Study of the relation between soil erodibility and hydrological characteristics

V V Alekseev¹, R I Aleksandrov², S A Vasiliev² and S I Chuchkalov²

¹Department of Information Technologies and Mathematics, Cheboksary Cooperative Institute, 24, Gor’kogo Avenue, 428025, Cheboksary, Russian Federation
²Chuvash State University named after I N Ulyanov, 15, Moskovskij Avenue, 428015, Cheboksary, Russian Federation

E-mail: av77@list.ru

Abstract. Hydrological characteristics such as soil water retention curve and hydraulic conductivity, for which, however, there are no standardized measurement methods for the entire range of soil moisture, are most important for assessing the erodibility of soil. In the article, based on the energy approach to soil erodibility analysis, a relation was proposed linking the characteristic of soil erodibility, – the specific power spent on the destruction and removal of soil in the places of its natural occurrence, with soil hydrological characteristics. Modeling erosion processes based on the proposed ratio may allow both describing the erosion properties depending on the initial soil moisture and obtaining numerical information on the soil hydrological characteristics using measured values of soil erodibility characteristics at any time during the vegetation period.

1. Introduction
Adequate assessment of soil erosion is necessary in order to predict possible soil degradation and to develop measures to prevent erosion. Soil susceptibility to water erosion depends on the combination of physicochemical and hydrophysical properties, which determine the hydrological indices of the soil and include such parameters as the chemical and mechanical composition, physical and chemical properties, biogenicity, humus content and its qualitative composition, carbonate content, aggregate composition, cations of the absorbing complex.

The most important soil hydrological indicators are the soil water retention curve (SWRC) and hydraulic conductivity of the soil, the first of which is the relationship between the capillary-sorption pressure of moisture and soil moisture, and the second characterizes the speed and direction of movement of soil moisture [1]. Despite the presence of a number of methods that allow one to experimentally determine different parts of the SWRC curve, there are no generally accepted standardized methods for experimentally obtaining SWRC over the entire soil moisture range [2]. SWRC assessment is carried out mainly with the help of pedotransfer functions developed on the basis of physically based models [3, 4]. Soil permeability is mainly determined by the mechanical composition of light soils (sand, sandy loam), the structure of heavy soils (loam, clay), as well as the density and moisture of the upper soil horizon. In the work [5] the possibility of estimating soil erosion losses based on measuring the saturated hydraulic conductivity of a soil was experimentally substantiated. A number of studies [6, 7] are devoted to prediction of soil saturated hydraulic conductivity by parametric properties of soil, such as volumetric density and distribution of soil particles by size. The intensity of
both surface erosion (soil washout) and internal erosion (landslide processes) largely depends on soil hydraulic conductivity [8].

In the research work [9], as a characteristic of soil erosion resistance, the potential of erosion resistance is proposed, which is the energy spent on the destruction and removal of a unit of soil mass from the places of its natural occurrence. The exponential character of the dependence of the erosion resistance potential on the volumetric water content for light-gray and dark-gray forest soils of central region of Russia was experimentally revealed.

Taking into account the energy sense of the soil water retention curve and the significant role of the capillary component in the binding energy of soil particles in a certain soil moisture range, it seems promising to evaluate hydrophysical indicators by soil erodibility and, conversely, soil erodibility by hydrophysical indicators. The aim of this study is to identify the relationship of erosion resistance potential with hydrophysical indicators of soil.

2. Materials and methods

In this study, the potential of erosion resistance $E$ (J/kg ≡ m²/s²) proposed in [9], which is the energy of water jet necessary for the destruction and removal of a unit mass of soil from the place of its natural occurrence, was used as a physically justified value characterizing the erosion resistance of soils:

$$E = \frac{\Delta W}{m_s},$$  

(1)

where $\Delta W$ was the energy expended in the destruction and removal the soil sample of the mass $m_s$. The jet device and method for measuring the potential of erosion resistance under field conditions was described in detail in [9]. Considering that the destructibility of soil structures depends not only on the impact energy, but also on duration $\Delta t$ of its exposure, we used the specific power $P$ (W/kg ≡ m²/s³), that is the ratio of the erosion resistance potential to the time of impact of water jet on the soil, to characterize erosion resistance:

$$P = \frac{E}{\Delta t} = \frac{\Delta W}{m_s \cdot \Delta t}.$$  

(2)

Phenomenological approach when considering the process of erosion suggests that the specific power is determined by the potential of soil moisture $\psi$ (J/kg ≡ m²/s²), soil hydraulic conductivity coefficient $K$ (m³/s/kg) and soil density $\rho$ (kg/m³), each of which depends on the particle size distribution and mineralogical composition, porosity and other soil characteristics. Assuming the power type of the desired dependence, we have, up to a dimensionless factor $k$

$$P = k \psi^\alpha K^\beta \rho^\gamma,$$  

(3)

where $k$ is a dimensionless factor.

To determine the exponents $\alpha$, $\beta$ and $\gamma$, we used the method of dimensional analysis. Equating the exponents for the dimensions of length, time and mass, respectively, in the left and right sides of the ratio (3), we obtained the system of equations:

$$\begin{cases} 2 = 2\alpha + 3\beta - 3\gamma, \\ -3 = -2\alpha + \beta, \\ 0 = -\beta + \gamma. \end{cases}$$  

(4)

Solving the system of equations with respect to $\alpha$, $\beta$, and $\gamma$ resulted in $\alpha = 1$ and $\beta = \gamma = -1$. Thus, dependence (3) took the form:

$$P = k \frac{\psi}{K \rho}.$$  

(5)

The total potential $\psi$ of soil moisture includes the potential $\psi'$ due to the interaction of moisture with the solid phase of the soil, and the potential $\psi''$ due to the interaction of moisture with the soil air. When the volumetric water content of soil $w$ exceeds 0.1, the potential $\psi''$ makes a major contribution to the value of the total potential of soil moisture $\psi$. 

