# Analysis of changes in moisture transport parameters in soils under waterlogged conditions

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**Abstract.** The article considers changes in natural patterns of moisture transport parameters under waterlogging and lowering of groundwater table, in conditions of filtration-anisotropic strata. The nature of anisotropy characteristic of river sediments (alluvial, pluvial, deltaic and their combinations) is the most widespread in the surface zone of the earth's crust. Impact factors: external and artificial, in the process of waterlogging and drainage, affect both positively and negatively the thickness of the active zone, capacity and water permeability values. The research method is based on the generalization of different approaches, causes and factors of moisture movement and on the results of field experiments to determine the nature to reveal the essence of "gravity moisture discharge". In more exact statement the problem of stationary filtration is solved by Laplace equation. The state of moisture in the aeration zone has been studied: unsteady, transient and gravitational. By investigating the nature of this process, it is established that the evaporation process takes place not from the surface of groundwater table, but from aeration zone located between air (above ground surface) and water space (lower boundary of aeration zone).

## 1 Introduction

In arid zones with developed irrigated agriculture, at present, the priority directions of scientific-research works are reclamation and protection from external factors of waterlogging and salinization of lands, as well as solution of problems of ecological safety. In particular, due to physical ageing and unsatisfactory condition of water management facilities, filtration losses are increasing, and drainage networks and drainage systems are not fully operational. Flushing irrigation and land irrigation also result in an intensive rise of groundwater levels. The scale of water management construction continues to have a

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noticeable impact on ameliorative-hydrogeological and engineering-geological conditions of the construction area and is accompanied by a negative impact on the environment (large-scale groundwater level rise, change in the composition of both river and groundwater). The changes that began to occur in the second half of the last century in the irrigated lands of the Aral Sea basin have manifested themselves in the rise of the groundwater table, secondary salinization, deterioration of soil physical properties and their degradation, waterlogging of lands in the regional (in the irrigation zone) and local scales (within built-up areas of settlements and cities) [1].

Flooding is the process of rising of the level of groundwater above the permissible norms. This negative process develops in both humid and arid zones. At the same time, when designing measures to improve the ameliorative state of cities and settlements, there are a number of significant shortcomings for estimating the parameters of moisture transport of soils. The process of waterlogging occurs with additional infiltration water inflow during irrigation both from above and from below at saturation of aeration zone at its initial stage with annual rise of groundwater table up to one meter, with completion of waterlogging phase as a result of saturation up to full moisture capacity. Then, depending on the time of year, the moisture content fluctuates and salts accumulate in the capillary rise zone after evaporation.

The main sources of waterlogging are water bodies: reservoirs, large canals, transit irrigators, irrigated land and natural precipitation due to infiltration cause groundwater level rise. Natural factors economic activities and failure to take into account the planned hydrogeological monitoring caused waterlogging, which intensified in the zone of influence of irrigated land, large canals and reservoirs [2, 3].

Flooding is the increase in the groundwater level and soil moisture in the aeration zones, which affects the built-up areas as well [4]. This also explains the widespread opinion about the determining influence of groundwater flows and their salinity on the land reclamation state.

The results of researches for last 20 years show that more than 120 cities and settlements, from 7322 cultural - historical objects 2050 or 28 % of Republic are under negative influence of waterlogging [5]. Therefore, in turn, researchers are faced with a huge responsibility to further address these challenges and innovative developments in drainage of these areas.

1. State of the matter, object and methods of research

One of the main reasons of waterlogging of near-arid lands is cultivation of row crops - cotton, alfalfa, maize, etc. - on adyrs and lands covered with pebbles, on which during vegetation high irrigation rates are supplied, the main part of which goes to deep filtration and the subsequent seepage to downstream old-irrigated lands.

On the basis of long-term field studies the direction of reclamation processes and degree of land drain ability in Fergana, Andijan and Namangan provinces have been established. Development and irrigation of pebble lands have a negative impact on productivity of downstream lands, worsening their reclamation state.

Significant losses of irrigation water for deep infiltration from mountain and foothill zones combined with imperfect irrigation technique contribute to waterlogging of downstream areas [5]. These problems have not yet been adequately studied.

