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The prediction of ground water recharge of landslide areas in Dnipropetrovsk region

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Abstract. The forecast of groundwater level together with the observation network of wells are important and mandatory components of hydrogeological monitoring. The reliability of predictive calculations is achieved by reasonable definition of boundary conditions (inverse hydrogeological problem), correct calculation of hydrogeological parameters (inverse problem), and reasoned choice of methods (inductive problem). The classical forecast of the level regime of groundwater is a direct hydrogeological problem.The calculated dependences are proposed for four variants of hydrogeological conditions in relation to landslide-prone areas. The first and second variants are watered ravine with boundary conditions of the first and second kind. The third option is a special case of boundary conditions of second kind "impermeable boundary". The fourth option considers the periodic watercourse formation in the water intervals of the time climate series. A comparative analysis of four hydrodynamic schemes "infiltration band" in unlimited and semi-bounded layers and half-plane is performed under the same conditions to estimate the error of schematization. Significant differences in the calculation results confirm the need for a clear choice of the design scheme. A method of accounting for evaporation from the groundwater surface lying above the critical depth was proposed. This scientific approach allows accurate and detailed characterization of the average monthly groundwater regime in the course of a year. Multivariate calculations allow us to assert that the main mode – forming factor at the depth of groundwater below the critical depth is infiltration replenishment. Evaporation is a negative component of the water balance. Its value depends on the depth of groundwater, lithological composition of the host rocks, vegetation cover and complex climatic factors. Accounting for the evaporation of ground water in the forward estimates is required if they lie above the critical depth. The critical depth for the territory of Dnipropetrovsk region is assumed to be 2.0 m. At this depth of groundwater level from the earth's surface, the evaporation rate is zero. The maximum evaporation or evaporability corresponds to the position of groundwater at the surface of the earth. The maximum evaporation is 800 – 820 mm for Dnipropetrovsk region.The evaporation value increases inversely with the depth of its occurrence from the surface of the earth when the rise of the groundwater level occurs above the critical depth. The process of changes in the groundwater level in the unsteady filtration regime is described by two-dimensional differential equations of the second order in partial derivatives of parabolic type. This equation has analytical partial solutions for all considered variants of boundary conditions with regard to the problems of meliorative hydrogeology. It is possible to transform correctly to hydrogeological conditions of landslide slopes using numerical forecast.Infiltration nutrition indices were calculated by comparing the monitoring data with the values of evaporation through the soil surface.

Keywords: groundwater, forecast, level, hydrodynamic schematization.

Прогноз рівневого режиму підземних вод зсувонебезпечних територій в Дніпропетровській області

