3 IRRIGATION AND THE IMPACT ON GROUNDWATER QUALITY

Irrigation is mostly used in arid to semi-arid zones (Table 3.1), here referred to as dry lands, but is also known from humid areas. Dry lands are poor in precipitation and suffer tremendous climate variability from year to year (Bruins & Lithwick 1998), thus increasing the vulnerability of cultivated ecosystems. Humans may partly govern aridity using rain and discharge harvesting, both stored in the unsaturated zone and not necessarily contributing to groundwater recharge. Due to the special boundary conditions and non-adapted cultivation tools in dry lands, they may often contribute simultaneously to desertification as well.

UNEP (1992) defines different forms of aridity using the precipitation/evapotranspiration ratio and the rainfall variability (Table 3.1).

Table 3.1 Classification of different forms of aridity according to a proposal of UNEP (1992)

	P/PET ratio	rainfall variability in % of the average
hyper-arid	< 0.05	100
Arid	0.05 - 0.02	50 - 100
semi-arid	0.02 - 0.5	25 - 50
sub-humid	0.5 - 0.65	< 25

Dry conditions negatively affect the two basic requirements of mankind, water and food. Since deserts and dry lands (Petrov 1976) comprise about 37% of the continental surface and about 50% of the nations on earth are totally or in parts affected by the constraints of aridity, irrigation has been developed as an important tool for the production of food and natural raw materials. Since mankind shifted from hunting to farming and systematically since the beginning of the last century irrigation was developed. Today about 17% of the world's croplands are irrigated (about 240 million hectares) and 75% of these areas are located in developing countries. From 1960 to 1970 the yearly growth rate of irrigation areas was about 2 to 4% and since then dropped to an actual growth of less than 1%. Today all these irrigation areas produce about 1/3 of the food demand in the world.

The actual efficiency of irrigation systems (Thorne & Peterson 1954, Shanan 1992) is mostly low because of significant water losses in surface reservoirs and distribution channels and due to an inefficient use of the water in the fields. These losses cause local increases of groundwater recharge and water logging (rise of groundwater table) and may adversely affect the quality of soils and groundwaters, constructions and public health. Other undesired effects are salinisation and the sedimentation in surface reservoirs reducing reservoir's life time, estimated at 50 to 100 years for the majority. Thus, already within the life-time of reservoirs the availability of irrigation waters decreases significantly.

Irrigation increases primarily transpiration and to a very small extend also evaporation from the effective root zone and soil surfaces, respectively. It has to be applied simultaneously with agrochemicals such as fertilizers and pesticides, which reach the groundwater together with irrigation return water, so affecting the groundwater quality for the public domain. This further imposes limitations of groundwater availability for reasons of water quality.

In most areas with dry and rainy seasons and in most of the arid regions irrigation is based on the use of groundwater. In many desert regions connecting mountain (Himalaya) or rainy areas (Ethiopia) with the ocean, surface waters are being gathered in reservoirs.

Surface water irrigation has natural limitations imposed by a huge variability of yearly precipitation in arid and tropical zones. Groundwater based irrigation is mostly performed by wells penetrating unsystematically to different depth, thus touching unsystematically the active and passive groundwater recharge zone; on the long run this produces a disturbance of the natural flow regimes facilitating the access of contaminants into the depth, that would not occur by natural mixing processes (Sect.1.7).

In many arid and semi-arid regions of the world waste waters are used for irrigation. In the past Israel gave an impressive example of saving water resources through the use of wastewaters for irrigation. Since wastewaters may negatively affect soil properties, crops and groundwaters, pretreatment of wastewaters and a control of wastewater impacts on subsurface systems is recommended. In between the characteristics of waste waters, the content of

- neutral salts,
- heavy metals and organics and
- pathogen organisms

are the most harmful for soil, crops and groundwaters.

Neutral salts (Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, CO_3^{2-}, HCO_3^-, Cl^-) may accumulate in soils according to the intensity of irrigation, causing toxic damage to plants and reducing the availability of water for plants through a high osmotic pressure of the soil solution or through changes in soil structure and texture properties; too high Cl^- contents generally affect tissues and plant leaves (Al-Radaideh 1992).

