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Method for obtaining water retention properties of soils by fractions of their granulometric composition

Abstract. This paper presents the method of obtaining water retention properties of soils (water retention curve (WRC) and water conductivity functions) is presented. These properties, or functions, allow describing the vertical movement of water in unsaturated soils as one of the components of the water balance expenditure item. They are widely used during the substantiation of water reclamations and during modelling of water transfer in the soil. The method is based on laboratory studies of soil samples taken in the field for granulometric composition. Currently, the results of laboratory analyses in Ukraine are obtained according to the Kachynskyi method with two components, the percentage of clay and sand. They are transformed graphically, using integral (cumulative) curves, into data corresponding to the international classification – with three components: the content of sand, dust, clay. The world community of soil scientists uses the latter factional distribution. Therefore, using data on the content of sand, dust, clay, thanks to the open access computer program "Rosetta" USDA (United States Department of Agriculture), water retention properties are found in the form of water constants (total water content, minimum hygroscopic water content, filtering coefficient), coefficients of the equations of Van Genuchten's mathematical model. This paper provides examples of calculating the water retention properties of soils using the method of dark chestnut soils and ordinary chernozems. The advantages of the proposed method include the low complexity of experimental studies, the availability of analyses and the presence of many experimental studies of the granulometric composition of soils, including in literature sources. As a development of the research area, the author showed the application of the obtained dependencies for modelling water transfer during water reclamation (irrigation in irrigation control systems). As for future research areas, the publication suggests comparing the accuracy of obtaining water retention properties of soils according to various methods, as well as obtaining an important water constant – the minimum soil water capacity (MSWC)

Keywords: Soil properties; integral (cumulative) distribution curves of soil fractions; USDA "Rosetta" computer program; total water capacity; minimum hygroscopic water capacity; filtration coefficient

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RELEVANCE

Water retention properties of soils are a fundamental characteristic during hydraulic reclamation. Today, there are many methods for their determination: they are given in literary sources and DSTU state standards, but their direct determination faces difficulties with the lack of appropriate laboratory equipment, the duration, and laboriousness of research. The availability of analyses and the availability of many experimental studies of the granulometric composition of soils, including in literary sources, on the one hand, the presence of studies on the connection of granulometric composition with water properties of soils prompted the author to use these scientific assets. Therefore, the idea of this paper was to develop a scientifically sound convenient methodological tool for obtaining water retention properties of soils (WRP) based on data on the granulometric composition of the soil.

ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

Research in theoretical (Van Genuchten, 1980; "Soil-hydrophysical maintenance", 1987; Schaap *et al.*, 2001; Kovalchuk & Kolomiets, 2007), field (DSTU B V.2.1 -24:2009), and laboratory (ISO 11274:1998; M.I. Romashchenko *et al.*, 2019) determination of water retention properties of soils was initiated quite a long time ago and has been covered extremely widely in the scientific literature, and a number of DSTUs were developed for this purpose (ISO 11274: 1998; DSTU ISO 11276:2001; DSTU B V.2.1-24:2009). These properties, the water retention curve (WRC) and the function of moisture conductivity, are used to substantiate hydraulic meliorations (Shang Songhao *et al.*, 2004; Kovalchuk *et al.*, 2008; Vozhegova *et al.*, 2013; Zeleke, 2019; Gadzalo *et al.*, 2019; Markovska, 2021), for scientific research during mathematical modelling of moisture transfer in soils (Ahmad *et al.*, 2018; Salugin, 2018; Ryzhova *et al.*, 2019; Silva Ursulino *et al.*, 2019; "System Modelling and Management", 2019). A substantial obstacle is the duration and complexity of field and laboratory studies to determine WRP.

To avoid the mentioned shortcomings in the determination of WRP, this paper proposes to use the results of analyses of the granulometric composition, according to the standardized method (DSTU ISO 11277: 2005; ISO 11277: 1998), of soil samples taken in the field. In the west, laser diffractometers are used for particle size analysis (Budanova *et al.*, 2013).

