

Monitoring of Water Flow and Solute Transport Through the Unsaturated Zone Using a Large-Diameter Borehole

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Abstract

A method for monitoring water flow and solute transport through the unsaturated zone is of crucial necessity for early detection of threats to ground water. A method developed by Ukrainian hydrogeologists in the 1970s involves a borehole of a large enough diameter for a person to enter, that provides the possibility of installing monitoring equipment, and enables collecting undisturbed sediment blocks and samples of pore water and gas. Practically, tensiometers and vacuum lysimeters are installed at various levels in the borehole walls. They provide high quality sampling and measurements, and enable determining parameters of unsaturated water flow and solute transport and their temporal and spatial variability.

The method was tested at several locations. Selected results from two sites, showing the temporal and spatial distributions of capillary pressure and solute concentrations, are presented. The results exhibit the difference between lateral variation in water flow and solute transport characteristics. The accuracy and representativeness of the measurements were tested against the mutual interaction between the various instruments installed in the borehole walls. Monitoring using the large-diameter boreholes provides the possibility of early detection of threats to ground water under areal contamination inputs, and of quantitative prediction of its future trends.

Introduction

A reliable method for monitoring contaminant transport through the unsaturated zone is important for early detection of threats to ground water. Unfortunately, ground-water pollution is usually detected after the contaminated water has already reached its consumers, which is obviously too late. Several techniques, such as the multilayer sampler for monitoring the water-table region (Ronen and Magaritz, 1985; Ronen et al., 1986), have been developed to obtain some earlier information concerning danger of pollution. However, Cullen et al. (1992) and Durant et al. (1993) argued that ground-water monitoring should be performed at an even earlier stage, namely when contaminants pass through the unsaturated zone. For this purpose the U.S. EPA has recommended the use of shallow boreholes or trenches, and installing in their walls vacuum lysimeters for pore-water sampling and tensiometers for capillary pressure and water content estimation (Everett and Wilson, 1986). However, this method is limited to the upper part of the unsaturated zone.

A method for monitoring solute transport in the deep unsaturated zone using a large-diameter borehole (a man-hole) was developed by Ukrainian hydrogeologists in the early 1970s. Such a borehole provides the possibility of installing the monitoring equipment in its walls. It ensures high quality sampling and long-term measurements, as well as replacement or addition of equipment. This method was initiated at the Kiev University (Zhernov et al., 1974; Sitnikov, 1978) and was improved at the Ukrainian Institute of Water Management (Zilberbrand and Negoda, 1976; Zilberbrand and Golovchenko, 1977). Methodological experiments were performed in such boreholes drilled down to a depth of 7-24 m. Practically, it was applied to monitor water and salt transport in the unsaturated zone of loess loam sediments, in irrigated, unirrigated, and drained lands (Muromtsev, 1973; Golovchenko et al., 1976; Sitnikov, 1978 and 1986; Golovchenko, 1984; Dzepo, 1988; Shvets, 1988; Zilberbrand, 1987 and 1993).

Long-term observations of capillary pressure, pore-water content, and ion concentrations were carried out, and calculations of specific flow velocities and ion transport rates were performed, providing a very useful, detailed, and accurate data base. These characteristics were studied at depth intervals of 0.5-2 m, all along the unsaturated zone. Unfortunately, as these studies were published in Russian, they are almost unknown to the international scientific community.

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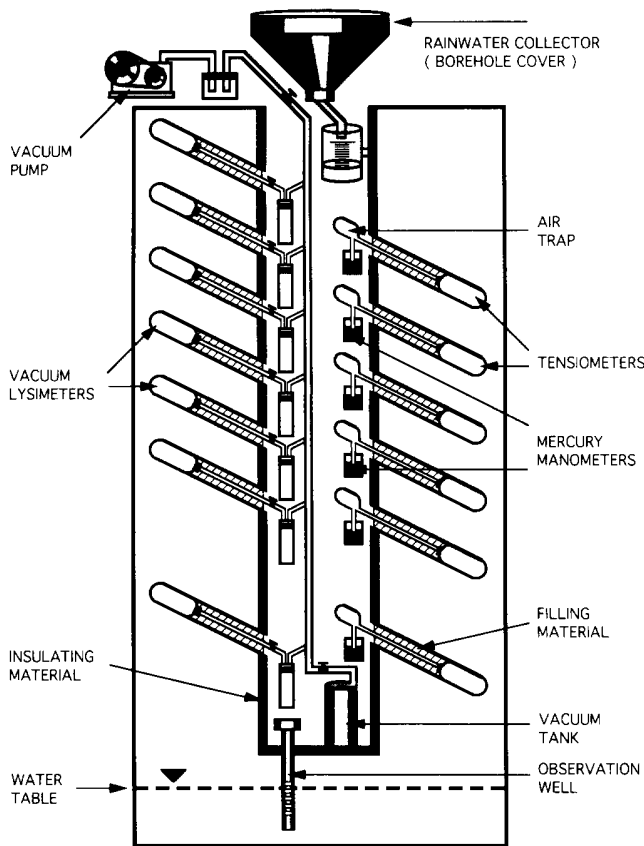


Fig. 1. Schematic structure of a large-diameter borehole and the monitoring devices installed in its walls.

