SLOW AND PREFERENTIAL FLOW IN THE UNSATURATED ZONE AND ITS IMPACT ON STABLE ISOTOPE COMPOSITION

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Abstract

Stable isotope methods ($\delta^{18}O$ and $\delta^{2}H$) have been used investigate the importance of bypass flow in the unsaturated zone which leads to unproductive water loss during flood irrigation. Field experiments have been carried out in Jordan and Pakistan in order to determine the occurrence of bypass flow, its amount and its velocity compared to piston flow. Results show that there is not only an advective component of flow (bypass flow) but a diffusive tracer exchange between piston and bypass flow. Infiltration calculations and analysis of tracer distributions are used to show that at the research sites, bypass flow amounts to about 25% of water recharged during winter. This estimate is important as it provides an assessment of the amount of water that passes the root zone and directly recharges groundwater.

Introduction

Sediments may be homogeneous or inhomogeneous in granulometry and thus in pore size distribution. Pore sizes, however determine variations in hydraulic conductivities and flow in the unsaturated zone.

Typical examples of pore size distributions in terms of total porosity are shown in Figure 1. Inhomogeneous pore size distributions are mostly bimodal, causing a corresponding bimodal distribution of flow velocities with slow piston flow (a few metres per year) and quick bypass or preferential flow (a few metres a day). Piston flow is characterized by horizontal break-through fronts; bypass flow always has a fingered front (Figure 2). These flow components may alternate.

Bypass flow is limited to a transition zone between soil surface to a depth of 3.0 in. Due to suction heads in this transition zone preferential (bypass) flow is increasingly incorporated into piston flow and finally disappears. Below 3 in depth seepage flow becomes homogeneous and is exclusively piston flow in nature.

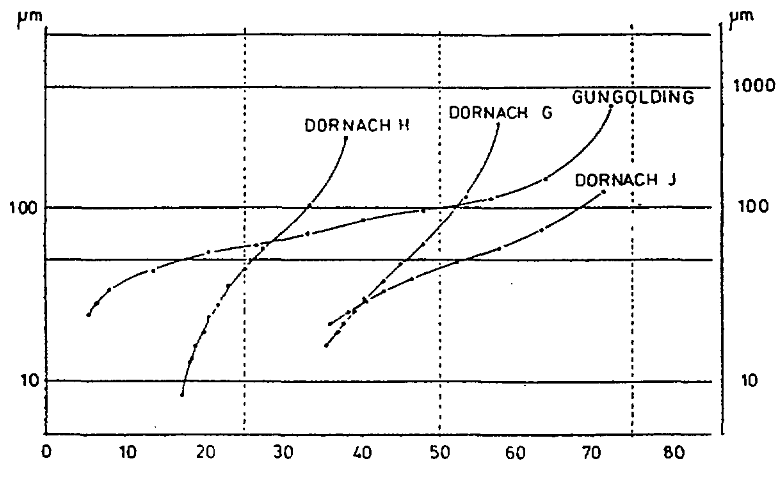

Figure 1: Pore sizes (μm) as a function of the available pore space (%)

