickness after simulation of 1,000, 5,000, 10,000, 15,000, 20,000, 30,000 years

exponential decline function in which soil thickness gradually increases till it reaches a steady state production rate. The evolution of soil thickness with time is presented in Figure 5.

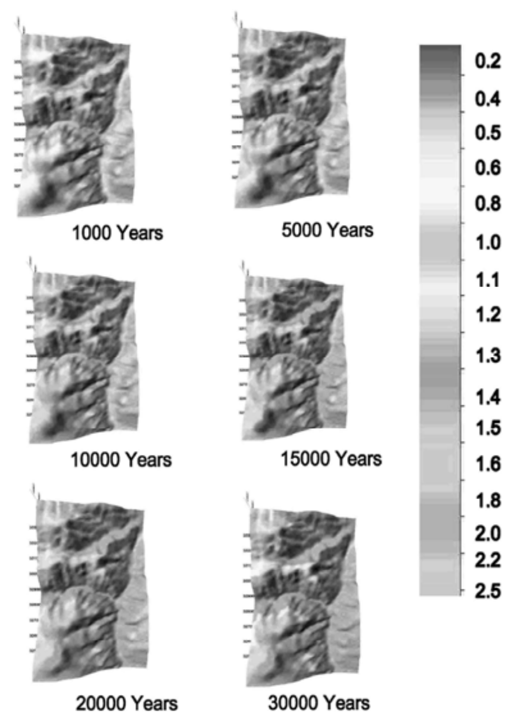

Fig. 8: The evolution of soil thickness for various ages ranging from 1,000 to 30,000 years

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.

Figure 6 shows the soil thickness of seven selected transect points with respect to time. Soil at point A, B and C remained relatively thick with respect to time as they are located in concave relatively flat area, whereas at point E, F and G with steep slopes, the soil is relatively thin.

In this study, the application and results of the model in 2D and 3D images are presented in Figures 7 and 8. In these images the evolution of soil thickness for different selected times ranging from 1,000 to 30,000 years are shown.

The model can simulate the distribution of soil thickness in a landscape. It was assumed that the material diffusely 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.

CONCLUSION

The following itemized facts and findings are concluded as follows:

- Simple mechanistic model based on mass-balance is able to simulate realistically the distribution of soil thickness in the landscape. It is interpreted the way in which soil has diversified and changed with respect to time.
- Modeling is an important tool and special issue of interest in the future for soil landscape development and for soil protection purpose.
- Soil protection requires appropriate models for prospective assessments of regeneration capacity of soil landscape.
- Ability to model soil development from early stage can give us a better understanding of pedogenesis and help us to answer the questions such as:

How does soil form; how does it evolve, where does it come from, how long does it take to form and reach this state and what will be the likely soil condition in the future?

- Pedogenesis modeling may not be able to replicate accurately the present condition; but it should be able to model the trend and this is the essential part of the modeling exercise.

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