A schematic structure of a large-diameter borehole is shown in Figure 1. It was drilled using a hollow stem auger driller without the addition of water. The borehole was typically 1.0 m in diameter and it reached to a depth of 0.5 m above the water table. Undisturbed sediment blocks were taken during drilling. These blocks were insulated using gauze and melted paraffin, and used later in the laboratory for the determination of water transfer parameters. The space between the sediments and borehole casing, up to 0.1 m thick, was filled by an impermeable and heat-insulating material (bitumen or paraffin). Tensiometers for capillary pressure measurements and vacuum lysimeters for pore-water sampling were pushed into the sediments at different horizons, through nearly horizontal holes drilled in the walls. Also, ceramic chambers for direct determination of vertical Darcian flux were sometimes added (Zhernov et al., 1974).

It was shown that when these devices were horizontally installed to a distance of more than 0.5 m from the borehole casing, they provided a reliable record of natural water and solute transport. Capillary pressures in sediments behind the borehole walls and in surrounding sediments equilibrated within a month after borehole installation (Sitnikov, 1978). The borehole head was covered with a funnel-like lid to collect precipitation in a closed bottle (Figure 1). At the borehole bottom there was a 5-cm-diameter hole for monitoring the water-table zone.

Initially, it was suggested that pore-water samples be taken from the tensiometers which equilibrated with the natural pore water (Sitnikov, 1978). However, because of the slow equilibration rate, in practice, this was very difficult, and thus, water samples were sucked using empty ceramic caps and a vacuum pump (Borisov and Negoda, 1974; Sukhobry, 1979). A question was raised regarding the mutual influence of the vacuumed pore-water sampling on the nearby tensiometer accuracy, and also, the influence of water within the tensiometers on the chemical composition of natural pore water. Therefore, at that stage, vacuum lysimeters were installed far from tensiometers, either in another borehole (Borisov and Negoda, 1974), or in the same borehole, but at different depths (Sukhobry, 1979).

This paper reviews several applications of the large-diameter borehole technique based on long-term monitoring of capillary pressure and ion concentrations along unsaturated profiles. The spatial variability of these parameters, their representativeness and accuracy are analyzed. The advantages and disadvantages of the method, possible complex sampling, and monitoring under dry climate conditions are also discussed.

Materials and Methods

Site Description

The research was carried out near the villages of Krestovka and Pavlovka in the southern Ukraine steppe zone where the Kahovskaya irrigation system had been functioning since 1972 (Figure 2). Prior to 1972, local ground water was used for irrigation at the Pavlovka site. The unsaturated zone, 7-24 m thick, is composed of chestnut soil and loam of loessial composition underlain by clays. Soil horizons A, B₁, and B₂ are of 0.4, 0.4, and 0.5 m thick, respectively. Clay percentage in the loessial sediments increases with depth from 30% to 45%. The bulk density of the sediments ranges between 1.5-1.6 g/cm³. The unsaturated zone contains soluble salts, mostly sulfates, in quantities of less than 1% of sediment mass. Below 2.5 m, gypsum accumulations are found.

Annual precipitation amounts to 350-400 mm, 70% of which falls in the summer. The average temperature in July is 22-24°C, and in January, -4°C. Grain and forage crops are grown with supplementary irrigation of about 400 mm/year, performed by sprinklers.

Ground-water replenishment was estimated to range between 2-20 mm/year at nonirrigated sites, while in irrigated fields it ranged between 40-110 mm/year (Sitnikov, 1986). Under very rainy years, replenishment reached values of up to 200 mm/year. Preferential water flow through fissures within the loamy unsaturated zone takes place only in the upper 2-3 m. At greater depths the porous material is much more uniform. In general, water content in the loess sediments gradually increases downwards. Below 3-4 m down to the capillary fringe, volumetric water content changes within a narrow range of 30-32%, wherein water motion is downward only.

At the Krestovka site, the Pliocene sandy aquifer contains good quality water, with a TDS of 400 mg/liter (mg/l),