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The dependence of the moisture potential \( \psi \) on the volumetric moisture of soil \( w \) was represented as [10]:

\[
\psi = \psi' + \psi'' = \frac{\Omega_0^3}{\rho} \left( \frac{1}{w^3} - \frac{1}{\Pi_0} \right) + \frac{\Omega_0 \sigma_\eta}{\rho} \left( 1 - \frac{w}{1 - \Pi_0 + w} \right) \left( 1 - \frac{w}{\Pi_0} \right)^{2.5},
\]

where \( \Omega_0 \) – volumetric specific surface, \( (m^2/m^3) \), \( w \) – volumetric water content, \( (m^3/m^3) \), \( \sigma_\eta \) – specific free surface energy at the water/air boundary \( (J/m^2) \), \( \rho \) – water density \( (kg/m^3) \), \( A \) – the dimensional constant \( (J) \); \( \Pi_0 \) – the porosity of the dry soil sample \( (m^3/m^3) \).

The assessment of the energy of moisture interaction with soil air was carried out by integrating the expression (6) in the range of moisture values from a fixed value \( w \) to a value \( w = \Pi_0 \) corresponding to the complete filling of soil pores with moisture (soil porosity can be considered as the maximum water content in the soil):

\[
\int_0^{\Pi_0} \psi(w) dw.
\]

In turn, dependence of hydraulic conductivity (moisture conductivity) on the volumetric moisture of soil \( w \) was represented as [10]:

\[
K = \frac{\pi^2}{\Omega_0 \eta S^2} \frac{\lambda \Pi_0^{2.5}}{1 - \Pi_0} \left[ 1 - \left( 1 - \frac{w}{\Pi_0} \right)^2 \right],
\]

gде \( \eta \) – water viscosity, \( (Pa\cdot s) \); \( S \) – cross-section area of soil sample the water flows through \( (m^2) \); \( \lambda \) – dimensionless coefficient.

3. Results and discussion

Numerical estimates of the moisture conductivity and the energy of the moisture interaction with the soil air were carried out using ratios (6-8) for various values of the volumetric water content in the soil. Calculations were carried out for soils of various types (sod-podzolic, dark-gray forest, light-gray forest and chernozemic soils) taking into account the values of their porosity and specific surface area in the dry state. The obtained calculated values of the complex presented on the right-hand side of the expression (5) are shown in figure 1. The arrangement of the curves in figure 1 adequately reflects the degree of soil erosion depending on the type of soil. The high level of water-holding capacity of the soil is related with a low level of moisture conductivity, and, conversely, the better the moisture conductivity, the worse the water-holding properties of the soil. Chernozemic soils have the highest erosion resistance. Soils of different types form the following sequence in decreasing order of their resistance to erosion: chernozemic soils → dark-gray forest soils → light-gray forest soils → sod-podzolic soils, what is agreement with the available data in the literature.

![Figure 1. Dependence of the complex \( k \frac{\psi}{K \rho} \) on volumetric water content for different types of soil.](image-url)
With increasing moisture, the value of the complex decreases; this is also true for the erosion resistance of the soil.

For dark-gray forest soils of oak forests of the Chuvash Republic (Russian Federation) measurements of the erosion resistance potential at various values of the volumetric water content according to the method described in [9] were carried out. The volumetric water content was determined by conventional methods (in particular, gravimetric method of water content determination). The following power dependence of erosion resistance potential on the volumetric water content of soil were obtained (figure 2):

\[ E = 0.06 \cdot w^{-3}. \]  \hspace{1cm} (9)

The obtained dependence shows that as the soil is moistened, the value of erosion resistance potential tends to a certain limit. The dependence of the specific power on the volumetric water content is of the same character, since the duration of the water jet impact on the tested soil area was kept constant during measurements.

![Figure 2. Dependence of erosion resistance potential on the soil moisture (dark-grey forest soil).](image)

With increasing moisture, the value of the complex decreases; this is also true for the erosion resistance of the soil.

The character of the dependences of the erosion resistance potential and specific power on volumetric water content is consistent with the results of the calculation of the complex for dark-gray forest soils, which experimentally confirms the validity of the ratio (5). The limiting value, to which the potential of erosion resistance tends during the increase in the volumetric water content, corresponds to the residual kinetic energy of the washed-out soil flow.

4. Conclusion

In the paper, based on the energy approach to soil erosion analysis, by dimensional analysis a ratio was proposed linking the characteristics of soil erodibility, – the specific power spent on the destruction and removal of soil in the places of its natural occurrence, with hydrological characteristics such as the potential of soil moisture and soil hydraulic conductivity (moisture conductivity). The values of the resulting complex, which includes the hydrological characteristics, were calculated for different moisture values for different soil types and are consistent with the available data on soil erodibility. The dependence of the potential of erosion resistance for dark-gray soils of the Chuvash Republic (Russian Federation) was obtained experimentally. The similar dependences of the potential of erosion resistance, specific power and complex of hydrological characteristics on soil moisture confirms the validity of the obtained ratio.

Modeling erosion processes based on the proposed ratio may allow both describing the erosion properties depending on the initial soil moisture and obtaining numerical information on the soil hydrological characteristics using measured values of the soil erodibility characteristic at any time during the vegetation period.
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