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Анотація. Прогноз рівневого режиму підземних вод відповідно даних спостережної мережи свердловин є важливою і обов›язковою складовою гідрогеологічного моніторингу. У комплексі з іншими дослідженнями такі сплановані тривалі спостереження є науковим підґрунтям ефективних природоохоронних заходів гідрогеологічної спрямованості. Достовірність прогнозних розрахунків досягається визначенням граничних умов (зворотна гідрогеологічна задача), коректним розрахунком гідрогеологічних параметрів (інверсійна задача), однозначно аргументованим вибором методів рішення (індуктивна задача). Класичний прогноз рівневого режиму підземних вод виконують рішенням прямої гідрогеологічної задачі. Для чотирьох варіантів гідрогеологічних умов запропоновані розрахункові залежності стосовно зсувонебезпечних територій. Перший і другий варіанти - обводнена балка з граничними умовами першого і другого роду. Третій варіант передбачає окремий випадок граничної умови другого роду «непроникний контур». Четвертий варіант розглядає періодичне утворення водотоку у водні інтервали часового кліматичного ряду. Для оцінки похибки схематизації виконаний порівняльний аналіз чотирьох гідродинамічних схем («смуга інфільтрації» в необмеженому і навпівбмеженому пластах та навпівплощині в цих же умовах). Суттєві розбіжності результатів розрахунків підтверджують необхідність однозначного вибору розрахункової схеми. Запропонована методика обліку випаровування з поверхні ґрунтових вод, що залягають вище критичної глибини. Ця методика дозволяє охарактеризувати середньорічний режим підземних вод і протягом року. Багатоваріантні розрахунки дозволяють стверджувати, що головний режимоутворюючий фактор при глибині залягання підземних вод нижче критичної глибини це інфільтраційне живлення. Випаровування є негативною складовою водного балансу. Його величина залежить від глибини залягання підземних вод, літологічного складу вміщуючих порід, рослинного покриву і комплексу кліматичних факторів. Якщо ґрунтові води залягають вище критичної глибини, то облік їх випаровування при прогнозних розрахунках є обов'язковим. Для території міста Дніпро і Дніпропетровської області цей важливий параметр в наших розрахунках становив 2,0 - 2,2 м. При такій глибині залягання рівня ґрунтових вод від поверхні землі витрата їх на випаровування дорівнює нулю. Максимальне випаровування або випаровуваність відповідає їх зниженню біля поверхні землі і для регіону середнього Придніпров'я становить 800 - 820мм за рік. Роль випаровування зростає обернено пропорційно глибині їх залягання від поверхні землі, коли підйом рівня ґрунтових вод відбувається при їх заляганні вище критичної глибини. Процес зміни рівня ґрунтових вод в нестаціонарному режимі фільтрації описується двовимірними диференціальними рівняннями другого порядку в часткових похідних параболічного типу. Дане рівняння має аналітичні часткові рішення для всіх розглянутих варіантів граничних умов стосовно до завдань меліоративної гідрогеології. Можливим є коректне перетворення у гідрогеологічні умови зсувних схилів з використанням чисельного прогнозу. Порівняльний аналіз розрахункових схем, характерних для зсувних процесів міста Дніпра, показує істотні розбіжності в результатах розрахунків. Тому достовірність результатів прогнозних завдань істотно залежить від однозначного обгрунтованого вибору проектної схеми. Індекси інфільтраційного живлення розраховувалися шляхом порівняння даних моніторингу зі значеннями випаровування через поверхню грунту.

Ключові слова: ґрунтові води, прогноз, рівень, гідродинамічна схематизація

Introduction. Groundwater is basically a dynamic resource that may be expressed as the quantity of water measured by the difference between optimum and minimum water table within the aquifer (Jannat et al, 2014). Groundwater recharge includes atmospheric, surface and underground components of the water balance and depends on both climatic and anthropogenic factors (Herrera-Pantoja and Hiscock, 2008; Holman et al., 2009; Jyrkama and Sykes, 2007). Various studies have employed different methods to estimate groundwater recharge including tracer methods, water table fluctuation methods, lysimeter methods and simple water balance techniques (Mohan et al., 2018). The number of studies related to the assessment of hydrogeological risks in the catchment areas of rivers is increasing in many countries (Kalf, and Woolley, 2005; Yihdego and Webb. 2015, Yihdego and Webb, 2016).

Often predictions and operation assessment using numerical models proceed without making an adequate conceptual groundwater balance model (Yihdego and Khalil, 2017). Landslides are one of the most common and dangerous natural phenomena in areas with rugged relief, including gullies and ravines. It is very difficult to predict landslides because of the complex mechanisms that affect their activation.

Therefore, research on landslide prevention and mitigation mainly focuses on the distribution forecasting of unstable slopes that are prone to landslides in specific regions and under multiple external forces (Zeng et al, 2017). The prediction of the spatial distribution of unstable slopes, termed landslide susceptibility zonation, is important in assistance with government land-use planning and in reducing unnecessary loss of life and property.