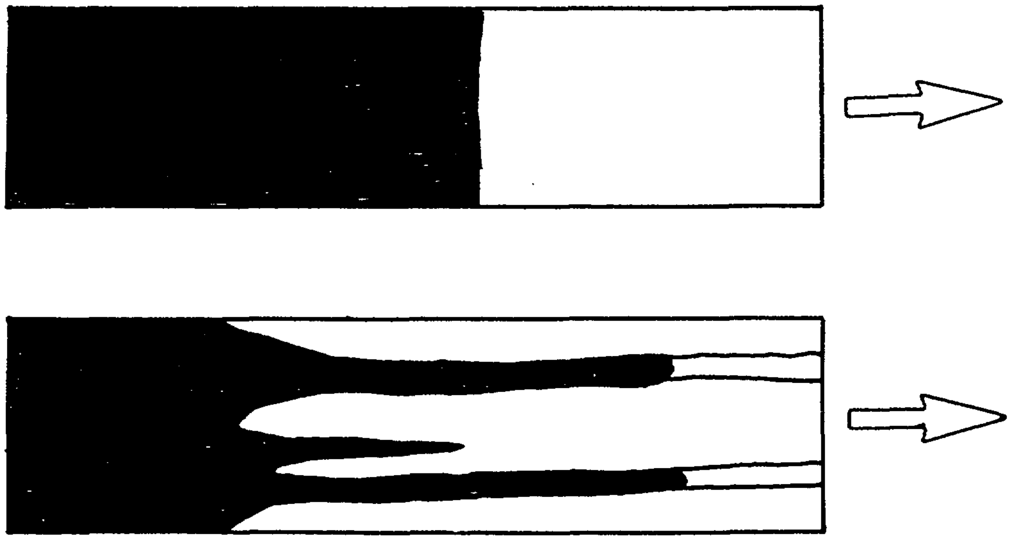

Figure 2: Fingered (bypass) and non fingered flow (piston flow) in the unsaturated zone

Water or tracer balance studies in the unsaturated zone mostly focus on near surface zones. Considering only water or tracer balance it is impossible to recognize equilibrated or non-equilibrated balances. To differentiate, tracer and water balances should be linked to infiltration rates; and a good knowledge of water contents before infiltration events.

From such investigations it can be established; (i) if and how much bypass flow occurs; (ii) if evaporation processes may change stable isotope information below the surface; and (iii) how bypass flow and piston flow interact.

Water balances and bypass flow in the unsaturated zone

Irrigation is commonly practiced in arid and semi-arid areas. Flood irrigation experiments have been conducted in order to study the importance of bypass flow in the unsaturated zone, which contributes to unproductive water losses. The tools for these studies are:

- coring before and repeatedly after flooding;
- the determination of changes in water contents;
- the extraction of water from cores to study time dependent changes of the concentrations of the non-reactive tracers (^{18}O, ^{2}H and Cl).

These experiments have been carried out in the Jordan valley, Jordan, and in the Punjab, Pakistan, applying:

- flood irrigation of 7.5 cm (75 mm/m^2);
- field sizes of 30 m x 30 m; and
- types of sediments in the unsaturated zone (Figure 3).

Fissured Lissan marls have also been selected in the Jordan valley (not reported in Figure 3) for irrigation experiments. On each field an experiment has been carried out at the end of the wet and during the dry season, respectively. No further flooding took place at the experimental site and its neighbouring fields following each experiment.

The quantities, isotopic and chemical composition of water:

- added to the field;
- pre-existing in the unsaturated zone; and
- changes following irrigation in the unsatured zone;

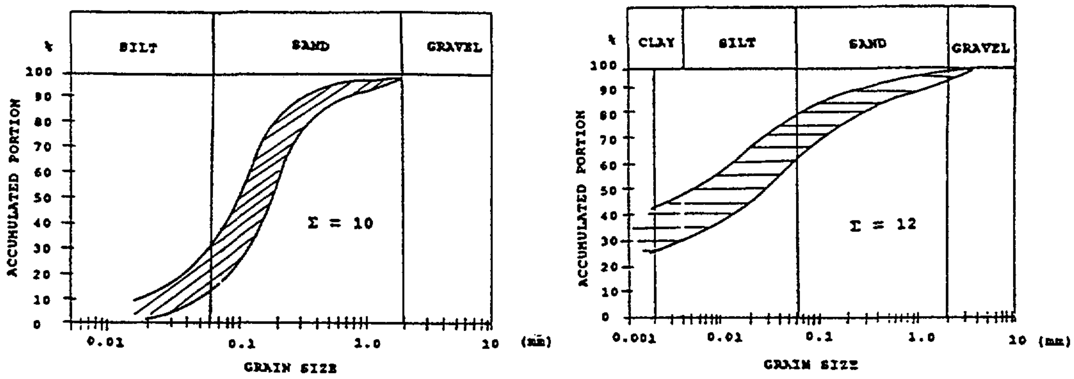

Figure 3: Rang of grain size distribution of some sediments used in irrigation experiments

have been measured over 2 m of depth. Water content was determined by gravity methods. For chemical and isotope analysis, water held in small core sections was diluted with Antarctic water, well mixed and extracted. From this data, flow rates and mixing have been determined in order:

- to prove the existence of bypass flow relative to infiltration quantities;
- to determine the amount of bypass flow;
- the importance of pre-existing suction heads for the origin of bypass flow; and
- the velocity of bypass flow as compared to piston flow.