The aim of this work is to investigate properties of mathematical models of moisture transfer processes in soil under irrigation and drainage operation. In spite of significant developments in this direction, there is a need to improve calculation methods, taking into account a number of factors characterizing waterlogging, water-logging and salinization of lands.

Experimental studies and works carried out by the authors: Dmitriev S.I., Nichaev V.K. [6], Brudastov R.A. [7] on existing polder systems have shown that irregular drainage is the result of features of flow formation in conditions of slope-free terrain not taken into account during design.

## 2 Methods

Object of research. Objects of ameliorative control are established depending on main factor, determining ameliorative state of irrigated lands, on degree of their natural drain ability. In irrigated area formed in zone of increased infiltration the hillock of depression curve is accompanied with ground water feeding. The level curve reaches the ground surface or is drained by the open drainage network, an area of waterlogging (seepage) is formed. The latter, in the course of time, expands along the area "in-c" and at $t \rightarrow \infty$ reaches some stationary position. At the periphery of the waterlogged area, zones of water escape from the soil to the ground surface are formed. Figure 1. shows the calculation scheme for the development of waterlogging when groundwater rises as a result of surface irrigation of the land.

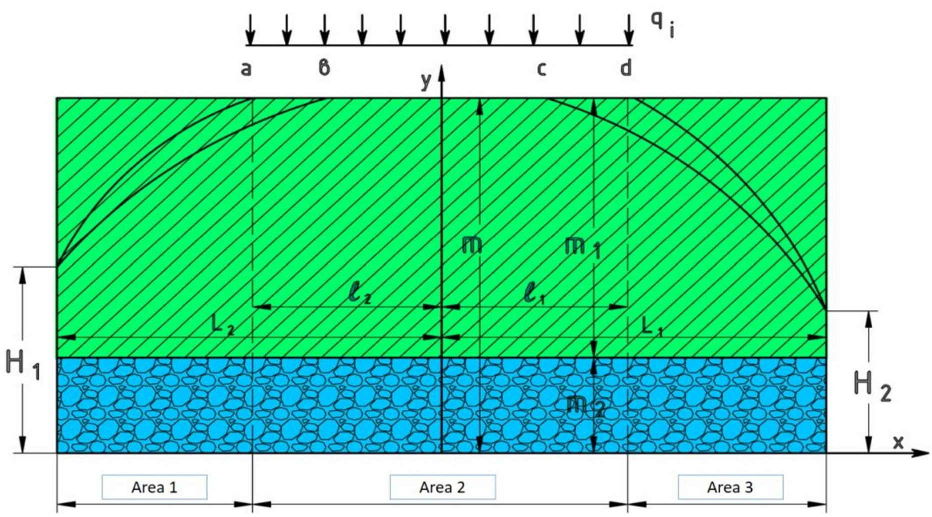


**Fig. 1.** Schematic for calculating the development of waterlogging when groundwater rises as a result of surface irrigation of irrigated land

As a result of irrigation at different humidity, capillary water in the zone "a, b and c, d" creates pressure P (back pressure) which varies from zero at the border with waterlogged zone "a, d" to at the border with free surface ($H_k$ - height of capillary vacuum of ground; $\gamma$ - water volume weight). The peculiarity of the considered case is the decrease of groundwater rise rate as soon as irrigation ends, where the area of its wedging out to the ground surface is formed. This is a special case, a pre-watering process, where the aeration zone is completely filled with moisture. Moreover, near the outlet area, the groundwater rises and then falls. Therefore, it is impossible to determine the size of the area under waterlogging using the methods for calculating the groundwater rise from filtration without taking into account the effect of this water outlet on the ground surface, i.e. in the nearest collector - drainage network [8]. The presence of the outlet area and diversion by collector-drainage network of a part of infiltration water reduces the level of groundwater flow obtained without taking into account the outlet area, and reduces the area of waterlogging of the irrigated area itself.

## 3 Results and Discussion

As a result of researches processing of field materials was carried out, generalized and solved problems on the basis of data analysis of long-term observation of groundwater regime and water balance. Factorial and field-experimental analysis in selection of protection means and drainage design are theoretically accepted.

Criteria for ground water interrelation with soil-soil their influence on potential waterlogging and their influence on meliorative state of irrigated lands are depth of ground water table and degree of its salinity, as well as their seasonal and long-term regime.