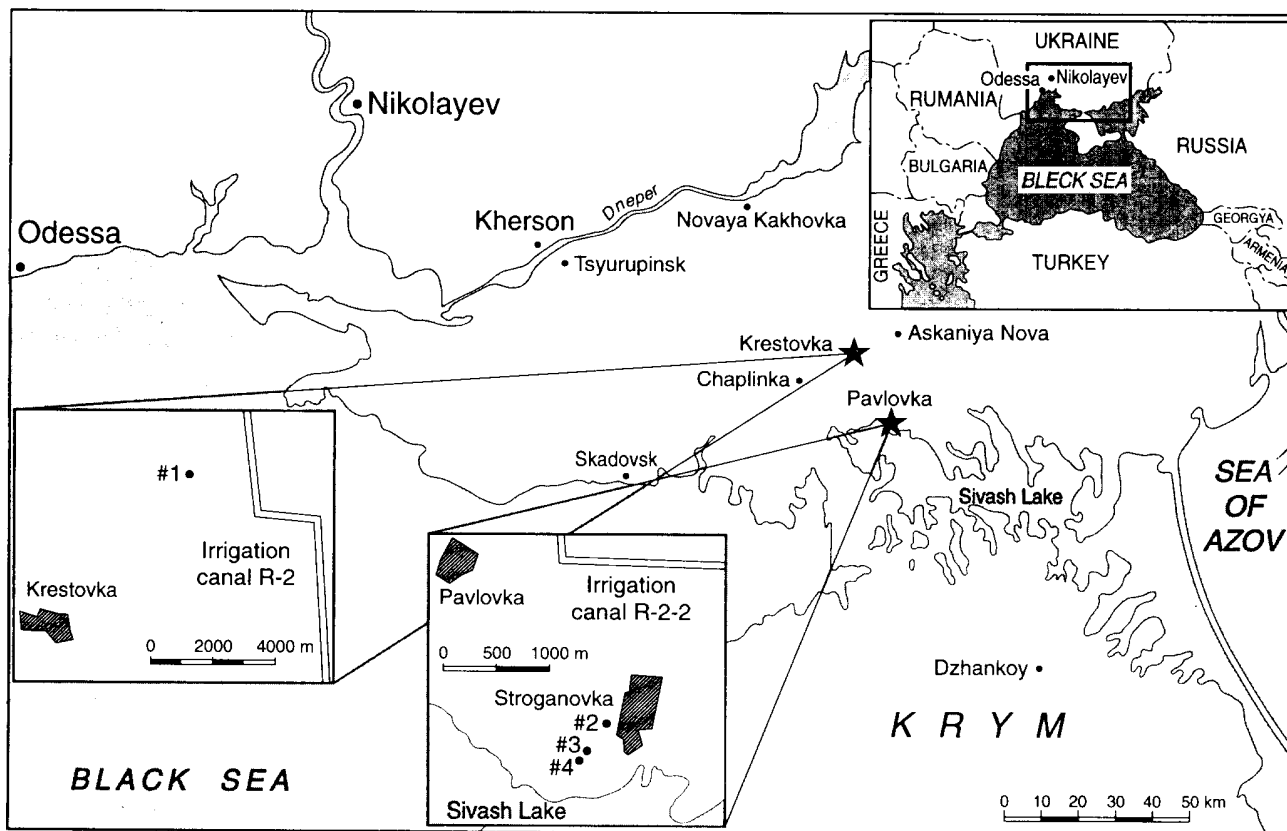


Fig. 2. Location map of research sites (stars) in the Ukraine.

and chloride concentration of less than 50 mg/l. At the Pavlovka site, ground water is of the sodium-chloride type with a TDS of 11,000-27,000 mg/l.

One research borehole was drilled at the Krestovka site in an intensively irrigated grain field (Borehole #1). Three other boreholes were drilled at the Pavlovka site: one located in an intensively irrigated grain and lucerne field (Borehole #2), and the other two (90 m apart) in an unirrigated field (Boreholes #3 and #4). Figure 2 shows the locations of these boreholes.

Sampling and Measurements

Both monitoring devices, tensiometers and vacuum lysimeters, were cylindrical ceramic chambers, which are known as "bacterial filters" of type 5A (Khoost Ceramic Factory). Their average length was 15 cm, external diameter 1.8 cm, and inner diameter 1.5 cm. They were characterized by a maximum pore size of 1.2-1.8 μm , and barbotation pressure of 60-80 kPa. The cylinders that were used as vacuum lysimeters were first washed by hydrochloric acid and then thoroughly flushed with distilled water until no chloride was detected in effluent. After drying, they were inserted horizontally into the sediments through holes of the same diameter, to a distance of about 0.5 m from the borehole walls (Figure 1). Those that were used as tensiometers were installed using a paste made of the same sediment. They were connected to U-form water manometers in the

upper part of the unsaturated zone, and to mercury manometers in its lower part. The measurement accuracy was ± 1 mm of the water or mercury column, which is equivalent to 0.01 and 0.14 kPa, respectively.

Chemical composition of pore solution was determined in two different ways. The first was by using water extracts prepared from sediments collected during drilling through borehole walls. Gravimetric water content was determined by weighing the sediment samples before and after oven-drying. The dried sediments were shaken with a fivefold mass of distilled water and filtered; then water extracts were chemically analyzed. Total error, combining sampling and analytical errors, amounted to $\pm 25\%$. The reason for this high error value was the dissolution of gypsum and carbonates during water extract preparation. The second method, which appeared to have a much higher accuracy, was the sampling of pore water using vacuum lysimeters. The water samples, each of 10-15 ml, were collected during 2-4 days by applying vacuum of 40-80 kPa. Sampling errors were estimated to be very small since uniform ceramic samplers were used, and the same preparation, installation, and vacuum suction were applied. Total chemical analysis errors amounted to $\pm 5\%$. Anion concentrations were determined by automatic titration: Cl by the Mohr method, SO_4 by complexometric method, and HCO_3 by potentiometric titration. Cation concentrations were determined by an ISP-51 flame photometer.

Results and Discussion

Lateral Variability of Capillary Pressure

The spatial and temporal variability of capillary pressure was tested by performing many measurements all around the borehole perimeter, at several depths of the unsaturated zone. At each horizon, up to a dozen tensiometers were installed. Continuous capillary tension readings were taken by each of the tensiometers during several days, including periods of wetting (rainfall or irrigation) and drying of the upper soil.

One set of results, shown in Figure 3, was obtained at the Krestovka site, where tensiometers were installed at 1, 3, and 6.5 m below land surface. Measurements were taken after a rainfall event, during 16 sunny days in July-August, when the soil became dryer from day to day. On the first day, capillary pressures observed in the 12 tensiometers installed at a 1.0 m depth varied between 37-49 kPa, with a standard deviation of ± 3.3 kPa. At 3.0 and 6.5 m depths, they varied between 30-31 and 24-25 kPa, respectively, with standard deviations of ± 0.5 and ± 0.3 kPa, respectively. Since manometer reading errors were estimated to be relatively small, less than 0.14 kPa, most variations were attributed to lateral variability. As was expected, increasing capillary tensions were observed during the 16 days of the drying process. On the 16th day, at 1.0, 3.0, and 6.5 m depths capillary pressures varied between 41-72, 32-34, and 24-25 kPa, respectively, with standard deviations of ± 6.5 , ± 0.6 , and ± 0.3 kPa, respectively.

