Byulleten Pochvennogo instituta im. V.V. Dokuchaeva. 2014. Vol. 76.

REGULARITIES IN ACCUMULATION, LOSS AND RETURN OF WATER AND CHEMICAL SUBSTANCES DURING THE WATER EXCHANGE IN SOIL

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The experimental studies permitted to determine the ratio between infiltration and transpiration of the ground water in a soddy podzolic soil, that accounts for 0.3–0.6 under dried conditions of atmospheric moistening, 2.6–2.9 as an average value for many years and 2.6–2.9 under moderately wet conditions. The loss of potassium, calcium, magnesium, zinc and manganese under the grass stand was calculated as 0.95, 89.0, 37.7, 1.42 and 1.40 kg/ha/yr respectively. Due to capillarity the root layer of this soil receives 0.19 kg/ha of potassium or 20% from its loss with water infiltration, 16.4% of magnesium, 15.0% of calcium, 13.4% of zinc and 9.0% of manganese. It is shown that the water transpiration in case of the close underground water level leads to rupture of capillary links. With increasing the soil thickness in lysimeter the water infiltration and the nitrate leaching become declined both under grass and bean-grass stands.

Keywords: water exchange in soil, ground water, capillary fringe, lysimeter, chemical elements, infiltration, transpiration, water flow.

The ground water mineralization is highly dependent on the very complicated interaction of salt solutions through vertical transportation of ascending and descending flux of water and salts from the ground water to the surface (root) soil layer and back. Bearing in mind that the ground water (GW) is a possible source of water and nutrient supply of plants, one should notice that this problem has been so far examined insufficiently and in soils of the humid zone in particular. When calculating the ground water discharge (evaporation) into the root layer and its share in the evapotranspiration, it seems reasonable not only to use economically the irrigation water but also to provide optimal conditions for the water supply of plants. Besides, the conditions can be created for decreasing the regenerated flux from the aeration zone into the ground water and eliminating the removal of nutrient elements from the soil.

According to many researchers the subsurface exchange of water and chemical substances conditioned by descending (infiltration, *I*) and ascending (evaporation of the ground water, *K*) flux is the most important hydro-physical and hydro-chemical process [5, 6, 2, 16]. Just these two different-directed flows of water and chemical elements determine the water regime type, peculiar features and intensive accumulation of water and chemical substances in soil to improve its fertility to a considerable extent. It is known that the loss of chemical elements from the soil together with infiltration is rather great, being a subject of research in detail as compared to compensation of this loss by chemical substances from the ground water [13]. In view of this, in the scientific literature there is scanty information on this problem to draw definite conclusions.

The data of experimental investigations using lysimeters have been obtained by specialists of V.V. Dokuchaev Soil Science Institute [14], Russian Fodder Institute named after R.V. Wiliams [13] and Meshchersky department of Research Institute of Hydraulic Engineering and Amelioration (RIHEA) [9]. There is a number of publications described the placing of lysimeters and methods of their usage [3, 14, 15].

The water balance of the calculated soil layer can be presented in the following way:

$$W_{о} + W_{ос} + W_{г} + W_{k} + W_{пр} + W_{б} = E_{исп} + E_{т} + W_{ин} + W_{пс} + W_{с} + W_{кз} \quad (1),$$

$W_{о}$ – the water reserve in soil at the beginning of observations; $W_{кз}$ – the water reserve in soil at the end of observations; $W_{ос}$ – precipitation + watering; $W_{г}$ – groundwater feed; W_{k} – condensation water; $W_{пр}$ – surface feed; $W_{б}$ – lateral feed; $E_{исп}$ – evaporation of plants; $W_{ин}$ – infiltration; $W_{пс}$ – surface runoff; $W_{с}$ – lateral runoff. If $W_{k} \approx 0$, $W_{пр} \approx W_{пс}$ and $W_{б} \approx W_{с}$ the following equation can be used:

$$W_{о} + O_{с} + W_{r} = E_{исп} + E_{т} + W_{ин} + W_{k} \quad (2).$$

With respect to Wk this equation can be written in the following way:

$$W_{k} = W_{о} + O_{с} + W_{r} – E_{исп} – E_{т} – W_{ин} \quad (3)$$

In this equation *W*г is the water input from the ground water or its evaporation – *I*; *W*ин is infiltration – *K* [6].