Heavy metals can damage microbial diversity in the effective root zone and disturb enzymatic processes and by that way may adversely influence natural attenuation processes. On the contrary, organics mainly affect groundwater quality if sorption and microbial disintegration are not sufficiently active. Considering the fact that most of the metabolites of organics

- are unknown and in general also not analytically detectable with routine tools,
- may increase in toxicity the smaller the molecular weight is becoming and
- often increase in mobility with decreasing molecular weight,

a detailed knowledge of the behaviour of organics in the unsaturated and saturated zone was needed to assess these dangers for health and life.

Pathogen organisms are quite common in wastewaters (parasites, bacteria, viruses). In fine grained soils and sediments these organisms with sizes between 0.5 and 5µm become mechanically retained. In coarse-grained soils and sediments they may be fixed or transported through bypass- and particle-favored flow, despite their high sorption tendency. This is quite common for parasites and bacteria, but hardly possible for viruses. Thus, mainly parasites and bacteria may cause hygienic and health risks. In this context it is of interest that these organisms survive longest in soils and shortest in crops (Al-Radaideh 1992).

To prevent the afore mentioned problems at least mechanical wastewater treatment including aeration in open ponds is recommended as a minimum activity. If the mean residence time in treatement ponds is not long enough to significantly reduce micro-organisms by natural UV radiation, a disinfections treatment is needed.

The use of environmental isotopes in irrigation studies can contribute to get a better understanding of

- storage and release of irrigation waters,
- soil salinity ,
- irrigation induced percolation in sediments,
- the contribution of return waters and agrochemicals to groundwaters ,
- the origin of salt waters in groundwater-based irrigation schemes and
- the groundwater flow field.

In most irrigation studies the stable isotopes ^{2}H, ^{18}O and radioactive ^{3}H are used in combination with hydrochemical methods.

3.1 THE IMPACT OF IRRIGATION ON PERCOLATION IN DRY LANDS WITH VARIOUS SEDIMENTS

Irrigation schemes generally focus on fine to medium grained sediments with sufficient water retention capacities that guarantee an equilibrated portion of water and air in the effective root zone. Mostly flood, often sprinkling and still seldom subsurface drop irrigation is applied; the latter preferentially under greenhouse conditions.

3.1.1 EXPERIMENTAL BOUNDARY CONDITIONS AND PERFORMANCE

The two study areas are situated in the Pakistan part of the Punjab (Sajjad et al. 1985, Sajjad et al. 1993) and in the Jordan part of the Rift Valley (Jiries 1991, Jiries & Seiler 1995), respectively. Both regions belong to arid/hyper-arid areas in which irrigation is mainly linked to rivers originating from neighboring areas (Himalayas and Golan/Ajlun, respectively); only in the Jordan Valley some irrigation water is also exploited from groundwaters out of Wadi river cones.

The Punjab plain is still today an active sedimentation area; therefore, it lacks any significant relief. Since sedimentation occurred under marine conditions or in flood plains, sediments are quite homogeneous in their grain- and pore-size distributions and contain syngenetic salt residuals. In the recent geologic past the flatness of the region resulted in frequent changes of the river courses (Nazir 1974). From the beginning of the last century the Punjab area has been covered with many blind ending, unsealed channels (Fig.3.1), importing the irrigation water to the fields.

Contrary to the Punjab, the Jordan valley is a young rift area in which erosion prevails on the graben shoulders. Even these days local sedimentation under quite varying river flow velocities creates alluvial cones and sediments with a broad spectrum of grain and pore sizes (Fig.3.2). These alluvial sediments lay on the partially compacted, fine grained and fissured lake sediments of the Lisan formation, which act as the base of perched groundwaters discharging to the Jordan river.

In Pakistan the rivers Indus, Suttley, Ravi and Chenab act as recharge and discharge systems, whereas in the rift valley the Jordan river and the Dead Sea act as discharge base.