These results exhibited significant lateral variability at 1.0 m depth, which diminished with further depth. This phenomenon was probably due to the peculiarities of wetting and drying processes in the uppermost soil. The existence of root channels and cracks within the upper soil could cause different rates of water percolation during rainfalls,

and different rates of vapor transport during dry periods, that might have resulted in the increase of lateral variability with time. At 3.0 m depth and below, the 12 tensiometers showed almost the same capillary tension, and the drying process was relatively negligible. Practically, it appears that at 3 m depth and below, two tensiometers per each investigated horizon would be representative of the capillary tension, while in the root zone, due to lateral variability, two tensiometers would not be enough. This is obviously a site-specific result. Different sediments, vegetation covers, and rainfall intensities could influence the minimum depth of significant lateral variability of media. Nevertheless, the general trend of decreasing lateral variability of hydraulic characteristics with depth can be concluded.

Lateral Variability of Ion Concentration

Vacuum lysimeters were installed all around the perimeter of the boreholes for sampling pore water and analyzing its chemical composition. Table 1 summarizes the chloride concentrations measured at three different horizons along the unsaturated zone (3.5, 7.2, and 8.5 m depths), each by 10-11 vacuum lysimeters. It is evident that lateral variability is still clearly significant at 3.5 m depth ($\pm 105\%$), but diminishes at deeper horizons (up to $\pm 3.3\%$). These results stand in contrast to lateral variability of capillary pressure which is significant only at 1.0 m depth and diminishes at 3.0 m and below (Figure 3). This might be the result of the relative difference in equilibration rate between flow and transport processes, due to the larger velocity of capillary pressure wave compared to the rate of ion transport (Zilberbrand, 1987). It should be noted that the total variations of $\pm 3\%$ were attributed not only to lateral variability, but also to sampling and analytical errors.

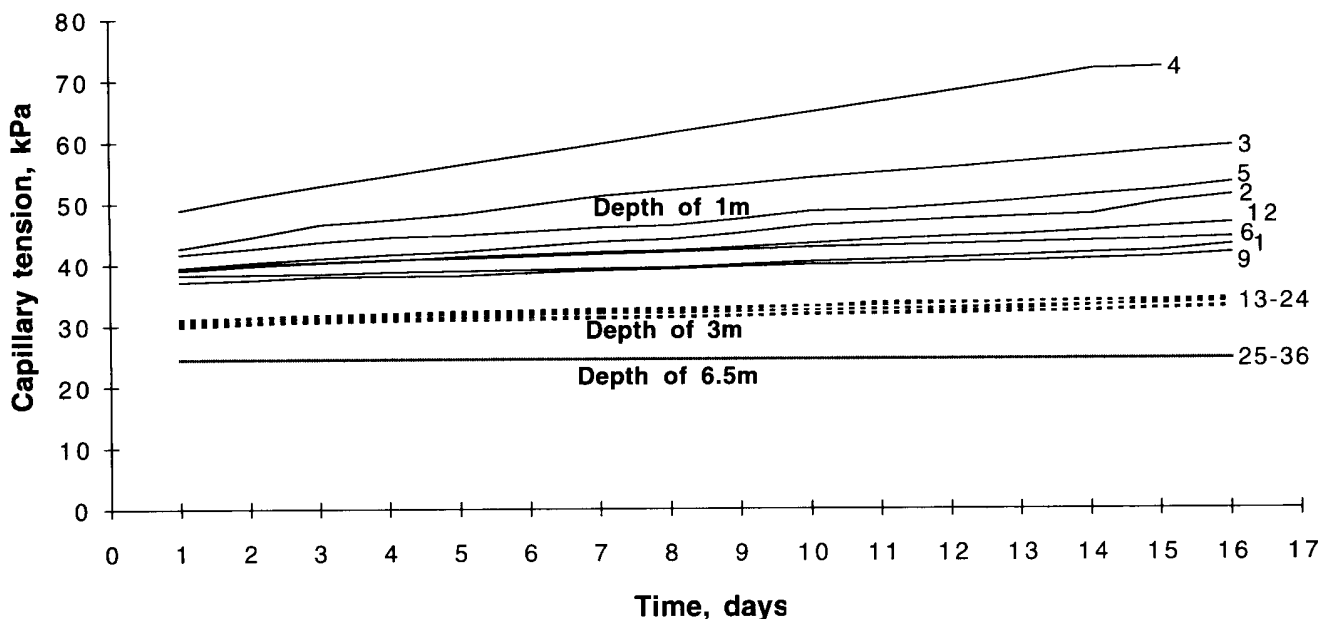


Fig. 3. Capillary tension vs. 17 days of natural drying, measured at three depths (a dozen at each) along the unsaturated zone at the Krestovka site. Tensiometers #1-12 at 1 m depth, #13-24 at 3 m depth, and #25-36 at 6.5 m depth. The drying process exhibited a significant lateral variability only at 1 m depth.