The role played by parameters of the subsurface water exchange in lysimeter can be determined by the following equation:

$$Ec = OC + \Pi + K - I \pm \Delta W \ (4),$$

where *E*c – total evaporation, mm; OC – precipitation, mm; П – watering, mm; *K* – groundwater evaporation, mm; *I* – infiltration, mm; ± ΔW – changes in the soil water reserves during the calculated period (from t_1 to t_2), mm

From the hydrological viewpoint the lysimeter is a device containing an elementary part of the aeration zone with the model of GW level [5, 9, 10, 8].

Fig. 1 demonstrates a scheme of lysimeter placing and the device for automated regulation of the water level in lysimeter proposed by specialists of the Fodder Institute named after W.R. Wiliams and Meshchersky department of RIHEA.

The ratio between elements of the water balance, removal and return of chemical substances in the soddy-podzolic soil has been studied in lysimeters at a depth of 130 cm of the soil profile. Lysimeters at a depth of 35 cm and 70 cm were used to study the intensity and the loss of chemical substances. Traditional methods and procedures were performed to detect the content of chemical elements in infiltrates and the ground water [1].

The studied soddy-podzolic loamy deep gleyed soil on the mantle loam has the following morphological description:

AY, 0–6 cm – grass sod, gray with brownish hue, fresh, friable, fine-crumbly structure;

AY1, 6–20 cm – gray, slightly yellowish-pale, fresh, compact, fine-crumbly, light loam, abundant fine plant roots, distinct transition;

EL, 20–29 cm – gray with the whitish hue, fresh, more compact, crumbly-porous with separate rusty-brown mottles, tongue-like, medium loam, few small roots, distinct transition;

BT 1, 29–62 cm – yellowish-brownish with whitish mottles, somewhat wet, coarse crumbly or blocky structure, it can be broken in prisms with light-whitish powdering on the edges, small roots, medium loam, very compact, black points of iron-manganese compounds, distinct transition;

BT2, 62–115 cm – more homogeneous in color, yellowish-pale, somewhat wet, coarse nutty and blocky structure, heavy loam, gleyic in the lower

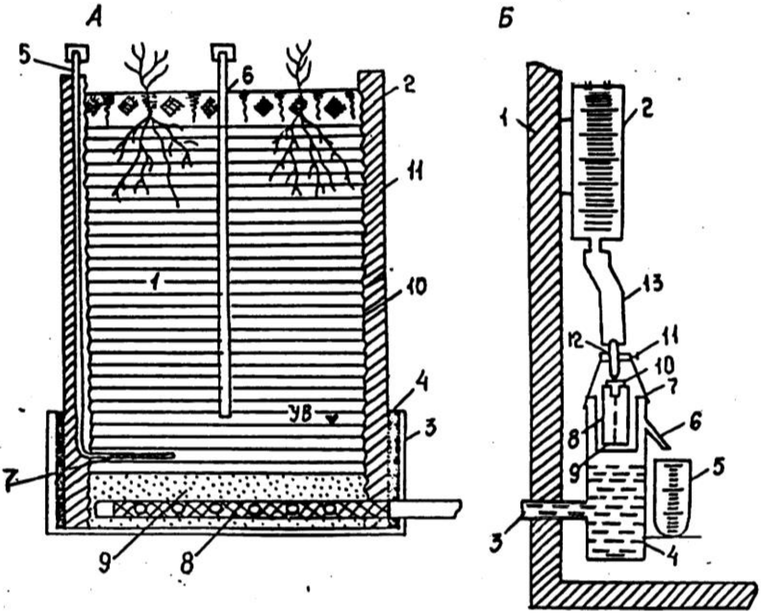

Fig. 1. Scheme of lysimeter placing (A); device for automated regulation of the water level in lysimeter (Б). *Lysimeter:* 1 – soil monolith (1 × 1 m^2); 2 – concrete filler; 3 – saucer; 4 – bitumen filler; 5 – piezometer; 6 – tube for observation of the moisture by means of neutron indicator; 7 – piezometer filter; 8 – tube filter with a net; 9 – sandy filter; 10 – bitumen isolation on the monolith wall; 11 – cassette. *Device for automated regulation of the water level in lysimeter*: 1 – a wall for observation; 2 – water-tight vessel; 3 – connecting tube; 4 – control tube; 5 – vessel; 6 – descent pipe; 7 – carcass of the water-level float; 8 – float; 9 – float axis; 10 – float cup; 11 – wedge bolt of the pipette; 12 – pipette; 13 – flexible hose.