The relationships between rainfall, hydrology and landslide movement are often difficult to establish (Malet et al, 2005). In this context, ground-water flow analyses and dynamic modelling can help to clarify these complex relations, simulate the landslide hydrological behaviour in real or hypothetical situations, and help to forecast future scenarios based on environmental change. Slow-moving landslides show complex mechanical and fluid interactions (Van Asch et al, 2009). Parameterization of hydrological and geomechanical factors by field and laboratory tests to describe the movement pattern of these landslides is difficult. The complete assessment of landslide susceptibility needs uniformly distributed detailed information on the territory (Sdao et al., 2013). This information is often fragmented, heterogeneous and related to the temporal occurrence of landslide phenomena and their causes.

The main goal of our research was to conduct a comparative analysis of the design schemes typical for landslide processes in Dnipro city.

Materials and methods. Four types of landslide slopes in Dnipropetrovsk region were identified taking into account the prevailing hydro-geological conditions conditions (Yevgrashkina et al, 2017; Yevgrashkina et al, 2018). First variant of hydrogeological conditions of landslide slope: ravine, pond and watercourse are the first kind boundaries (Fig.1). The second type: ravine, pond and watercourse are the second kind boundaries (Fig.2).

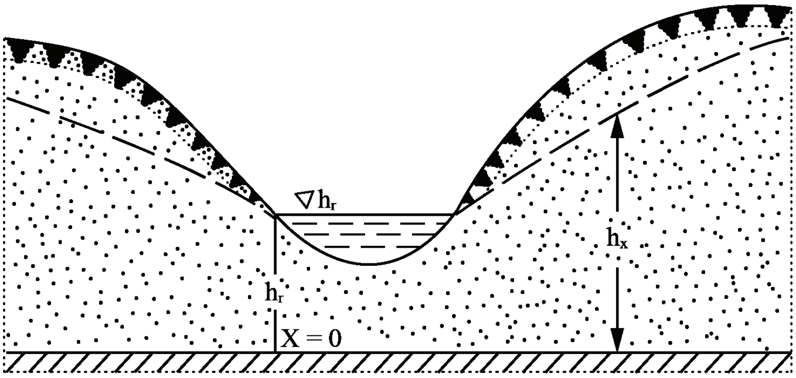

Fig. 1. First variant of hydrogeological conditions of landslide slope

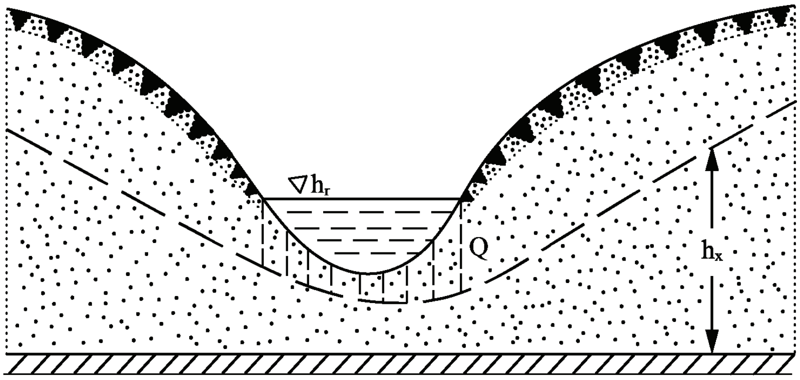

Fig. 2. Second variant of hydrogeological conditions of landslide slope

There is no water flow in the ravine (Fig.3). Two options are considered here.

The centre of the ravine with reasonable assumptions can be considered as a boundary of the II kind with a homogeneous structure of the aquifer (Fig.3a). In this case, the underground flow does not go up, but is combined with the flow from the opposite slope. As a result, they together change the direction under the bottom of the ravine to perpendicular r.

The second option (3b): the opposite slope is composed of weakly permeable rocks. This is a classic example of a particular case of boundary conditions of type II "impermeable boundary". The flow rate in this direction is equal to zero.The watercourse in the ravine occurs periodically in years with high rainfall. In this case, the forecast problem is solved by time intervals reflecting changes in hydro-geological conditions. A detailed characterization of infiltration feed and monthly evaporation is necessary as initial data to calculate the negative component of groundwater water balance – their evaporation rate, if they lie above the critical depth.