The changes in water contents have been determined using:

$$\Delta M = \int_{x_a}^{x} \Theta_1 dz - \int_{x_{a1}}^{x} \Theta_2 dz$$

the changes in isotope as well as chloride concentrations have been used to calculate mixing ratios:

$$n = \frac{c_3 - c_2}{c_1 - c_2} \; .$$

M	quantity of water	θ	water content
z	depth	n	quantity ratio
c_1, c_2	pre-existing and added tracer concentration	c_3	final tracer concentration

Table 1 indicates the measured changes in water contents do not always reflect the calculated changes using Cl or ^{18}O-concentrations. Obviously there exists not only an advective change of water but also a diffusive tracer exchange between piston and bypass flow. This effect is most pronounced in the fissured Lissan marls, and changing its extent with season.

These results give a good explanation for e.g. the discrepancy in seepage velocities determined in the same gravels of southern Germany: (a) as a few metres a week (Seiler & Baker, 1985) by tracer tests; and (b) a few metres a year (Eichinger et al., 1984) by stable environmental isotopes. Tracer experiments determined the velocities of bypass flow. Environmental tracers determine the velocity of piston flow.

Table 1 Observed and calculated changes of water contents in the unsaturated zone in connection with irrigation experiments. shadowed during the dry season, unshadowed just after the wet season. nd = not determined

SEDIMENT	IRRIGATION QUANTITY IN l/m^2	INITIAL WATER CONTENT IN %	RESULTING WATER CONTENT IN %	STORED WATER QUANTITIES BASED ON CALCULATIONS OF CHANGES OF		
				WATER CONTENT	CL CONCENTRATION	^{18}O CONCENTRATION
SAND	190	10	15	38	53	53
SAND	150	6	12	58	nd	60
SANDY SILT	150	22	25	26	30	29
SANDY SILT	150	6	12	53	nd	68
LISAN MARLS	150	45	50	16	36	nd
LISAN MARLS	150	30	37	nd	34	36

Considering seepage recharge in the unsaturated zone of tertiary sediments during the winter months (November to April) results in infiltration quantities that should have completely exchanged the water contents in the first metre of the profile. Stable environmental isotope concentrations on the first metre of the profile, however, indicate that winter input is not reflected; the profile reflects a mixing between winter rains and the isotope composition of soil water from the previous summer (Fig. 4). This again is attributed to bypass flow and diffusive tracer exchange between bypass and piston flow. Both infiltration calculations and admixture of tracers from winter recharge are used to quantify bypass flow; in the area of research it amounts to about 25% of water recharged during winter.

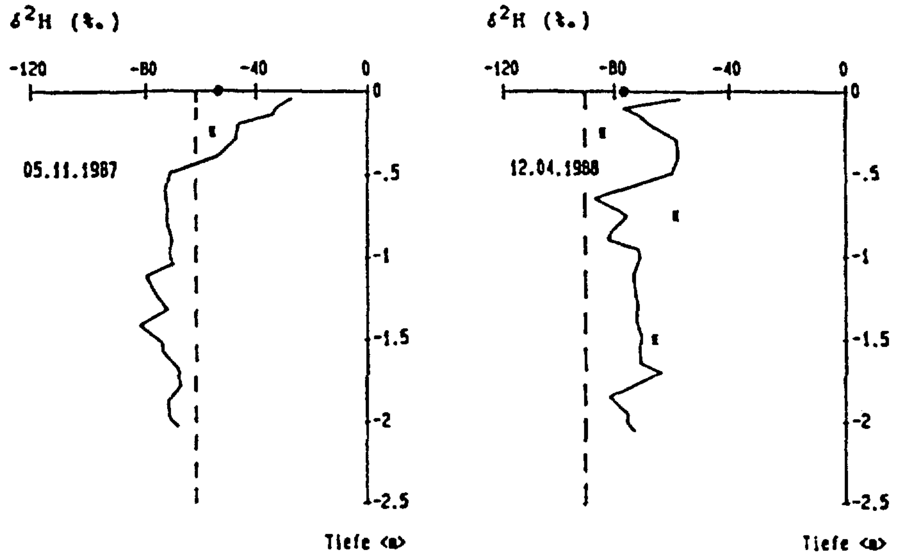

Figure 4: Stable isotope profils from the beginning (05-11-1987) and the end (12.04.1988) of the winter season. Broken line represents mean isotope concentration in precipitation, unbroken line samples from water extraction out of cores, point sampling by sucction cups. Samples from tertiary silty sand north of Munich

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