As stated above, despite the existing developments [7,8,9] in this direction there is a need to improve methods of calculations, taking into account a number of factors characterizing the process of waterlogging. On the basis of the above analysis the purpose and tasks of researches are determined. In more exact statement the steady-state filtration problem is solved by Laplace equation:

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}=0 \tag{1}$$

The boundary conditions in the waterlogged and capillary outlet areas respectively will be:

$$h(x,m)=m;\quad \psi(x,m)=\varepsilon x+c_1 \tag{2}$$

For a free-surface flow, formula (2) is as follows:

$$h(\chi,y)=m:\ \psi=\varepsilon(\chi-l)+c\ ;\ h=-\frac{\varphi}{k} \tag{3}$$

However, in the presence of non-steady infiltration due to irrigation in irrigated areas, the problem becomes more complicated and takes the form of

$$\frac{1}{\mathrm{X}}\cdot\frac{\partial}{\partial x}\left(XK_X\frac{\partial\bar{h}}{\partial x}\right)+\frac{\partial}{\partial\varepsilon}\left(K_\eta\frac{\partial\bar{h}}{\partial\varepsilon}\right)=0 \tag{4}$$

where: h- groundwater head.

For the convenience of solving the problem we will introduce dimensionless variables:

$$X=\frac{l}{m};\quad \varepsilon=\frac{Z}{m};\quad \bar{q}=\frac{q}{K_Z};\quad \bar{h}=\frac{h}{m};\quad \tau=\frac{K_Z^*\cdot t}{\mu^*\cdot m} \tag{5}$$

where: m is the vertical distance from the confining aquifer to the surface equal in thickness to aquifer $m_1$ and fine-grained rock $m_2$.

$K_z^*$ and $\mu^*$- some characteristic values of filtration and drainage coefficient (at drainage) or lack of saturation (at rise of levels) of soils, e.g. values for the considered rocks are determined by experimental field studies [10, 11].

When solving equation (4) the corresponding boundary conditions may change. If one takes into account the presence of drainage, including the infiltration area on the time-varying free surface, then equation (4) has a non-linear form:

$$\frac{\mu}{\mu^*}\cdot\frac{\partial \bar{H}}{\partial \tau}=\frac{K_Z}{K_Z^*}\left[\frac{\partial \bar{h}}{\partial \xi}+\left(\frac{\partial \bar{H}}{\partial x}\right)^2\left(1-\frac{\partial \bar{h}}{\partial \xi}\right)\right]+\bar{q}-\varepsilon-0_T \qquad (6)$$

where: $\bar{h}=\xi=\bar{H}$; $\bar{H}=\frac{H}{m}$; - relative values at free surface; H - groundwater thickness; ε - intensity of evaporation from free surface of aeration zone; $O_t$ - outflow intensity. According to (6) it can be assumed that

$$\varepsilon=\begin{cases} e_0\left[1-\frac{m-H}{H_{kp}}\right]^{\alpha} & \text{at} \quad m-H \prec H_{kp} \\ 0 & \text{at} \quad m-H \succ H_{kp} \end{cases} \qquad (7)$$

where: $l_0$ - intensity of evaporation from the ground surface; $H_{cr}$ is critical depth of groundwater table, from which evaporation starts; α - power index 1<α<3, usually α ~ 2[4].

Besides, conditions at external boundaries of the flow and underlying water bed should be set, namely:

$$h(-L_2 y)=H_2; h(L_1,y)=H; \ \frac{\partial h(xo)}{\partial y}=0 \qquad (8)$$

where $L_l$-distance from centre of waterlogged zone to external boundaries of flow by given head H2. In homogeneous medium, where: m=∞ this problem is solved by A.Zh. Muftakhov [7].

In approximate statement of the same problem for unsteady filtration plane flow is reduced to one-dimensional. It is divided into 3 zones (figure 1). In zones 1 and 3 filtration is described by linearized Boussensck equation and in zone 2 by two-layer filtration equation.