In both areas flood irrigation is applied. In both regions its impact on the unsaturated zone has been studied for sediments covering the range from silts to sands with many transitions in between. To execute these studies, fields of 50 x 50 m in size have been dammed in both areas which were irrigated in the Punjab with 75 mm and in the Jordan valley with 150 mm of water. In coarse and fine grained sediments of both regions irrigation waters disappeared quite immediately after irrigation (sands) or within half a day (sandy silt), respectively; in the fissured Lisan Marls waters disappeared surprisingly as fast as in sands (Sect. 3.1.2).

Before and repeatedly after irrigation two to three meter long cores were hand-drilled for soil water extraction in the central part of the experimental sites, to study changes of water contents and of the chemical and isotope composition of soil waters. Soils were sampled at 10 cm intervals and the samples hermetically sealed in plastic tubes (5 cm in diameter and 20 cm in length). Physical, chemical and isotope analysis were performed on extracted waters (Sect.6.4)

Since by nature the Punjab area is not drained by perched groundwaters, contrary to the Jordan area, only in the Punjab also groundwater studies were executed.

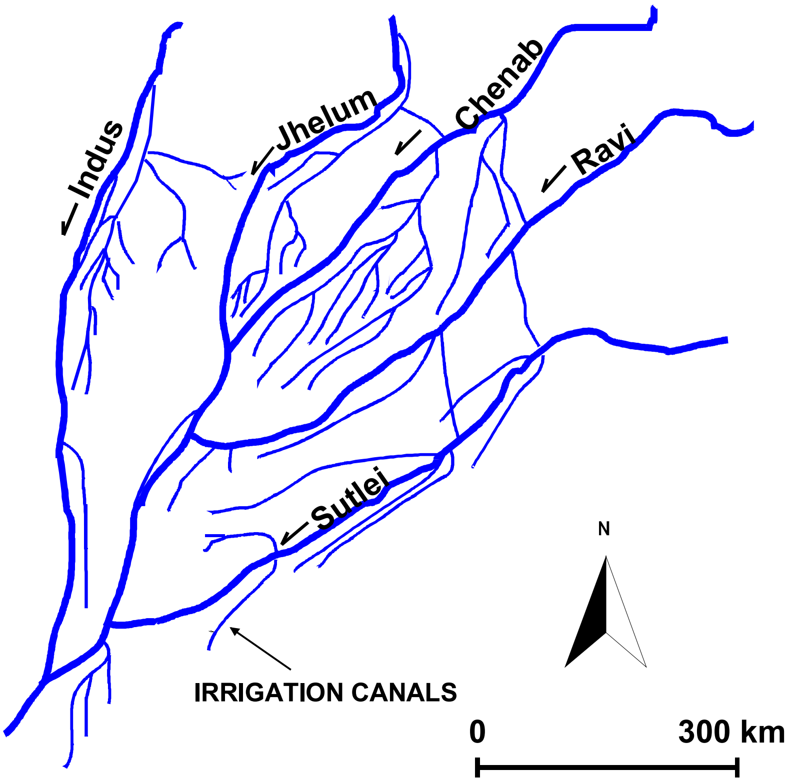


Fig.3.1 The Punjab study area between the rivers Ravi and Chenab and the existing distribution system of irrigation waters.

3.1.2 DISCUSSION OF RESULTS ON PERCOLATION

Based on the natural water content before and one day after irrigation and integrating in profiles the increase of water content due to irrigation, it could be shown for the Punjab (Fig.3.3) that in all sediments the applied irrigation water is stored to 100% within a maximum of three meters below ground level. The more silty the sediment, the less irrigation water penetrates to depth, and conversely. Obviously these sediments have quite homogeneous pore sizes and are not significantly biologically disturbed (roots, worm and mouse holes). Therefore, they produce a homogeneous flux of seepage waters (matrix without by-pass fluxes).

Contrary to the Punjab, in the Jordan valley sediments are quite inhomogeneous either by texture or by structure. Therefore, only a small portion of irrigation water is stored in the matrix, while the rest percolates as bypass-flow (Sect.1.3) to perched groundwaters and discharges subsurface to the Jordan river. As a consequence soil waters are better leached from salts in the Jordan than in the Punjab area.