Table 1. Chloride Concentrations (mg/l) in Pore Fluids at Three Depths, Their Mean (X), Standard Deviation (S), and Variation Coefficient (C_v)

Depth m	Site	Vacuum lysimeter number											X mg/l	S mg/l	C _v %
		1	2	3	4	5	6	7	8	9	10	11			
3.5	Pavlovka	284	365	233	233	226	284	182	2107	1432	966	—	631	661	105
7.2	Pavlovka	4740	4750	4880	4790	4700	4880	4840	4810	4810	4680	4680	4778	74	1.5
8.5	Krestovka	6668	7129	6987	7058	7306	7590	7200	7058	7101	7145	—	7124	234	3.3

Table 2. Statistical Characteristics (Mean, Standard Deviation, and Variation Coefficient) of Major Pore-Water Ions and Gravimetric Water Content

Parameter	Ca mg/l	Mg mg/l	Na mg/l	HCO ₃ mg/l	Cl mg/l	SO ₄ mg/l	TDS mg/l	θ _s %
Krestovka site, 8.5 m depth - 10 lysimeters								
X	752	1552	3952	464	7124	6637	20,077	19.32
S	29	35	56	31	234	282	751	0.30
C _v (%)	3.9	2.3	1.4	6.7	3.3	4.2	3.7	1.6
Pavlovka site, 7.2 m depth - 11 lysimeters								
X	526	1737	3696	224	4778	9246	20,098	23.15
S	25	69	50	9	74	535	558	0.28
C _v (%)	4.7	4.0	1.4	4.0	1.5	5.8	2.8	1.2

Similar results have been observed for other ions. Table 2 summarizes the statistical analyses of major ion concentrations found in pore water. It can be seen that at 7-8 m depth, the coefficient of variation (1.4-6.7%) remained within the range of measurement error. Thus, lateral variability can be considered negligible. The slightly larger lateral variability found in the HCO₃ concentration may be attributed to its equilibrium with dissolved atmospheric CO₂, which may be disturbed to different degrees during the sampling procedure.

For monitoring purposes at these specific sites, at 6-7 m depth and below, two lysimeters per each horizon are enough to be representative. However, at 3-4 m depth (and obviously at the root zone) the lateral variability is significant, and thus, two vacuum lysimeters would not be sufficient to represent the pore-water chemical composition (Zilberbrand and Golovchenko, 1977). Practically, under areal contamination inputs, reliable flow and transport monitoring could be achieved using a few monitoring devices only if installed at depths characterized by small lateral variability. It should be noted that these depths are different for tensiometers and vacuum lysimeters.

Mutual Influence Between Vacuum Lysimeters and Tensiometers

Due to the lack of knowledge regarding the mutual effects of tensiometers and vacuum lysimeters, traditionally, they were not installed next to each other. It was assumed that the pore water sucking through the vacuum lysimeter might increase the capillary tension measured by the nearest tensiometer. There was also a question whether the chemical composition of pore water might be affected by the tensiometer installation. Later, the actual effect was studied quantitatively through field experiments (Zilberbrand and Golovchenko, 1977). At the Krestovka site, at a depth of 7.0 m below the land surface, where flow conditions were found

to be under steady state (capillary tension of 24.5 kPa, and volumetric water content of 31%), the tensiometer and vacuum lysimeter were installed at distances of 0.1, 0.2, and 0.3 m from each other. In the first stage, vacuum lysimeters were installed and water samples were collected by applying 90 kPa vacuum. Chemical composition of sucked pore water was determined. Subsequently, tensiometers were installed nearby, and after their reading stabilization, capillary tensions were measured. Following, pore-water sampling was repeated by applying the same vacuum of 90 kPa for seven days and chemical analyses were repeated as well. During the collection of the pore water, no changes were observed in capillary pressure, even at a distance of 0.1 m from a vacuum lysimeter. Moreover, no changes in chemical composition were observed. Results of the chemical analyses are summarized in Table 3.

As can be seen, changes in ion concentrations fall in the range of 1-8% of their initial values, which is actually within the range of analytical error. However, changes in HCO₃ concentration were significantly larger (about 25-75%), probably due to changes in dissolved CO₂ concentration induced by the tensiometer installation and vacuum application.

The absence of mutual effect between tensiometers and vacuum lysimeters, even at 0.1 m distance apart, is evident under an intermediate degree of water saturation. However, under wetter conditions it is expected that the mutual effect might be more significant due to the enhancement of induced water and solute fluxes. Practically, since the usual duration of sampling did not exceed 3-4 days (1-2 times a month), and relatively low average vacuum (about 30-40 kPa) was applied, it is recommended that ceramic caps be put at distances of at least 0.5 m from tensiometers. Thus, for a borehole diameter of 1 m, installation of about four monitoring devices at the same depth (two tensiometers and two vacuum lysimeters) is recommended.

Table 3. The Effect of Tensiometer Installation on the Chemical Composition of Pore Fluids Collected by Vacuum Lysimeters

Installation distance (m)	Sampling stage	Concentrations (mg/l)						
		Ca	Mg	Na	HCO ₃	Cl	SO ₄	TDS
0.10	pre-inst.	25.6	160.4	162.8	4.2	140.1	218.8	21858
	post-inst.	25.4	164.3	175.6	3.2	144.6	217.7	22304
0.15	pre-inst.	25.6	159.7	162.8	4.0	139.1	208.2	21389
	post-inst.	25.6	163.5	174.0	3.6	145.1	207.4	21829
0.20	pre-inst.	26.1	157.5	157.2	5.1	139.1	205.7	21199
	post-inst.	25.2	157.9	166.7	3.8	141.1	199.7	21086

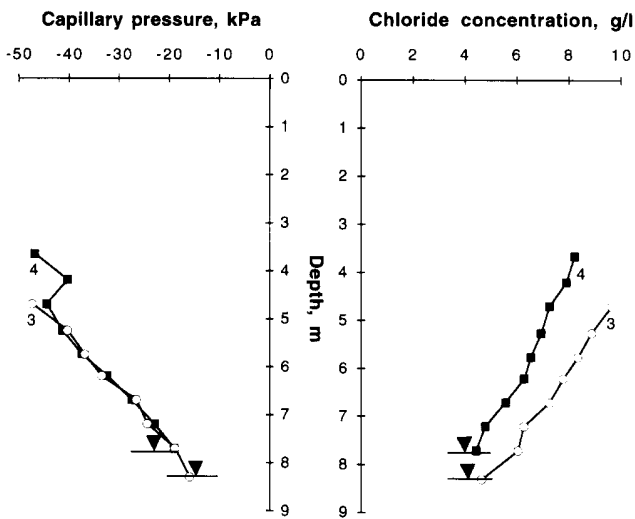


Fig. 4. Capillary pressure and chloride concentration vs. depth in two boreholes (#3 and #4), 90 m apart, at Pavlovka site. Water-table levels are indicated by triangles.