The boundary of zones of flood formation and drainage can be between the source of flooding and the area to be protected. Then, at the boundaries between zones "1, 2" and "2, 3" balance conditions are set:

$$h(l_1)=h(-l_2)=m-h_k \qquad (9)$$

where: $l_2$ are the coordinates of the boundaries between zones 1, 2 and at the outer boundaries of zones 1 and 3 take 2, 3 of condition 1,

$$h(-l_2)=H_2;\ h(l_1)=H_1 \qquad (10)$$

The process of waterlogging occurs when infiltration water is added during irrigation from both above and below when the aeration zone is saturated at its initial stage [12], for example from 7.5 to 5.6 m annually, as a result of saturation to full moisture capacity. Depending on the time of year, the depth varies, but in the capillary rise zone salts accumulate after evaporation from the ground surface. Here, after cessation of short irrigation, the depth of groundwater changes from 2.1 m to 2.8 m, which influences soil salt exchange. As a result of irrigation, in upper parts of Kokaral massif, (pilot plot near Buka river in Tashkent oblast) in comparison with the first year of development the groundwater table started to increase. At the same time total salt content in soil started to increase from 0.04 % up to 0.24 % of soil dry weight [4].

The initial groundwater table in the lower horizon as a result of regional backwater from the Kokaral massif began to rise (from a depth of 7.5 m) and reached 5.6 m in the second year. Vertical changes in groundwater table, total salt content and soil moisture content in the pilot plot were measured annually before and after vegetative irrigations for 40 years. The long-term studies have yielded extraordinary results. The process of soil salinization occurred irrespective of changes in the depth of groundwater, salt accumulation at the surface was observed due to moisture evaporation. Total salt content of ∑Ms (1) and ∑C1 (2) from above accumulated 3-4 times more intensively than from below. From the geological and lithological point of view, according to the experimental and available exploration boreholes, it is established that the area under consideration from the surface is composed of loess-like loam, compacted with depth, and containing interlayers of sand and pebbles with thickness from 7 to 60 m. Diversification of relief, presence of thick loamy cover and slope towards ravines form separate micro-basins of groundwater runoff from vegetative irrigation and infiltration of on-farm canal, crossing along watershed of the pilot plot. Groundwater tends to spread out along the edges of the irrigation plot when shallow from the ground surface. The presence of salts is caused by the addition of a portion of water in the ground as a result of land irrigation in subsequent years (5 or 7 years later), located in the area of the originally created depression funnel. The change in total salt content and calculated moisture content at the beginning and end of the wetting is shown in Figure 1a. Irrigation in the area of the irrigation funnel leads to the formation of a groundwater dispersion hillock (in local conditions), the backwatering of groundwater flows in the lowland steppe parts of irrigated lands (in regional conditions), results in the rise of the groundwater table at the periphery.

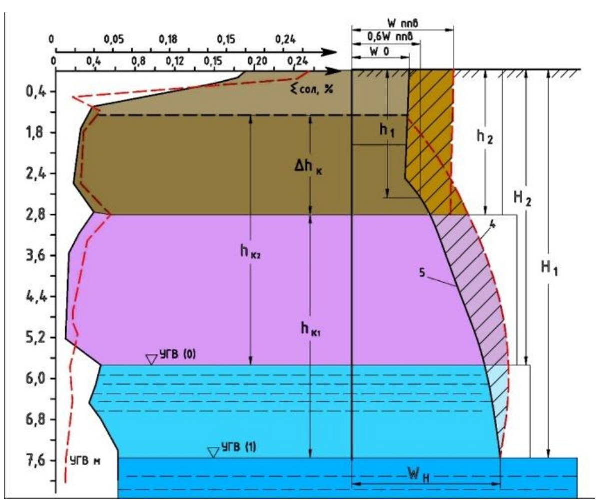


**Fig. 2.** Changes in total salt content (Σsol. (1), ΣC1 (2)) and calculated moisture content at the beginning (3) and the end (4) of moistening (shaded area - moisture content change under irrigation).

$H_1$ and $H_2$ - depth of groundwater table from the surface at the beginning (3) and the end (4) of moistening; $h_1$ and $h_2$ - depth of full field moisture capacity ($W_{floor}$) of soil; $h_{k1}$ and $h_{k2}$ - height of capillary rise at different depth of groundwater table; $W_H$ and $W_K$ - initial and final total capillary moisture capacity of soil at different groundwater table depths; $\Delta h_k$- difference in capillary elevation.