Results. The process of change in the level of groundwater in the unsteady filtration regime is described by two-dimensional differential equations of the second order in partial derivatives of parabolic type (Bochever et al, 1969):

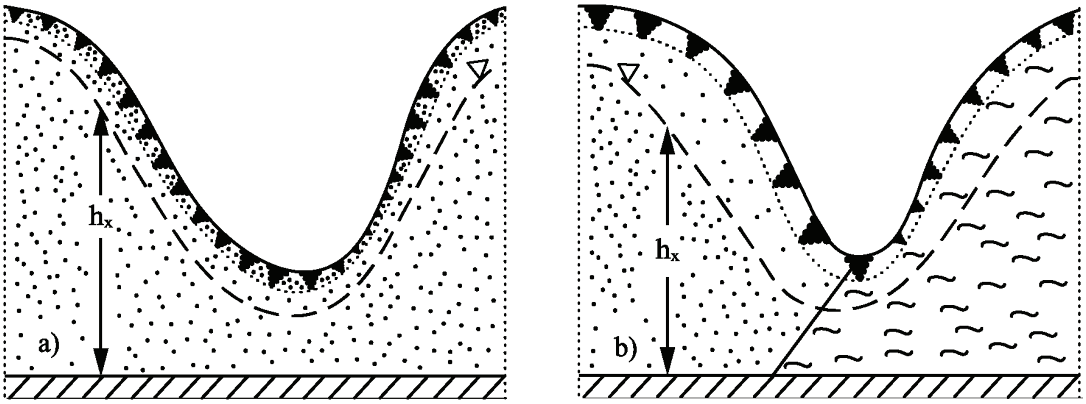

Fig.3. Third variant of hydrogeological conditions of landslide slope

(a) homogeneous structure of the aquifer; b) impenetrable opposite slope

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\varepsilon}{T}=\frac{1}{a}\frac{\partial h}{\partial t} \quad (1)$$

where

h

x, y distance from the aquiclude to the surface, m;

ε – spatial coordinates of the calculated points, m;

T – infiltration feed, m/day

a – water supply, m^2/day;

t – level conductivity, m^2/day;

the temporal coordinate, the time of the forecast, day.

This equation has analytical partial solutions for all considered variants of boundary conditions (Rudakov and Andreyeva, 1970; Yevgrashkina and Andreyeva, 1973). It is possible to transform to hydro-geological conditions of landslide slopes correctly using numerical prediction. Two computational schemes are applicable for the first variant of boundary conditions (Fig.1). The first scheme - the infiltration band in the semi - bounded layer will be legitimate if the ravine is parallel to the next one. This does not mean necessarily that the ravine is watered. The width of the infiltration strip is equal to the distance from the water edge in the watercourse to the highest point of the watershed (Fig.4).

Application of the scheme “half-plane infiltration in a semi-bounded formation” in the modification $b_1 = 0$ is appropriate if there is no parallel ravine, as in the previous scheme (Fig.5).

Variety of scheme $b_1 \neq 0$ in the study area is absent. Analytical solution of equation (1) for the computational scheme “infiltration band in a semi-bounded layer” (Fig.4b) has the following form:

$$z = 2\frac{\varepsilon \cdot t}{\mu}\left(i^2 erfc\xi^{ii} - 2i^2 erfc\xi^{i} + i^2 erfc\eta^{i}\right), \quad (2)$$

$$\xi^{ii} = \frac{x - b\cdot 2}{2\sqrt{a\cdot t}};\ \xi^{i} = \frac{x}{2\sqrt{a\cdot t}};\ \eta^{ii} = \frac{x + b\cdot 2}{2\sqrt{a\cdot t}};$$

The following designations are accepted in equation (2):

z –

the value of groundwater level rise above its initial

μ – position, m;

the coefficient of hydrocapacity, share units;

$i^2 erfc$ – tabulated function.