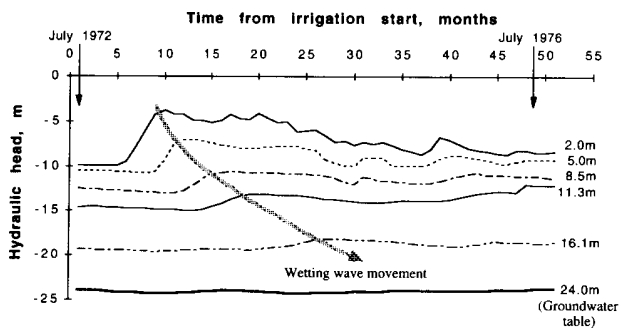


Fig. 5. Changes of hydraulic head values during 50 months, at selected depths of the unsaturated zone at the Krestovka site (reprocessed from Sitnikov, 1986). The land surface was taken as the datum level. Detailed profiles of capillary pressures on the two dates indicated are given in Figure 6. The introduction of an irrigation system created a wetting wave which slowly moved downward.

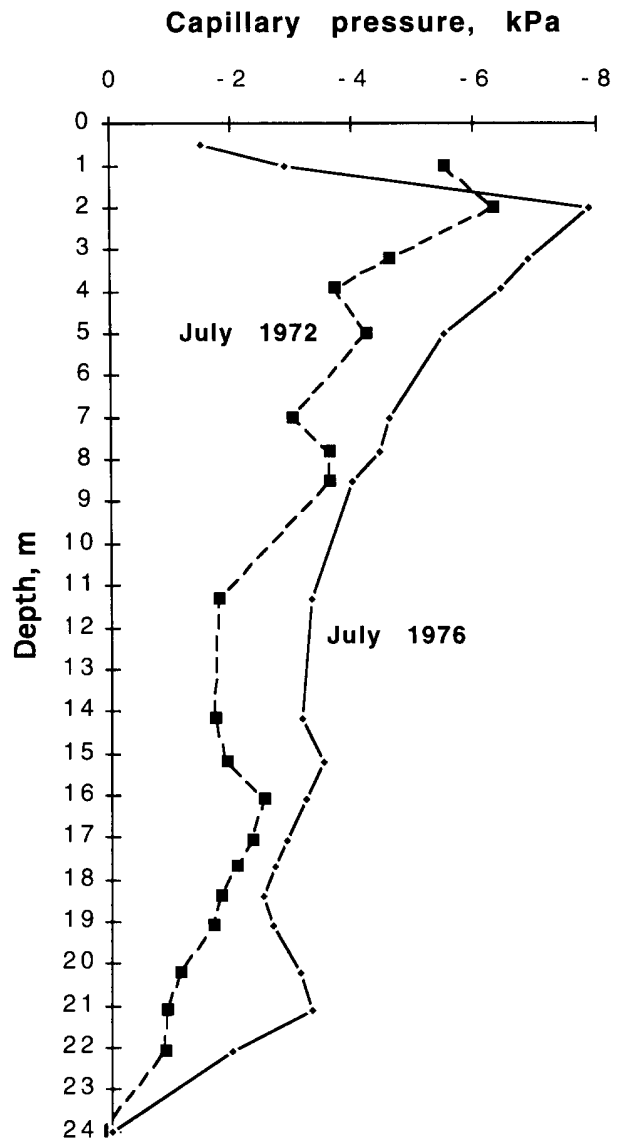


Fig. 6. Two profiles of capillary pressure in the same borehole at Krestovka site (reprocessed from Sitnikov, 1986). The first exhibits a steady-state profile under an unirrigated land; the second was taken after four years of irrigation (detailed temporal variations of hydraulic head at selected depths are given in Figure 5).

Borehole Representativeness

Because of the heterogeneity of natural sediments, the question arising is whether data obtained from a single large-diameter borehole are representative. At the Pavlovka site, two large-diameter boreholes (#3 and #4) were drilled at a distance of 90 m from each other (Figure 2). Capillary pressures and chloride concentrations were measured at both. Since the uppermost part of the unsaturated zone was very dry, only data below 4 m depth were collected and compared. The results are summarized in Figure 4.

The capillary pressure profiles in both boreholes were found to be very similar, while chloride concentration profiles were different, by about 16-18% (Figure 4). However, the two profiles exhibited the same trend of gradual decrease in both capillary pressures and chloride concentrations with depth. The slight difference between the absolute values of chloride concentrations may be attributed to the difference of about 0.6 m in ground-water levels. Normalizing to the datum of ground-water level, the two profiles showed no significant difference. Based on these two boreholes, it seems that in some cases a single borehole could be representative, however, no generalization can be drawn; i.e., the number of required monitoring boreholes will be a site-specific issue. Obviously it would depend on climate, stratigraphy, anthropogenic activity, and other conditions.