part, small stones, somewhat compact, fine sand lenses, black-colored inclusions of Mn–Fe concretions, gradual transition;

BTg, 115–150 cm – pale-yellow, wet, sandy loam, blocky structure, Mn-containing points and voids, somewhat compact, mixed with sandy grains, the yellow sand in the lower part, wet, gleyic, gradual transition;

Cg, 150–210 cm – light-yellow with pale hue, wet, light-textured, silt light loam, gleyic, yellow lenses of sand (middle-sized sand grains), the wadose water can be present.

It has been already shown [14] that the ground water plays a significant role in evapotranspiration and formation of crop yield. The share of water discharge from the ground water into evapotranspiration of different crops on the soddy-podzolic soil makes up 19–38%. During the dried periods the total water discharge from the aeration zone and the ground water can reach 40–50% from the total evaporation. The agricultural crops have a considerable effect on the groundwater evaporation as well. When the ground water is at a depth of 1.5 m the stand predominating by orchard grass has a higher amount of the biomass and discharges the water in a greater volume, thus revealing a greater total evaporation as compared to that composing of timothy and fescue grass. If the ground water at a depth of 2.0 m, the discharge and total evaporation in both experiment variants are almost identical [12].

The experimental data to show the content, removal and return of chemical substances into the soil under the grass stand are given in Tables 1 and 2. The maximum content of calcium is 90.1 mg/l, the minimum is 55.0 mg/l. The maximum and minimum concentration of some other ions is found to be in the range from 12.1 to 5.6 mg/l of magnesium, 0.081 to 0.007 mg/l for zinc and 0.123 to 0.063 mg/l for manganese.

In the soddy-podzolic soil the ratio between groundwater infiltration and evaporation makes up 0.3–0.5 under middle-dried conditions, 2.5–2.7 under middle-moistened conditions and 2.6–2.8 as averaged for many years, what reflects the peculiar features of these processes in dependence on the precipitation sum and the water amount within the aeration zone. The maximum removal of chemical elements is observed during the vegetation period as well as in the autumn and winter. In the annual cycle the removal of calcium accounts for 89.0 kg/ha, the other chemical elements can be presented in the following order: calcium – magnesium – zinc – manganese – potassium. Due to capillary feeding the root layer of the soddy-podzolic soil receives 0.19 kg/ha or 20% of potassium, 16.4% of magnesium, 15.0% of calcium, 13.4% of zinc and 9.0% of manganese. When comparing to the alluvial loamy soil, it is reasonable to stress that the return of chemical substances from the ground water into this soil is estimated at 200–160 kg/ha or 104–77% of calcium, 82–53 kg/ha of zinc, 65–44% of

Table 1. Content of chemical elements in the infiltration flux of lysimeter, mg/l

Content of chemical elements, mg/l	K	Ca	Mg	Zn	Mn
Maximum	2.6	90.1	12.1	0.081	0.123
Minimum	0.7	55.0	5.6	0.007	0.063
Average	1.4	80.1	8.8	0.053	0.089

Table 2. Removal of chemical substances and their return from the ground water in lysimeters with the soil layer 130 cm thick