The system of moisture transport equations over pore films can be written in the form of Navier-Stokes equations:

$$\begin{cases} \dot{d} + \nabla(d\vec{V}) = 0 \\ \dot{\vec{V}} + (\vec{V}\nabla, \vec{V}) + a\nabla d = 0 \end{cases} \tag{11}$$

where d is the film thickness, m; V is the average velocity across the film, m/s; V is the velocity of the wave, one of the empirical formulas for this velocity is as follows:

$$V_{\max}(d_s) = 0{,}62 + 45{,}0\exp\left(-\frac{2{,}4}{d_s - 0{,}8}\right) \tag{12}$$

where ds is expressed in layers of water molecules).

Capillary transport of moisture is described by the following system of equations proposed by N.M. Kashchenko [13].

$$\begin{cases} (\mu_0 - \sum_{i=1}^{n} \mu_i)\dfrac{\partial H}{\partial t} = \nabla( \int_{H_d - kL_d}^{H} K_\phi(z)dz \cdot \nabla H) + \xi - \sum_{i=1}^{n} \mu_i f_i \\ \dfrac{\partial H_i}{\partial t} = f_i, \quad i = \overline{1,n} \end{cases} \tag{13}$$

where: H - groundwater level, m; $\mu_0$ - water yield coefficient; $\mu_i$ - relative capillary volume; $\xi$ - total inflow and outflow, m/s; $H_i$ - water level in capillaries, m.

$$f_i = V_{ki}\frac{H_{ki} + H - H_i}{H_i - H} \tag{14}$$

$V_{ki}$ - capillary ascent rate, m/s; $H_{ki}$ - height of capillary rise, m.

Moisture exchange between film and capillary water in film continuity equations and capillary equations are accounted for by adding a term of the form [13]:

$$\frac{1}{\tau_p}\left(1 - \frac{d}{d_0}\right)$$

where $d_0$ - is the film thickness, $\tau_p$ - is the rate of moisture exchange.

The flow of groundwater from the centre of the test section to the edges should be shown on a map of hydroisogyps and depths of groundwater occurrence. In order to intercept the infiltration flow in the depressed areas, horizontal drains [10] must be laid, which should be equipped with a pumping station or necessary facilities in order to create a free outflow of groundwater. In terms of practice, vertical drainage wells are applied [14];

against the background of existing pilot drainage systems, such drainages, consisting of 5-7 wells with a linear horizontal network, allow quantifying the characteristics of groundwater drainage. Based on experimental data modeling of polder systems operation has revealed existence of inter drainage distance (E) and drained massif area (F) interrelation, which has a form:

$$E = 8 + 32 \cdot \exp\left(-\frac{F}{1250}\right) \quad (15)$$

Presence of such significant dependence of drainage distances and area of drained massif requires precise detailing of drainage calculation methods taking into account dynamic water release in drainage regime. The field studies carried out by D.A. Manukyan managed to construct dependence curves in Fig. 1c - changes in specific surface area of phases in soil-soil under aeration zone moisture exchange with groundwater.

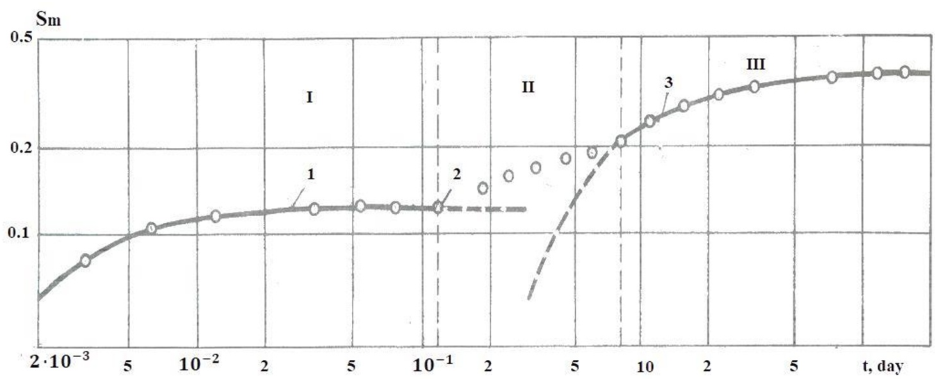


**Fig. 3.** Variation of specific surface area of phases in soil-soil during aeration zone moisture exchange with groundwater

Figures on the abscissa axis are time in days. 1 - curve plotted according to dependence (12); 2 - transition point, the drop (capillary discharge) of which is determined by formula (13); 3 - curve with dependence (14).