Long-Term Monitoring of Flow Characteristics

The large-diameter borehole provides the possibility of conducting long-term monitoring of capillary pressure and hydraulic head values. Such a study was performed at the Krestovka site. The results (summarized in Figures 5 and 6) exhibit typical temporal changes of hydraulic head along a 24-m-depth unsaturated zone. Capillary pressure readings were taken on a daily basis during four years (1972-1976).

Irrigation was started at Krestovka in 1972, and as a result, a wetting front started to move downward. Figure 5 shows the flow regime at selected depths, by means of changes in hydraulic head. The wetting wave is seen as a wave-shaped decrease in hydraulic head values. The wetting wave moved downward, arriving at the ground-water table after about 30 months. The amplitude of the wave decreased during its downward penetration. During the following years, smaller wetting waves formed after every irrigation period. Usually they decayed at a depth of about 15 m. This information is shown in an alternative way in Figure 6, where the capillary pressure profile is shown at two different times. In July 1972, before irrigation was started, the whole unsaturated profile had relatively higher capillary pressure, i.e., it was relatively dryer. After four years, in July 1976, the capillary pressure profile exhibited a wetter profile, with relatively smaller values of capillary pressure.

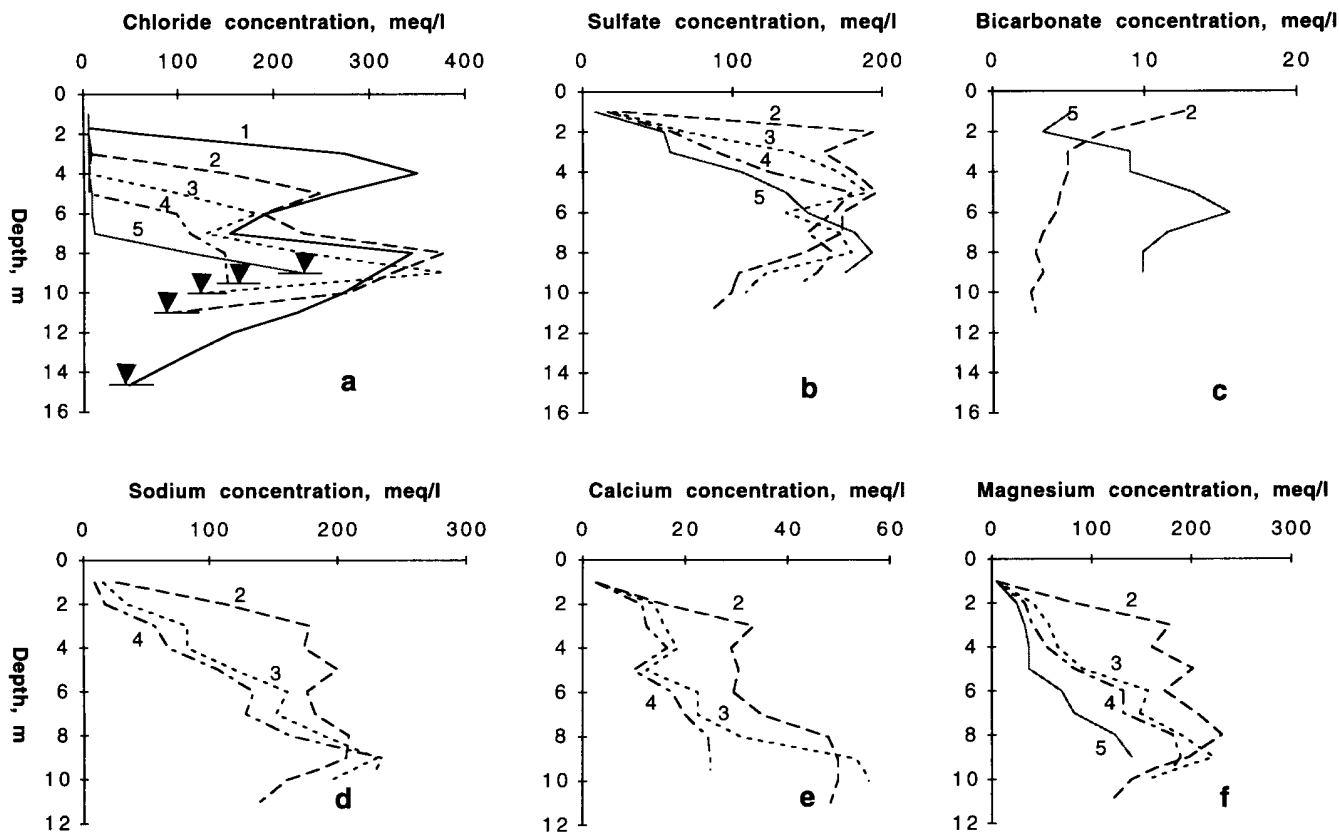


Fig. 7. Pore-water concentration profiles of chloride (a), sulfate (b), bicarbonate (c), sodium (d), magnesium (e), and calcium (e), obtained at Pavlovka site at different times: 1—July 1975; 2—July 1976; 3—August 1977; 4—September 1978; 5—September 1979. Ground-water level, which rose with time, is indicated by triangles (a).