Period of observations	K	Ca	Mg	Zn	Mn
Removal of chemical elements, kg/ha					
Vegetation period (V–IX)	0.47	43.0	19.3	0.65	0.65
Autumn-winter (X–II)	0.30	29.7	11.1	0.44	0.51
Early spring (III–IV)	0.18	16.3	7.3	0.33	0.24
For a year	0.95	89.0	37.7	1.42	1.40
Return of chemical elements, kg/ha					
For a year	0.19	14.2	3.4	0.19	0.23
Return of chemical elements, % from removed ones					
For a year	20.0	15.0	9.0	13.4	16.4

anganese and 54–25% of magnesium. The difference is explained by the fact that the GW evaporation in the alluvial soil is higher by 2 times as compared to that in the soddy-podzolic soil. It is interesting to compare such data about the other soils. For instance, the irrigational-hydromorphic soils within the steppe zone of the Southern Ural reveal the following picture [8, 15]. With decreasing the water supply (*P*) the input of salts to soil is increasing at all the GW levels. When the groundwater level is at a depth of 1.0 m the salt input is estimated at 6.78 t/ha if P = 5%, 9.80 t/ha in case of P = 50% and 13.32 t/ha at P = 95%. An identical picture can be observed at the GW level equaled to 1.5 and 2.0 m. In case of decreasing the groundwater to 2.0 m and lower the salt input to soil is sharply decreased and makes up 6.78 t/ha at the GW depth of 1.0 m, at the GW depth of 2.0 m it accounts for 0.10

t/ha. The intensity of the water evaporation from the soil surface depends on many factors and in the first place on the groundwater level. Having studied this process in case of the GW level close to the soil surface, several peculiarities were established including the rupture of capillary transit ways in case of the high water content in soil due to the lack of correspondence between the intensity of soil water flow and the evaporation intensity at the soil surface. It is worth of note that the capillary fringe rupture takes place when the groundwater level is close to the soil surface. This is testified by the model experiment in the soil column with the groundwater level at a depth of 55, 40, 30 and 20 cm. Tensiometers placed at the same depth seemed to be at the different distance from the ground water and even under its level. A comprehensive analysis of the obtained results served as evidence that the groundwater depth equaled to 55 cm well agrees with its level. The other tensiometers indicated a water deficit in the capillary fringe and even in its lower part. With increasing the distance from the groundwater level from 15 to 35 cm the tensiometer values are increasing from –8 to –36 cm of the water column. It speaks about the capillary fringe that represents the aeration zone being a layer of active water rotation; the water loss happens simultaneously along the whole 0–55 cm soil profile.

With increasing the groundwater level (to 40, 30 and 20 cm from the surface respectively) the difference becomes decreased between the other tensiometers located above the groundwater level.

In Table 5 there are data about the state of different parts of the capillary fringe characterizing by the water saturation deficit. It accounts for –7 and –33 cm of soil column in lysimeter when the capillary fringe level is at a depth of 15 and 35 cm from the ground water.

Table 3. The water deficit (< total water capacity) at GW evaporation in case of its close level to the soil surface (*1* – tensiometer values; 2 – water deficit in the capillary fringe), cm

GW level	T1		T2		T 3		T 4		*I*, mm/24 hours
	1	*2*	*1*	*2*	*1*	*2*	*1*	*2*	
55	0	0	–22	–7	–37	–12	–68	–13	0.7–1.1
40	+ 16	0	0	0	–10	0	–55	–45	1–2
30	+ 28	0	+ 9	0	–5	–5	–30	–20	1–2→15
20	+ 35	0	+ 20	0	+ 7	0	–5	–5	2→11

Note: T1–T4 – No of tensiometer.

Table 4. Capillary fringe state in case of the ground water at a depth of 55 cm

Capillary fringe level from the ground water, cm	Distance of the capillary fringe level from the soil surface, cm	Energetic state of the capillary fringe, cm of water column		Deficit of the water saturation in the capillary fringe, cm
		theoretical	Tensiometer values	
15	40	–15	–22	–7
35	20	–35	–68	–33