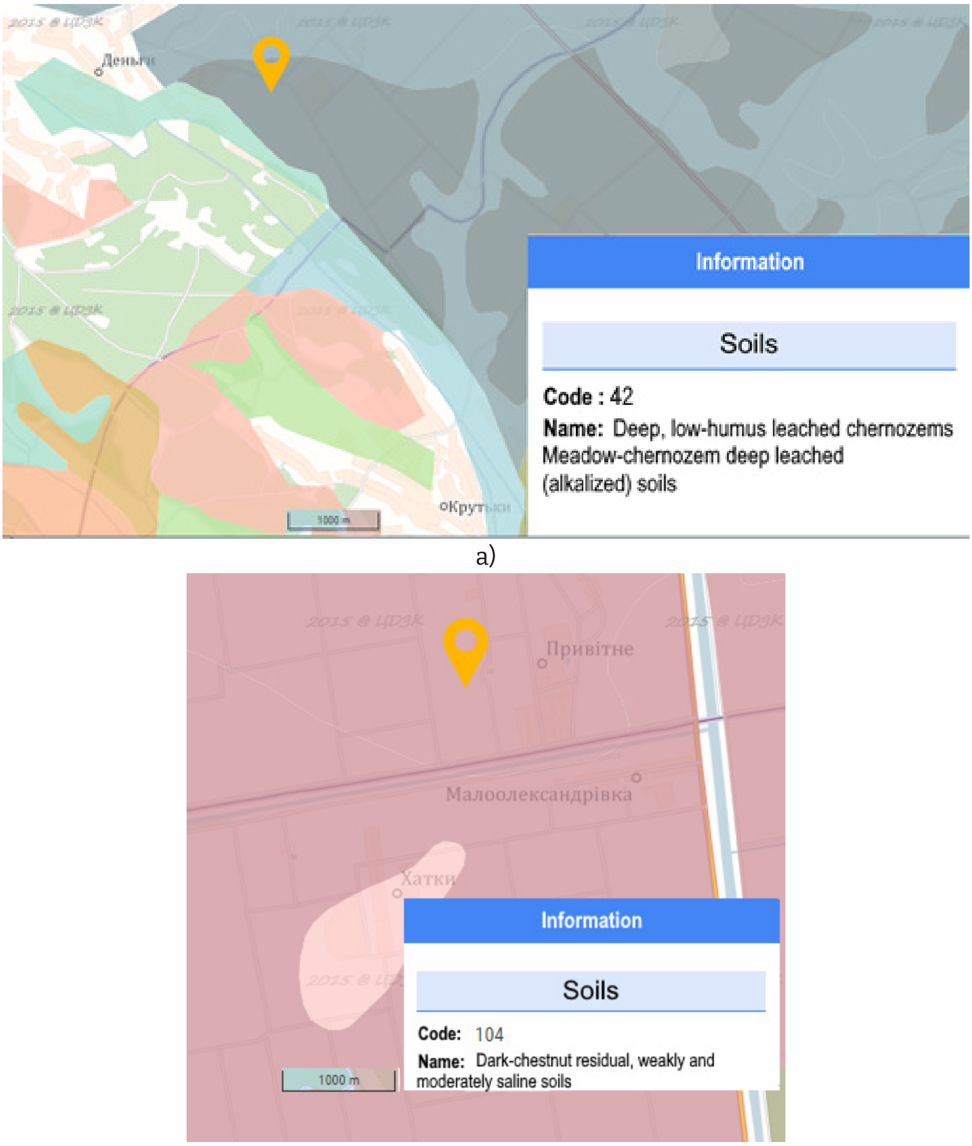
Since the results of laboratory analyses are obtained according to the Kachynskyi method, they can be transposed to the international classification according to a graphical method using graphical interpolation based on the obtained cumulative curves of the granulometric composition of soils. This method for determining the content of sand-dust-clay fractions in the soil is proposed in publications (Baboshkina *et al.*, 2016; Zamin, *et al.*, 2020).