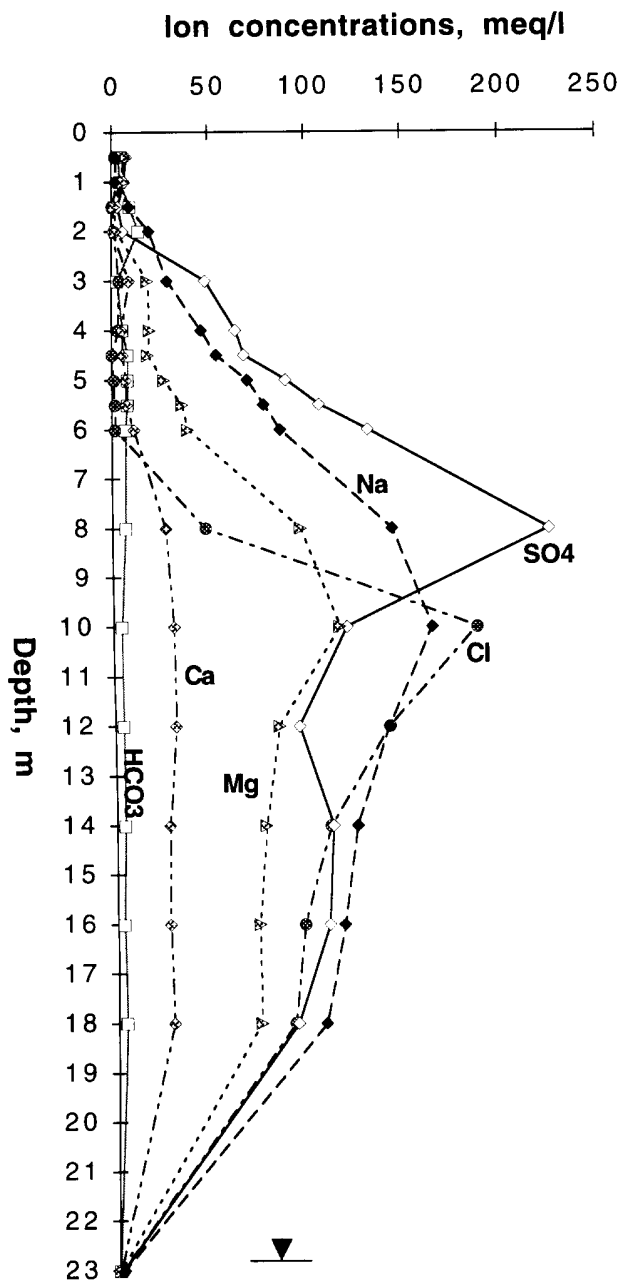


Fig. 8. Ion concentration profiles along the unsaturated zone taken in 1977 at the Krestovka site. The intensive irrigation (started five years earlier) washed solutes down the unsaturated zone, posing a threat to ground-water quality.

Long-Term Monitoring of Transport Characteristics

Typical results of temporal changes in solute concentration profiles obtained at the Pavlovka site over four years are shown in Figure 7. Although not all ions were determined on each of the sampling dates, the general trend of ion displacement beneath an irrigated field can be seen. The concentration fronts of most ions can be distinguished. An especially clear front can be seen in the chloride profiles, and its average displacement rate was estimated to be 1.2 m/year (Zilberbrand, 1993). For other ions this rate is essentially

lower. The absence of a bicarbonate front may be explained by the combined influence of irrigation water input, biological activity, and soil alkalization-dealkalization processes associated with carbonate precipitation in the root zone (Zilberbrand, 1995).

The double-peak chloride profile reflects sequential periods: times of excess soil flushing due to overirrigation (until 1972, 1975-1979), and times of soil overdrying induced by cultivation of highly transpired crops under limited irrigation conditions (1972-1975). A similar pattern can be seen in most other ion profiles, but they are blurred due to ion exchange and mineral dissolution-precipitation. The intensive irrigation caused a rise in ground-water level (as shown in Figure 7) and an increase in ion concentrations in ground water.

The potential possibility for early detection of ground-water pollution is expressed in Figure 8. At the Krestovka site, the initial ion concentrations in ground water were less than 2-3 meq/l. Irrigation which started in 1972 caused downward washing of salts, and may eventually cause deterioration of ground-water quality. Based on the estimated chloride travel rate (Figure 7), high chloride concentration may reach the water table within 5-15 years. This would not have been evident in common ground-water monitoring.

Summary and Conclusions

A method for monitoring water flow and solute transport through the unsaturated zone, using a large-diameter borehole, was tested at different sites in the Ukraine during a period of six years. This method provided the possibility of obtaining reliable long-term flow and transport records. Detailed information on vertical water flow rate, aquifer replenishment, and ion transport was obtained along 7-24-m thick unsaturated profiles. Results indicate that lateral variability of both, capillary pressure and ion concentration, decreased with depth. Also, they show that lateral variability of capillary pressure diminished faster with depth compared to solute concentration. In other words, there is an intermediate horizon in which capillary pressure exhibits small lateral variability, while ion concentration still exhibits significant lateral variability. These observations may be generally applicable to most irrigated lands. However, the depth of this intermediate horizon is obviously a site-specific issue.

The large-diameter borehole could be useful for areal inputs of contaminants, enabling early warning of ground-water pollution before it reaches the water table. This would include threats to ground water from infiltration of rainfall where fertilizers and pesticides were heavily applied, or where cultivated soils contain dangerous leachable elements. However, this method is not recommended in cases of point-source contamination, or where flow through fissures or cracks is dominant. Moreover, since tensiometers and vacuum lysimeters are not effective for studying dry sediments, the upper part of the unsaturated zone in arid regions may not be suitable for such monitoring. In any case, the lower part of the unsaturated zone, and especially the capillary fringe, would always be suitable for such monitoring.

toring, and thus, warning of pollution threats would be achieved at a significantly earlier stage.

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