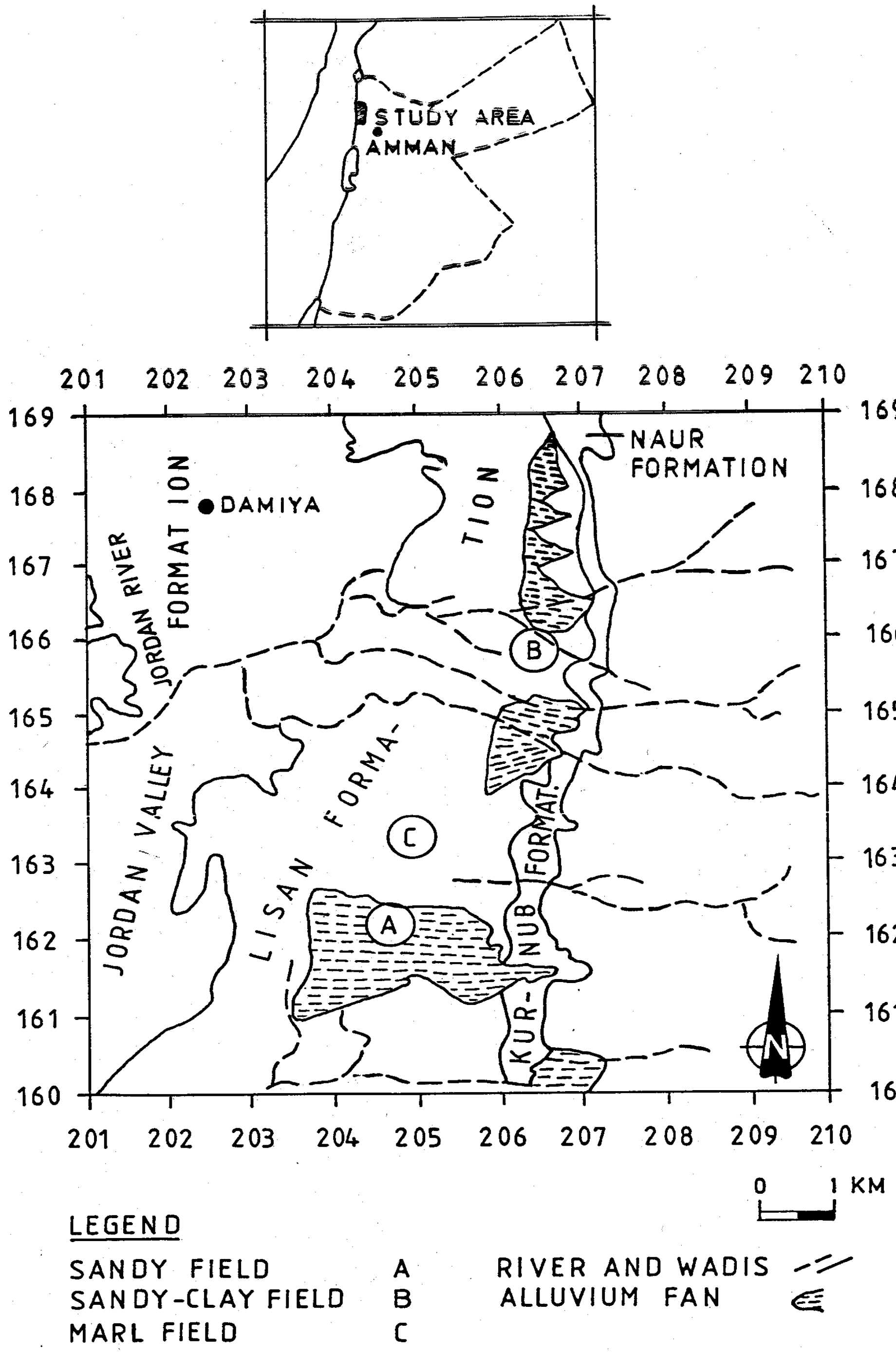


Fig.3.2 The Jordan study area with three different experimental sites (1 to 3).

With respect to the behaviour of soil waters after irrigation, in the Punjab region the following observations were made (Figs.3.3 and 3.4):

1) At the beginning of the experiment seepage moves continuously downward. Since water contents at the surface reach a lower threshold value of 5-10 vol.%, seepage turns against gravity.