Analytical equation solution (1) has the form for the calculation scheme «half-plane infiltration in a semi-bounded layer»:

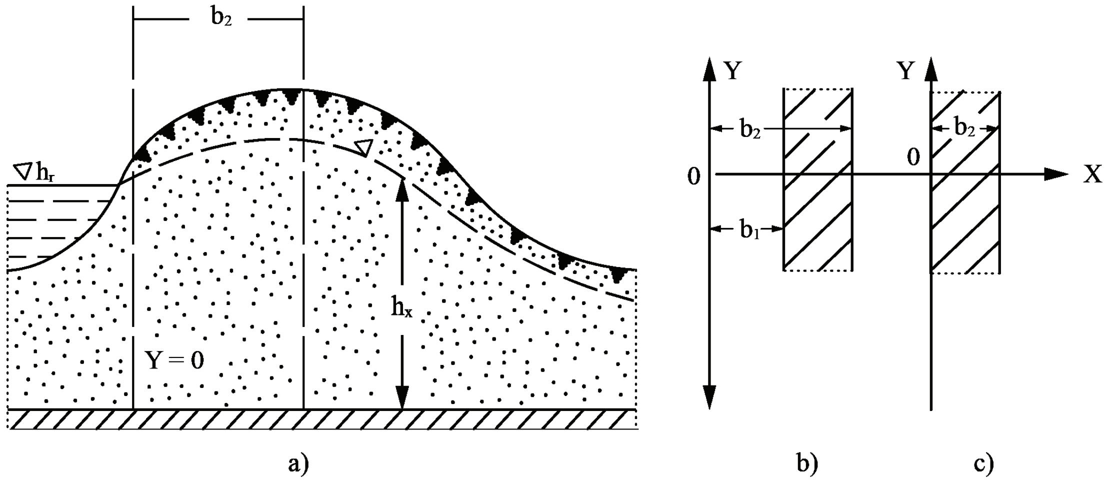

Fig.4. The block diagram, the band of infiltration in the semi- bounded layer

a –hydro - geological section; b - scheme of the section $b_1 \neq 0; b_2 \neq 0$;c - the scheme of the section $b_1 = 0; b_2 \neq 0$

$$z = 2\frac{\varepsilon \cdot t}{\mu}\left(0{,}5 - 2i^2 erfc\xi^{i}\right), \quad (3)$$

Analytical solutions (2) and (3) correspond to the hydrogeological conditions shown in Figure 1.

Two design schemes in Figure.6 can be applied to the hydrogeological conditions shown in Figure 2 above.

The first design scheme-“band infiltration in an unlimited reservoir” (Fig.6a)

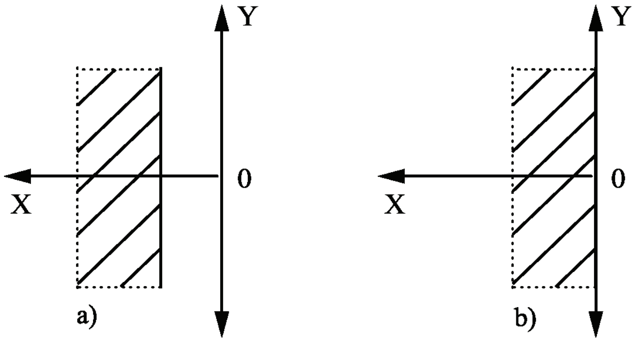

Fig.5. Computational hydrodynamic scheme " half-plane infiltration in a semi-bounded layer»
a - $b_1 \neq 0$; b-section diagram $b_1 = 0$;

$$z = 2\frac{\varepsilon \cdot t}{\mu}\left(i^2 erfc\xi_x - i^2 erfc\eta_x\right), \ \xi_x = \frac{x-b}{2\sqrt{a \cdot t}};$$

$$\eta_x = \frac{x+b}{2\sqrt{a \cdot t}}; (4)$$

The second design scheme is "half-plane in an unbounded layer" (Fig.6b).