According to the content of sand-dust-clay fractions in the soil, based on the USDA (United States Department of Agriculture) open access software "Rosetta" (Schaap *et al.*, 2001; "Rosetta v. 1.0"), there are water retention properties in the form of water constants – total water capacity, minimum water retention capacity, filtration coefficient and coefficients of equations of Van Genuchten's mathematical model (Van Genuchten, 1980).

Therefore, the purpose of this study was to develop a method for calculating the coefficients of the equations of Van Genuchten's mathematical model and water constants: total water retention (TWR), minimum water retention content (MWRC), and filtration coefficient, for scientific and practical use for substantiation of hydrotechnical reclamation. Such a method will be developed based on the graphical transformation of the results of laboratory analyses according to the Kaczynski method to the international soil classification and using the USDA "Rosetta" open access computer program. The main tasks of this paper were to present the essence of the method with an illustration of it using the example of several soils. At the same time, the comparison of different methods was not the task of this paper.

MATERIALS AND METHODS

As for the objects of the study (Fig. 1), on the example of dark-chestnut soils of the village Pryvitne of the left-bank Kherson Oblast, at the State Enterprise "Experimental Farm "Brylivske" of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine and chernozems of deep low-humus soils in a complex with meadow-chernozem soils of the village of Denhy, Zolotonskyi District of Cherkasy Oblast, the study will illustrate the calculation of water-physical properties according to the proposed and described method. Soil samples were taken from several horizons of the soil profile: arable, sub-arable, and the horizon of the parent rock (Table 1).



a)

b)

Figure 1. Location of experimental plots and soil sampling points (according to the public cadastral map): a) chernozems, Denhy village; b) dark chestnut soils of Pryvitne village

Table 1. Results of laboratory analysis of soil samples according to granulometric composition

No.	Place of selection	Selection depth, cm	Diameter of fractions (in mm) and their content (in %) by weight of dry soil						Soil classification by granulometric composition	
			1-0,25	0,25-0,05	0,05-0,01	0,01-0,005	0,005-0,001	< 0.001	> 0.01 mm	< 0.01 mm
1	village of Denhy	10-25	0.20	22.28	50.88	6.53	6.12	13.99	73.36	26.64
2	village of Denhy	36-61	0.12	14.00	61.65	3.79	8.36	12.08	75.77	24.23
3	village of Denhy	71-93	0.38	15.41	56.02	4.73	8.81	14.65	71.81	28.19
4	village of Pryvitne	0-20	30.2	38.5	9.64	5.12	6.76	9.76	78.36	21.64
5	village of Pryvitne	20-35	25.85	37.15	6.44	6.40	9.6	14.56	69.44	30.56
6	village of Pryvitne	75-85	15.2	43.72	4.6	15.92	0.16	20.40	63.52	36.48

Soil dispersion is characterized by a granulometric composition, the relative content of particle fractions of different sizes in the soil. Therefore, laboratory studies using standardized methods (DSTU ISO 11277 : 2005; ISO 11277:1998) established the percentage of the size of soil particles according to Kachynski's classification (Table 1). Grapho-analytical studies were methodically applied, USDA "ROSETTA" open access software was used, and water-physical properties of soils were found in the form of Van Genuchten formula coefficients (Van Genuchten M. T., 1980):

$$\frac{\theta-\theta_0}{\theta_{TWC}-\theta_0}=\left(\frac{1}{1+(\alpha\psi)^n}\right)^{1-\frac{1}{n}} \text{ or } \psi=\left(\left(\frac{\theta-\theta_0}{\theta_{TWC}-\theta_0}\right)^{-\frac{1}{1-\frac{1}{n}}}-1\right)^{\frac{1}{n}} \tag{1}$$