2) Irrigation dilutes the pre-existing salt concentration and increases again when evaporation turns seepage from vertical down to vertical up.

3) After irrigation soil shrinking starts, while dew dilutes the salt concentration close to the surface of the profile.

4) At a groundwater table of 3 to 4 m below ground level irrigation practice in silty sediments does no longer influence groundwater quality (see below). Therefore, low chlorinated groundwater moves from the groundwater table by capillary forces into the unsaturated zone, diluting and narrowing the Cl^- peak that was broadened in the unsaturated zone by irrigation. On the contrary, in sandy sediments with a water table close to the ground surface (e.g. 2.5 m) salt is imported by irrigation into the groundwater and becomes reimported into the unsaturated zone as far as seepage changes from downward into an upward direction.

5) During the rainy season (monsoon) some through-flow in all types of profiles takes place, causing dilution and leaching of salts that accumulated during the dry season in both irrigated and non irrigated soils. This produced the low chloride concentrations in sandy silts (Fig. 3.4) before the irrigation experiment started.

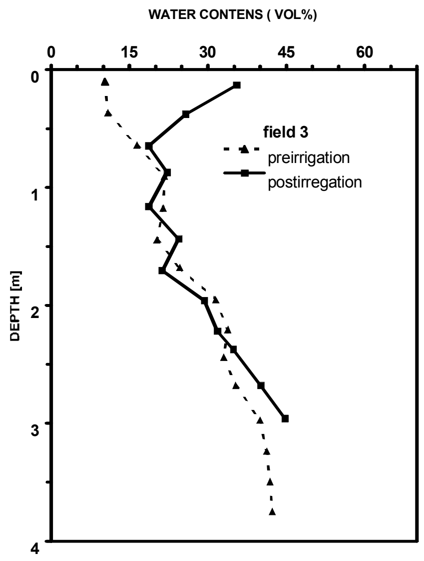
The salinisation of sediments in the unsaturated zone in the Punjab is mostly caused by evaporation:

- salts accumulate permanently in the unsaturated zone if the water table is below 3 m and irrigation is not applied too often; these salts do not reach the water table;
- at least once a year monsoon rains dilute and export salts
- salinisation enhances if the water table nearly reaches the surface (<3 m).

In the Punjab with missing morphology, i.e. the differences in morphologic altitudes are smaller than the differences in hydraulic heads needed for groundwater flow, there is an additional effect enhancing salinisation. To protect the effective root zone and constructions against groundwater, deep drainage channels have been constructed that often do not discharge effectively due to missing topographic gradients. The channels favour evaporation even to deeper than 3 m.

Since the very slow process of water logging can not be avoided due to the existing infiltration of irrigation water, buried drainages or water pumping was recommended to better manage water logging and soil salinisation. Pumped or drained subsurface waters, however, should not be discharged to irrigation channels from where it reinfiltrated to the underground.

On the contrary, in the Jordan valley 150 mm irrigation increased the water content of all profiles under study only partially (Fig.3.5), because most of the water was lost as bypass-flow to the perched groundwater discharging along the alluvial/Lisan marl interface.