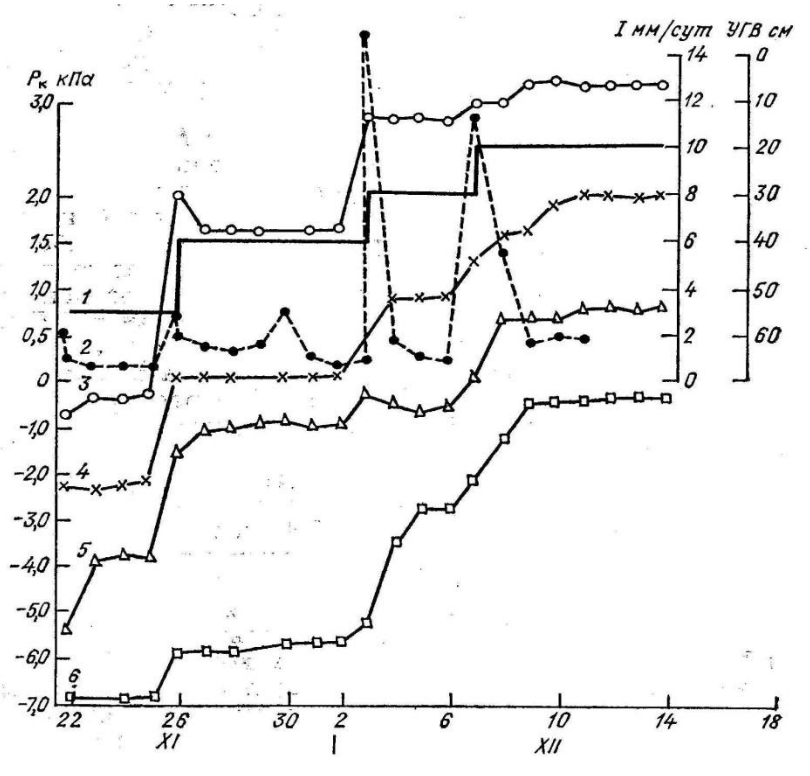

Fig. 2. The groundwater level (*1*), intensive discharge of the ground water at a depth of 5 cm (*2*) dynamics of the water potential ($P_к$) at depth of *3* – 5; *4* – 15; *5* – 25; *6* – 35 cm from the GW level.

At a depth of 55 cm the intensity of the groundwater evaporation is estimated at 0.7–1.1 mm/24 hours being equal to 1.5–1.7 mm/24 hours at a depth of 20 cm. With increasing the groundwater depth from 20 to 55 cm from the soil surface the water reserve in the capillary fringe and intensity of the groundwater discharge become decreased. The maximum intensity of the GW evaporation is observed when its level proves to be close to the soil surface and the pore space is filled by water (compensation of the water saturation deficit). For instance, if the GW level is at a depth of 40 cm the flow intensity increases to 3 mm during 24 hours being decreased to 1.1–1.5 mm/24 hours. The intensity of the GW evaporation is maximal, when its level increases from 40 to 30 and from 30 to 20 cm (11–15 mm/24 hours).

In the soil-ground water system the intensity of the water exchange is highly affected by the thickness of the soil column in lysimeter, the applied fertilizers and the grass species. As it was already shown [13], the water infiltration and the nitrate removal are dependent on the type of the grass stand being considerably higher under grass stand as compared to that comprising the bean-grass species. The nitrogen loss from the 0–35 and 0–130 cm soil layers is also lower than that under bean-grass species (Table 6).

The loss of chemical substances is dependent not only on the thickness of the soil profile but also the type and rate of fertilizers. The increase in the rate of fertilizers (ammoniate and nitrate forms) from N180 to N480 leads to increasing the loss of nitrogen, nitrates, pho sphorus, potassium, calcium and magnesium by 1.5–6.0 times of total

Table 5. The infiltration flow and the nitrate content in it affected by the thickness of the soil profile and grass stand for the 2005 vegetation period (Semenov et.al, 2005)

Experiment variant		Infiltration flow in different months of the vegetation period, l/m^2					Total infiltration flow, l/m^2	The nitrate content in the flow, mg/l
depth, cm	Grass stand	V	VI	VII	VIII	IX		
35	Grass	19.7	14.2	21.8	21.0	7.3	74.0	1.3
35	Bean-grass Grass	7.9	8.9	11.1	9.8	9.3	47.0	8.1
130	Grass	5.6	9.4	9.0	10.3	6.7	41.0	1.0
130	Bean-grass	3.7	4.8	6.0	5.5	3.0	23.0	2.4

N, 3.5–8.0 of nitrate N and 1.2–2.7 of the other chemical elements. However, this increase is highly dependent on the soil layer thickness and the nitrogen fertilizer form. It is quite different for every chemical element [13].