$$k=k_{\Phi}\sqrt{\left(\frac{\theta-\theta_0}{\theta_{TWC}-\theta_0}\right)}\left(1-\left(1-\left(\frac{\theta-\theta_0}{\theta_{TWC}-\theta_0}\right)^{\frac{n}{n-1}}\right)^{\frac{n-1}{n}}\right)^2 \tag{2}$$

where θ, θ_{TWC}, θ_0 – bulk soil moisture, total water content, minimum possible moisture content, fractions 1; ψ is the water framework potential; k, k_ϕ are water conductivity and filtration coefficients, respectively, *cm/day*; n, α are coefficients.

The granulometric composition for determining the parameters of the Van Genuchten model can be found in the laboratory or in the Atlas of soils of Ukraine (Atlas of soils of the Ukrainian SSR, 1979) for approximately 70 soil profiles.

RESULTS AND DISCUSSION

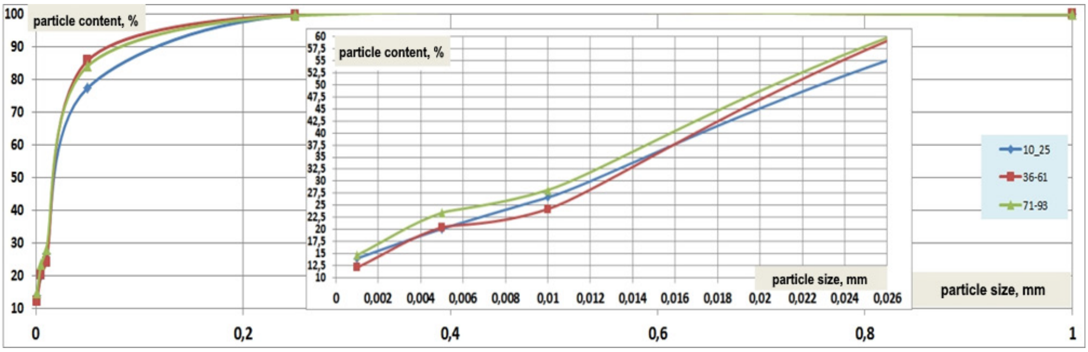
As a result of the *sand/clay* gradation, which underlies Kachynskyi's classification, some soil types were obtained according to the granulometric composition (Tsytsiura *et al.*, 2020): loose sand, cohesive sand, loamy sand, sandy loam, medium loam, clay loam, light clay, medium clay, heavy clay. It does not fully show the real diversity of soils in terms of granulometric composition. Especially due to the failure to consider the role of dust (swelling and subsidence, substantial influence on the anisotropy of moisture conductivity, etc.) in the formation of the physical properties of the soil, the classification is still far from reality.

Since the vast majority of Ukrainian laboratories provide the results of analysis on the granulometric composition of soil in the form of the Kachynskyi's classification, there is a need to transform these experimentally obtained results into the FAO international classification. The international classification consists of 12 soil classes according to granulometric composition, where three fractions are distinguished – sand, dust, and clay (Table 2). The translation of class names is taken according to the monograph of L.M. Globus (1987).

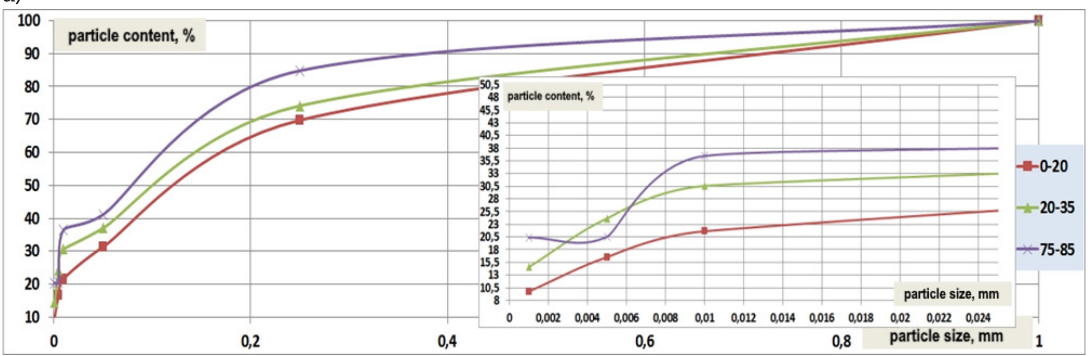
Table 2. Distribution of soils into structural classes according to granulometric composition