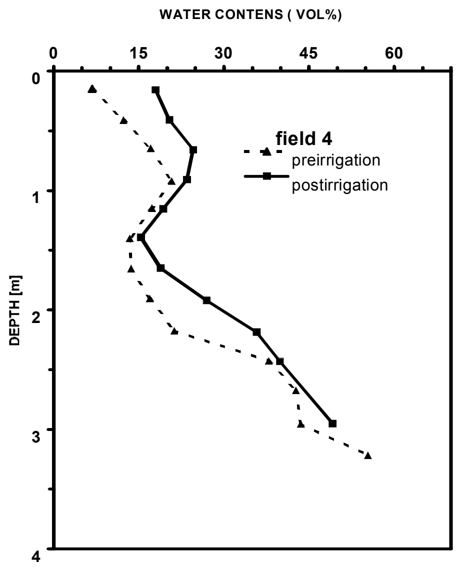
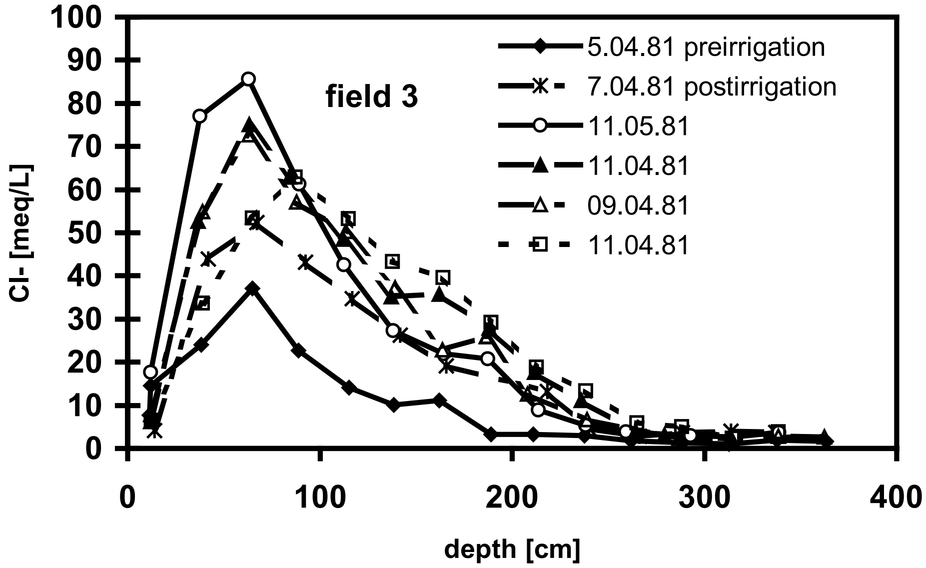


Fig.3.3 Profiles of changes in water content just before and after irrigation for four typical sediments in the Punjab. The irrigation quantity was 75 mm.

After the wet season only 20% of the applied irrigation water is stored within two meters from the surface, while during the dry season 50 to 60% is stored in the unsaturated zone, because during the dry season the water content did not reach field capacity (Table 3.2). This low storage of water in the unsaturated zone (Table 3.2) is observed in all types of irrigated sediments of this region, even in the Lisan Marls. They are related to bypass-, macropore- or preferential-flow (Sect.1.3, Beven & German 1982), occurring typically

- in fluvial sands and gravels, deposited in areas with high relief energy or
- in cohesive sediments crossed by shrinking or crystallisation cracks.

In the fluvial sediments of the Jordan valley both these peculiarities lead to discontinuous pore size distributions resulting in the coexistence of slow matrix and quick bypass-flow. Bypass-flow moves with apparent velocities of decimetres to meters/day, matrix flow with less than 5 m/year. This contrast primarily has sedimentologic reasons in arid and semiarid areas and may become enhanced by bioturbation and human activities. By experience these two flow systems reach limited depth because capillary gradients increasingly force bypass-flow into the matrix flow system. Penetration depth of bypass-flow reaches to more than 3 m in gravels and more than 2 m below ground floor in sands. Annually bypass-flow may amount to 50% of the infiltrated water.



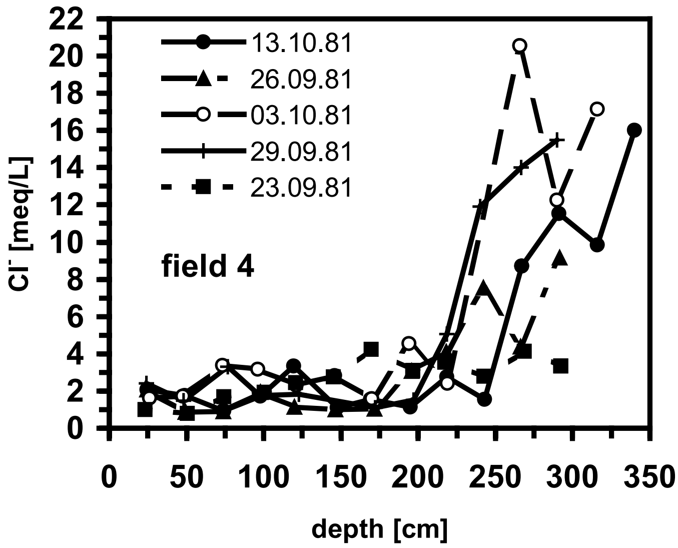


Fig.3.4 Profiles of changing chloride concentrations in the unsaturated zone of fields 3 (sandy silt) and 4 (sand) (Fig.3.3) after irrigation of 75 mm.