As shown in graph there are three sections of curve: 1 - non-stationary, 2 - transitional and 3 - gravitational.

In the transitional stage (2) water droplets occupying air space of aeration zone are influenced by forces of adhesion with ground particles and gravitation. During drainage operation with falling of ground water level, moisture liberated from these groundwater particles goes to "discharge" into groundwater, while with rising of level the opposite process - replenishment of pores "capillary reserves" and after sufficient saturation to full moisture capacity goes to evaporation [15]. Therefore, when investigating the nature of this process, it can be correctly assumed that the evaporation process does not come from the surface of groundwater, but from the aeration zone located between the open air (above the ground surface) and the water space of groundwater level.

In drainage operation [16], the stationary nature of infiltration is established. Together with infiltration, evaporation occurs, i.e. part of the water in the soil aeration zone evaporates and is spent for plant nutrition (evotranspiration) [17]. As a consequence, with the increase of evaporation, additional nutrition ε- from the lower horizons comes to the groundwater table during the operation of the drainage well:

$$\varepsilon_0 = \varepsilon_1 - \varepsilon_2 + \varepsilon_3 \qquad (16)$$

$\varepsilon_0$ - is the infiltration rate; At $\varepsilon > 0$ GWH increases and $\varepsilon < 0$ at GWH decreases

$$\varepsilon_1 = \alpha \, q_1$$

$\alpha$ - coefficient of infiltration intensity; $q_1$ is the steady-state infiltration flow rate, equal to the sum of the intensities; the average flow rate per unit area is equal to the modulus of groundwater supply through their mirrors:

$$\bar{q} = \frac{q}{R_2} \qquad (17)$$

At that, evaporation during daytime with intensity $\varepsilon_2$ and condensation at night and in the morning with intensity $\varepsilon_3$ occurs when the groundwater table is close to the groundwater level. Besides the loss of water from irrigated lands, within settlements under the influence of leakages of irrigation, municipal and industrial water, the man-made infiltration with the supply modulus $\varepsilon_T$, and in the presence of pressurized groundwater with the supply modulus $\varepsilon_W$ is superimposed on the natural infiltration [18,19]. Then the total infiltration modulus becomes equal to:

$$\varepsilon = \varepsilon_0 + \varepsilon_T + \varepsilon_W \qquad (18)$$

where: $\varepsilon_T$ - evaporation rate; $\varepsilon_W$ - feeding rate from discharge water.

Assuming $\varepsilon_O = 0$ we have, additional feeding from pressure water [20], which is described by the expression

$$\varepsilon_W = -\frac{k_3}{m_3}(h - H_0) \qquad (19)$$

where: $K_3$ - filtration coefficient of weakly permeable water-bearing (separating) horizon; $m_3$ - thickness of water-bearing layer; h and $H_0$ - pressures in the dried 1 and 2 and the underlying 4 pressure horizon;

## 4 Conclusions

1. Calculation of moisture movement in soil and data of calculations with experimental data allows concluding that under waterlogging and drainage conditions moisture movement through pore medium and capillaries gives the most acceptable coincidence of calculated data with experimental data.
2. The available ideas about the pore space structure in the form of capillary capillaries with its characteristic range of pore distribution, which changes its characteristics depending on the location in the soil volume is acceptable for use in calculations of moisture transport in the soil for capillary rise or gravitational discharge.
3. The application of gradients of the potential waterlogging and moisture conductivity coefficient allows obtaining a more accurate dependence of groundwater table distribution in the transverse direction to the drainage system.

4. During drainage operation with lowering of groundwater table the moisture released from these groundwater particles and goes to "discharge" into groundwater, and at rise of groundwater the opposite process - replenishment of pores "stock" and after. Sufficient saturation to the value of full moisture capacity goes to evaporation. Therefore, investigating the nature of this process, it is correct to consider that the evaporation process does not come from the surface of the groundwater table, but from the aeration zone, located between the air (above the ground surface) and the water-saturated space (below the aeration zone boundary).

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