English (USDA)	Designation	Cyrillic (according to L. M. Globus)
1. Clay	C	Глина
2. Clay Loam	CL	Важкий суглинок
3. Loam	L	Суглинок
4. Loamy Sand	LS	Супісок
5. Sand	S	Пісок
6. Sandy Clay	SC	Опісчанена глина
7. Sandy Clay Loam	SCL	Опісчанений важкий суглинок
8. Sandy Loam	SL	Легкий суглинок
9. Silt	Si	Пилуватий (мулистий) ґрунт
10. Silty Clay	SIC	Пилувата глина (лучний ґрунт)
11. Silty Clay Loam	SICL	Пилуватий важкий суглинок
12. Silty Loam	SIL	Пилуватий суглинок

Therefore, the next step in implementing the method is to construct integral curves of the distribution of soil particles by fractions based on laboratory analysis data (Fig. 2).



a)



b)

Figure 2. Integral curves of the distribution of soil particles of experimental plots by size and fractions: a) chernozem, Denhy village; b) dark chestnut, Pryvitne village

New values of the content of fractions of particles of different sizes (sand, dust, clay) in the soil are obtained from the integral curves. The margins of sand, dust, and clay fractions according to the USDA classification are as follows:

- between fractions of sand and dust, the marginal particle size is 0.05 mm;
- between fractions of dust and clay, the marginal particle size is 0.002 mm.

Thus, for the objects of this study, the soils of experimental sites, the fractional composition according to the international classification is obtained, which is presented in Table 3. Thus, according to the international classification, chernozem soil from the Cherkasy region is silty loam (Class 12), and soil from the Kherson region is sandy loam (Class 8) (Fig. 3).

Table 3. Distribution of soils of experimental plots into structural classes according to granulometric composition according to the international classification

No.	Selection location, horizon	Sand (%)	Dust (%)	Clay (%)	Soil class according to granulometric composition	Density, g/cm^3
1	Denhy village, 10-25 cm	22.48	62.32	15.2	silty loam	1.35
2	Denhy village, 36-61	14.12	71.18	14.7	silty loam	1.36

Table 3. Continued

No.	Selection location, horizon	Sand (%)	Dust (%)	Clay (%)	Soil class according to granulometric composition	Density, g/cm^3
3	Denhy village, 71-93	15.79	67.71	16.5	silty loam	1.4
4	Pryvitne village, 0-20	68.7	19.8	11.5	sandy loam	1.6
5	Pryvitne village, 20-35	63	20	17	sandy loam	1.7
6	Pryvitne village, 75-85	58.92	21.08	20	sandy loam	1.7