The quality of the perennial grass sod and the methods of land grassing play a significant role in the formation of the regenerated flow. Based upon experimental data it is possible to show the impact exerted by the disintegrated biomass of wood vegetation in admixture with meadow grass on the physical state of soil and its productivity. In lysimeters the topsoil at a depth of 10–22 cm included the biomass consisted of willow (13.6 t/ha), birch (27.7 t/ha), asp (28.6 t/ha) and wood-reed (17.2 t/ha). The annual rye grass was sown and after the sprouting the soil was fertilized in the amount of N60P60K60. After 2 years the grass fertilized by N45K45 and grass-bean mixtures (K45) were sown on the same soil. For 2 years the fertilizer in the sum of N105P60K105 was used. Taking into account the content of N, P, K and Ca in the biomass the plants received 239, 176, 206 and 117 kg/ha for willow, 406, 269, 272, 171 for birth, 195, 146, 256, 44 for wood-reed. 105, 60, 105 and 0 kg/ha of active substance were introduced into the soil in control variant. The obtained results showed that the infiltration is maximal in the arable soil (206 l/m^2) being minimal in the variant with grass stand (52 l/m^2). In variants with the biomass of different wood vegetation the infiltrate volume was in the range from 170 to 194 l/m^2. The Ca content (ml/l) was increased in different variants and can be written in the following order: control (14.0) < meadow grass (34.3) < willow (34.7) < arable land (41.6) < birch (44.1) < wood-reed (45.9) < asp (46.1). In variants with fertilizers its concentration is appreciably lower what is probably explained by its removal with the rye grass biomass. One should notice the same picture of the calcium loss with the infiltrate. It is significantly lower in variants with fertilizers as compared to those without fertilization. The highest loss of Ca is in arable soil (92.2 kg/ha), in variants with asp birch, wood-reed, willow and meadow grass it is 85.8, 85.5, 78.0, 60.4, 39.2 kg/ha respectively and in the control – 7.3 kg/ha.

CONCLUSION

Maximal values of total evaporation of the soil water and infiltration are observed under middle-moistened conditions, the groundwater evaporation – under middle-dried conditions. The ratio between the groundwater infiltration and evaporation in the soddy-podzolic soil makes up 0.3–0.6 for middle–dried conditions, 2.6–2.9 for middle-moistened conditions and 2.6–2.9 as average for many years. In the annual cycle Ca is highly removed (90 kg/ha). The removal of all the studied chemical elements is decreasing and can be presented in the following way: Ca – Mg – Zn – Mn – K accounting for 0.95, 89.0, 17.7, 1.42 and 1.40 kg/ha respectively under grass stand.

In the course of the groundwater evaporation the root layer of the soddy–podzolic soil receives through capillaries 20% of K, 16.4% of Mg, 15.0% of Ca, 13.4% of Zn and 9% of Mn. In case of the close groundwater level to the soil surface (to 20 cm) the thickness of the capillary fringe and the water reserve in it are decreased but the intensity of water evaporation becomes increased. The maximum is observed in the course of filling the pore space (compensation of the water saturation deficit) when the groundwater level seems at a higher depth.

In case of the close groundwater level the water evaporation from the soil surface leads to the capillary fringe rupture due to the absence of correspondence between the intensity of the flow from the ground water to the soil surface and the water evaporation from the surface of soil.

The maximum loss of Ca ions in variants with the biomass comprising the woody vegetation is in the arable soil (98.2 kg/ha), in variants with asp, birch, wood-reed, willow and meadow grass it makes up 85.8, 85.5, 78.0, 60.4 and 39.2 kg/ha respectively. In control the Ca loss accounts for 7.3 kg/ha.

With increasing the thickness of the soil profile the water infiltration and removal of nitrates are decreasing under grass and bean-grass stands, being somewhat greater under grass species as compared to bean-grass ones. The N loss from the 0–35 and 0–130 cm soil layers are lower under the grass stand.

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