$$z = 2\frac{\varepsilon \cdot t}{\mu}\left(1 - 2i^2 erfc\xi\right), \ \eta = \frac{x+b}{2\sqrt{a \cdot t}}; \qquad (5)$$

Two calculation schemes with boundary of II kind of "tight circuit" for the hydrogeological conditions are presented in Fig. 3. The scheme of the "strip infiltration in the bounded aquifer" (Fig.4 c) can be represented by the equation:

$$z = 2\frac{\varepsilon \cdot t}{\mu}\left(i^2 erfc\xi^{ii} - i^2 erfc\eta^{i}\right), \quad (6)$$

The calculated dependence (5) is valid for the scheme "half-plane in an unbounded aquifer" (Fig.5c). A comparative analysis of the calculation schemes typical for landslide processes of Dnieper city shows significant discrepancies in the results of calculations. Therefore, the reliability of the results of predictive problems significantly depends on the unambiguous reasonable choice of the design scheme.

It is known that evaporation gradually increases from the critical depth to the earth's surface. In our case, the evaporation from the groundwater level was calculated by the formula (Aver'yanov, 1978):

$$E = E_0(1 - \frac{z}{z_k})^n, \qquad (7)$$

where E – evaporation from groundwater level, mm;

E_0 – evaporation, mm;

Z – depth of groundwater level from the ground surface, m;

Z_k – critical depth, m

n – an exponent that depends on the above factors.

n is taken to be 1-3 for the conditions of the Dnipropetrovsk region. The practical calculation is performed in three variants n = 1, 2, 3 and the average value n = 2 is preferred more often. We will take groundwater evaporation into account when their level reaches a critical depth. In this case, we subtract the value from the infiltration feed in the calculated dependences (2) - (5).The dependence (5) takes the form:

$$z = 2\frac{(\varepsilon - u) \cdot t}{\mu}\left(1 - 2i^2 erfc\xi\right), (8)$$

All the rest is likewise. The rise of the groundwater level will stop at $\varepsilon = u, z = 0$. The point depth is calculated from the surface of the earth. In this case, the condition $E = \varepsilon$ is fulfilled: in each case, we find from the solution (7) with respect to z .

$$z = (1 - \sqrt[n]{\frac{E}{E_0}})z_k = (1 - \sqrt[n]{\frac{\varepsilon}{E_0}})z_k \, (9)$$

The territory of Dnipro city is dissected by several ravines. Hydrogeological conditions of the "Evpatoriyska" ravine were considered as an example. " Evpatoriyska " ravine is located in the southern part of Dnipro city within the watershed slope of the Right

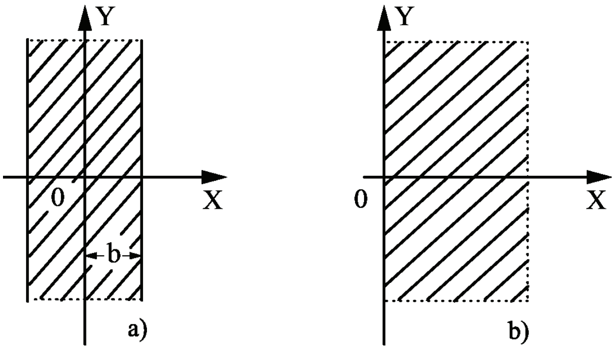

Fig.6. Band infiltration and half-plane infiltration in an unbounded layer a) band infiltration; b) half-plane

Bank of the Dnieper River. The average annual value of infiltration replenishment according to the results of treatment of regime observations is m/day or 6.2 mm / year.Substitute in the formula (9) the original data as follows:

$\varepsilon = 6{,}2 mm/year;\ E_0 = 800 mm/year;\ z_k = 2{,}0 m;\ n = 2$.

$$z = \left(\sqrt{1 - \frac{6{,}2}{800}}\right) \cdot 2 = 1{,}97 m$$

Following the calculations, the rise of groundwater level in long-term incision in this area will cease when the depth of its occurrence from the ground surface is 1.97 m with account of evaporation. However, seasonal variations are possible. Large values of groundwater level rise are possible during the period when the maximum amount of precipitation falls with minimal evaporation. The average annual value of infiltration replenishment in February reaches a maximum value of 8.37mm with evaporation of 10.3 mm (Table.1).

Enter this data in the formula (9):

$$z = \left(\sqrt{1 - \frac{8{,}37}{10{,}3}}\right) \cdot 2 = 0{,}2 m.$$

According to the calculation it, follows that the groundwater level in February may be at a depth of 0.2 m from the earth's surface.

Discussion. Evaporation is a negative component of the water balance. Its value depends on the depth of groundwater, lithological composition of the host rocks, vegetation cover and complex climatic factors. Accounting for the evaporation of ground waters in the forward estimates is required if they lie above the critical depth. The critical depth for the territory of Dnipropetrovsk region is assumed to be 2.0 m.

At this depth of groundwater level from the earth's surface, the evaporation rate is zero. The maximum evaporation or evaporability corresponds to the position of groundwater at the surface of the earth. The maximum evaporation for the Dnipropetrovsk region is 800 – 820mm (Yevgrashkina et al, 2018).

Evaporation gradually increases from the critical depth to the earth's surface. This parameter is determined experimentally in lysimeters or by calculated dependences. Currently, standard methods for assessing infiltration nutrition at the regional level most often include a long-term assessment of soil moisture (Jannat et al., 2014).

This approach is used to estimate surface runoff, evapotranspiration, and recharge in the unsaturated zone. Another approach is used when water is discharged from the atmosphere to the surface of the earth.

Meanwhile, most of the precipitation passes through the surface of the earth and enters the unsaturated zone, while precipitation that does not penetrate forms surface runoff and flows into the river network (Yeh et al, 2007). Water in the unsaturated zone vertically seeps into the deeper soil layers under the influence of gravity.

Uncertainty in the calculation of infiltration supply and discharge of groundwater seriously hampers the development and implementation of effective environmental policies for groundwater management. Further studies on the hydrology of landslides should therefore be carried out on the basis of the various databases.

Conclusion. The substantiated definition of infiltration feed is the main factor in the reliability of the predicted calculation at the depth of occurrence of groundwater level below the critical depth. The role of evaporation increases inversely with their depth, if the rise of groundwaters exceeds their critical depth. The stabilization of the level corresponds to the depth of its occurrence of ground waters of 1.84 m without taking into account additional sources of technogenic

Table 1. Evaporation and infiltration replenishment of the territory of Dnipro city during one year

Balance elements	**Balance sheet items by month**												
	mm												**mm**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**year**
Evaporation	8.86	10.3	22.5	55.2	93.8	134.3	178.5	150.9	93.8	43.1	17.4	11.0	819.75
Infiltration	3.69	8.37	4.44	1.14	0.9	1.14	-216	-2.01	-0.69	0.45	2.07	1.77	+23.97
м/сут $\mathbf{10^5}$													
Evaporation	0.27	0.34	0.75	1.84	3.13	4.48	5.95	5.13	3.13	1.44	0.58	0.37	
Infiltration	12.3	27.9	14.8	3.8	3.0	3.8	-7.2	-6.7	-2.3	1.5	6.9	5.9	

influence, including emergency situations. A significant error in the results of the forecast is proved by calculations due to insufficiently substantiated schematization of boundary conditions. Separate periods of the year are characterized by significant rise in groundwater level (up to 0.2 m from the surface of the earth).

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