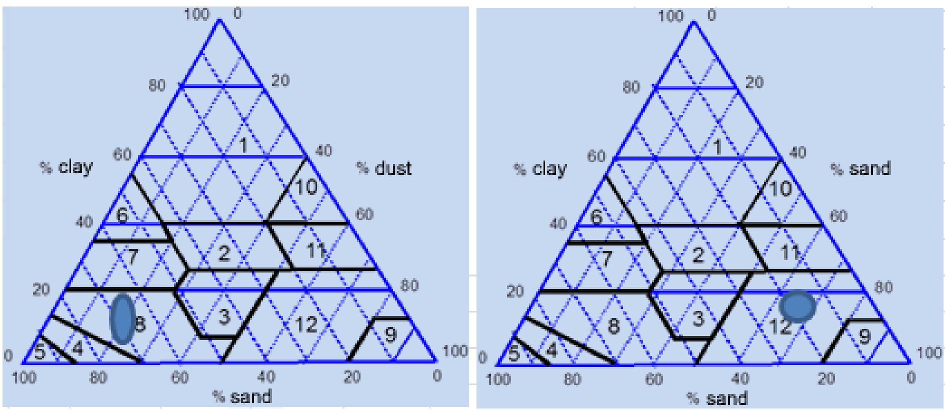


Figure 3. Diagram of the classification of the soils of the experimental plots according to the granulometric composition: a) dark-chestnut, Pryvitne village; b) chernozem, Denhy village

The "ROSETTA" program allows obtaining hydraulic properties – the water retention curve $\psi = f(\theta)$, and the water conductivity correlation $k = f(\theta)$ proposed by Van Genuchten (M.T. Van Genuchten, 1980), water constants *TWR and MWRC* at different levels of input information about soils:

- by soil type according to granulometric composition – these are the most generalized water retention functions that can be used in the preliminary evaluation calculations of Table 2;
- presence of granulometric composition and soil density (Table 3) allows obtaining adequate water retention functions of the soils under study;
- presence of granulometric composition and density of the soil, supplemented by reference points of the main water retention characteristic $\psi = f(\theta)$ at pressures of 300 and 1500 *kPa*, give the most accurate water retention correlations according to the "ROSETTA" program.

For the soils of the experimental plots, the results of the calculations of water constants and curve coefficients are presented in Table 4 (parts 1 are converted to % volume by multiplying by 100%). There are also data from (Atlas of Soils of the Ukrainian SSR, 1979) for somewhat comparable soils (meadow-chernozem soil on loess-like loams and dark-chestnut saline soils on loess). As the data in Table 4 show, in general, each *soil* is unique in terms of water retention properties, since the properties change during agricultural use. That is why the proposed method is useful and will help accurately determine them.

Table 4. Results of calculations of water retention properties of soils of study objects and their comparison with data from literature sources

No.	Selection location, horizon	θ_{TWR}	θ_0	α	n	k_ϕ	θ_{MSWC}	θ_{TWR}	θ_{MSWC}
		parts 1	*parts 1*	-	-	*cm/day*	*parts 1*	*parts 1*	*parts 1*
1	Denhy village, 10-25 cm	0.385	0.060	0.0057	1.638	14.22	0.254	0.565	0.282
2	Denhy village, 36-61 cm	0.427	0.065	0.0049	1.689	29.26	0.198	0.563	0.32
3	Denhy village, 71-93 cm	0.419	0.067	0.0051	1.672	21.18	0.217	53.2	0.29
4	Pryvitne village, 0-20 cm	0.311	0.040	0.3825	1.238	35.96	0.258	0.55	0.305
5	Pryvitne village, 20-35 cm	0.331	0.047	0.3547	1.251	10.71	0.252	0.5	0.275
6	Pryvitne village, 75 cm	0.368	0.059	0.2879	1.372	8.2	0.270	0.44	0.268

Notably, the fundamental constant, *the minimum soil water capacity* (MSWC), is determined according to the method proposed in the study (T.H. Barros *et al.*, 2017) using the authors' proposed method of calculating water retention properties (Table 4). The authors of the present paper will present these studies in further publications.

In this publication, the authors did not set a task and did not investigate the question of the accuracy of WRP calculations according to the described method, since this is the subject of further studies, where several methods will be compared.

The reliability of the results obtained according to the described method is confirmed by the use of granulometric composition data according to standardized methods, transformation of laboratory analysis results into an international classification according to the tested method, further calculation of water retention properties according to a computer program recommended by the US Department of Agriculture. Notably, the empirical results that form the basis of the program are based on the analysis of over 6 thousand soil samples. Van Genuchten's correlation has been well known for many years. Its use is confirmed by many studies that are described in many publications, and is used in FAO software (AquaCrop, CROPWAT). The correlation is convenient for modelling the water regime of soils.