Changes in water content reflect the immediate storage of infiltration events in the percolation zone, whereas the stored waters calculated on the basis of concentration changes of non-reactive tracers (e.g. Cl and ^{18}O) indicate both immediately stored waters and diffusive tracer exchanges between bypass and matrix flow. Therefore, the calculated values of stored waters using isotope or chemical tracers are systematically higher (Table 3.2 columns 2 and 3 as compared to column 1) and thus document the existence of bypass-flow.

As a result of the experiments in the Jordan valley much water becomes wasted due to bypass-flow when applying flood irrigation.

Some typical pore size distributions of sediments from areas with low and high relief energy are shown in Fig.3.6 as cumulative curves. The more these curves become S-shaped and steep the more the pore sizes in the two flat branches of the S dominate; the more homogeneous the pore sizes the more these curves remain flat.

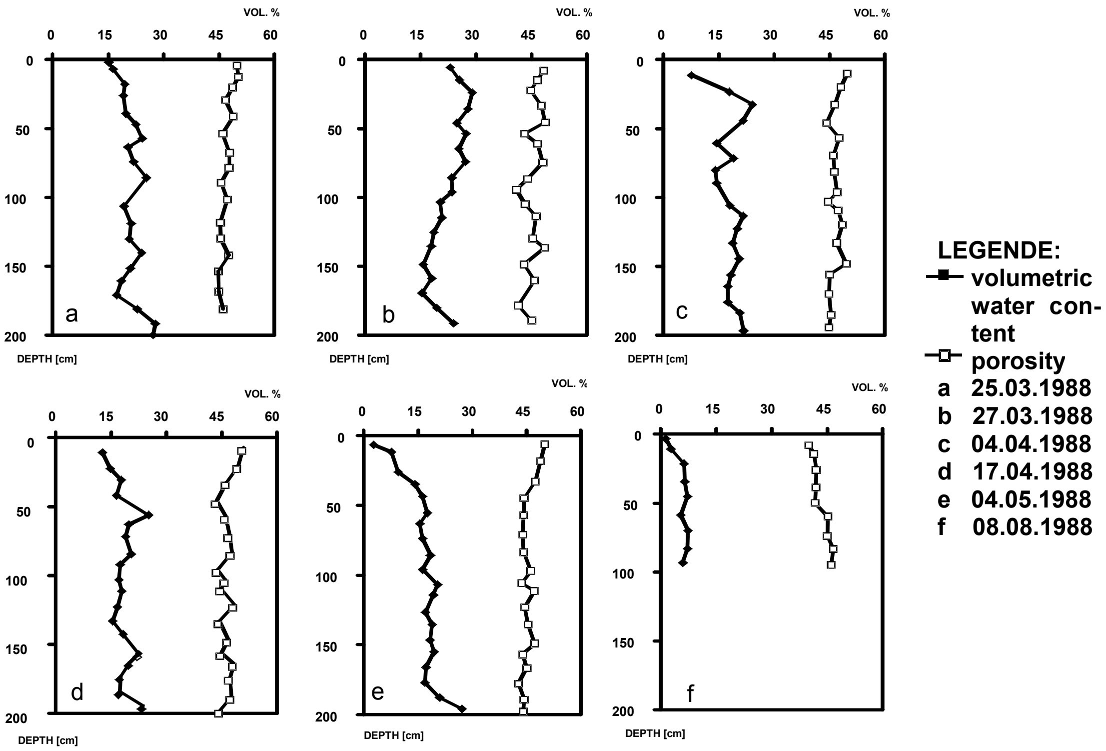


Fig. 3.5 Water contents in a sandy-silt sediment of the Jordan valley before (a) and days after irrigation (b to f).