Therefore, having obtained water retention properties, it is possible to model water transport in the soil (Ahmad *et al.*, 2018; Salugin, 2018; Ryzhova *et al.*, 2019; Silva Ursulino *et al.*, 2019; "System Modelling and Management", 2019), calculate irrigation rates, watering times based on smart systems, as in (Kovalchuk *et al.*, 2008; Gadzalo *et al.*, 2019), or based on programs AquaCrop, CROPWAT, etc., recommended by FAO, as it is done in publications (Vozhegova *et al.*, 2013; Zeleke, 2019; Markovska, 2021).

CONCLUSIONS

This paper presented a new method of determining water retention properties of the soil, based on the laboratory determination of the granulometric composition of the soil. The method combines a number of international standardized and widely known methods, computer programs for calculating the water retention properties of soil with Ukrainian methods for determining the granulometric composition. The method allows determining the TWR, MSWC, MWRC, soil filtration coefficient, coefficients of the Van Genuchten model. This method is very useful for substantiation water reclamation, as it increases the accuracy of calculations of irrigation regime parameters. The further development of this line of research will be a comparison of the accuracy of the obtained water constants and correlation coefficients according to several laboratory and field methods.

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Метод отримання водно-фізичних властивостей ґрунтів за фракціями їхнього гранулометричного складу

Анотація. Представлено метод отримання водно-фізичних властивостей ґрунтів (основної гідрофізичної характеристики (ОГХ) і функції вологопровідності). Ці властивості, або функції дають можливість описати вертикальний рух вологи в ненасичених вологою ґрунтах, якодну зі складових частин видаткової статті водного балансу. Вони широко застосовуються під час обґрунтування водних меліорацій і під час моделювання вологоперенесення в грунті. А в основу методу покладено лабораторні дослідження зразків ґрунту, що відбираються в полі, на гранулометричний склад. Результати лабораторних аналізів натепер в Україні зазвичай отримуються за методом Качинського з двома складовими, процентний вміст глини й піску. Вони графічним методом, за допомогою інтегральних (кумулятивних) кривих перетворюються в дані, відповідні до міжнародної класифікації – з трьома складовими: вміст піску, пилу, глини. Останній пофракційний розподіл використовує світове спільнота ґрунтознавців. Тому з використанням даних про вміст піску, пилу, глини, за допомогою комп'ютерної програми з відкритим доступом «Rosetta» USDA (United State Department of Agriculture) знаходяться водно-фізичні властивості у вигляді водних констант (повної вологоємності, найменшої гігроскопічної вологоємності, коефіцієнта фільтрації), коефіцієнтів рівнянь математичної моделі Ван Генухтена. У публікації наведено приклади розрахунку водно-фізичних властивостей ґрунтів представленим методом темно-каштанових грунтів і чорноземів звичайних. До переваг запропонованого методу варто віднести невелику трудомісткість експериментальних досліджень, доступність аналізів і наявність великої кількості експериментальних досліджень гранулометричного складу ґрунтів, у т.ч. у літературних джерелах. Як розвиток напряму досліджень, автор показав застосування отриманих залежностей для моделювання вологоперенесення за водних меліорацій, (зрошенні в системах керування зрошенням). Щодо напрямів майбутніх досліджень, публікація пропонує провести порівняння точності отримання водно-фізичних властивостей ґрунтів за різними методами, а також отримання важливої водної константи – найменшої вологоємності (НВ)

Ключові слова: ґрунтові властивості; інтегральні (кумулятивні) криві розподілу фракцій ґрунту; комп'ютерна програма «Rosetta» USDA; повна вологоємність; найменша гігроскопічна вологоємність; коефіцієнт фільтрації