As can be seen from Fig.3.7 the infiltration of irrigation water diminishes the chloride concentration in the sediments of the Jordan Valley. After irrigation, chlorides primarily concentrate at the soil surface and decrease more or less exponentially to a certain depth, since dew occurs in this area only at the soil/air interface, because shrinking cracks are missing (Allison & Hughes 1974). Similar to the results from the Punjab also in the Jordan valley the water table contributes to an upward movement of non-saline waters as far as the water content at the soil surface reaches 5 - 8 vol.% in coarse and fine grained sediments, respectively. Hazardous rains, however, disturb this equilibrium distribution of fluxes and chlorides, in the dry season producing a variety of salt peaks and valleys in the unsaturated zone and again becoming leached during the wet season.

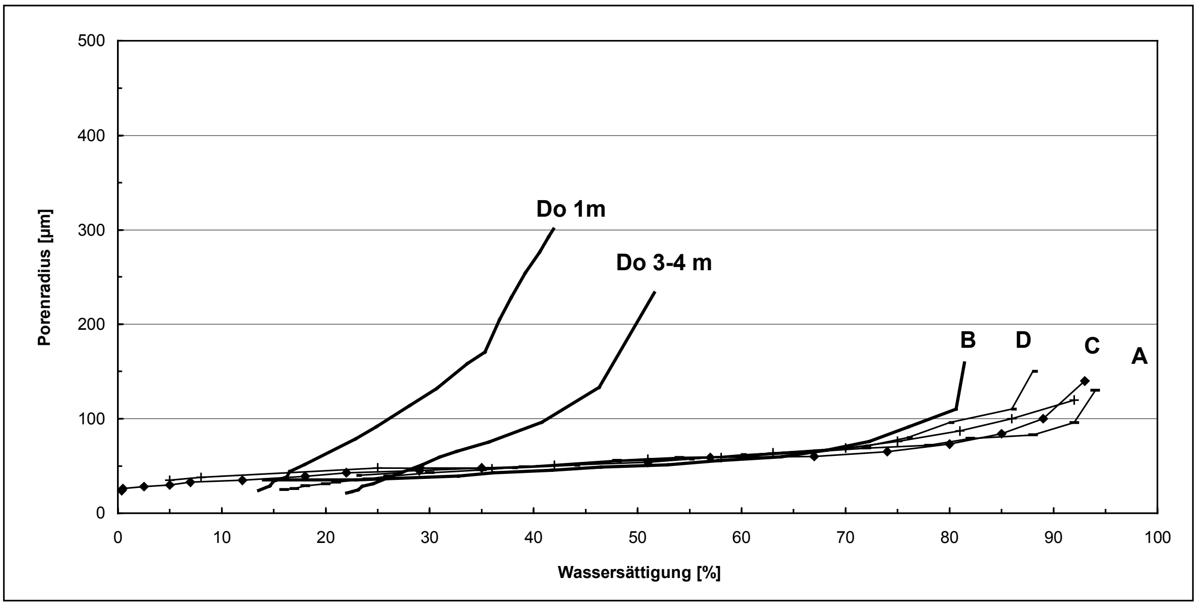


Fig.3.6 Typical pore size distributions of sediments with prevailing matrix flow (curves A-D) and sediments with matrix and bypass-flow (S-shaped curves Do). Since measuring accuracyis low at very high and low pore radius the S-shape is not too clear to demonstrate.

Table 3.2 Jordan valley: measured and calculated water contents immediately after irrigation. Light rows: after the wet season (March); shaded rows: during the dry season (August). nc = not calculated.

Sediment	Applied irrigation	Initial water content	Resulting water content	Stored irrigation water based on calculations of changes of		
	L/m²	%	%	water content	[Cl⁻]	$\delta^{18}O$
Sand	190	10	15	38	53	53
Sand	150	6	12	58	nc	60
Sandy silt	150	22	25	26	30	29
Sandy silt	150	6	12	53	nc	68
Lisan Marls	150	45	50	16	36	nc
Lisan Marls	150	30	37	nc	34	36

Contrary to the Punjab, irrigation does not continuously increase soil salinity in the Jordan valley, because groundwaters in the erosion area of the Jordan valley experience stronger natural recharge and have greater hydraulic gradients than in the Punjab. As a first approximation groundwaters may be considered as stagnant in the Punjab and as flowing in the Jordan valley.

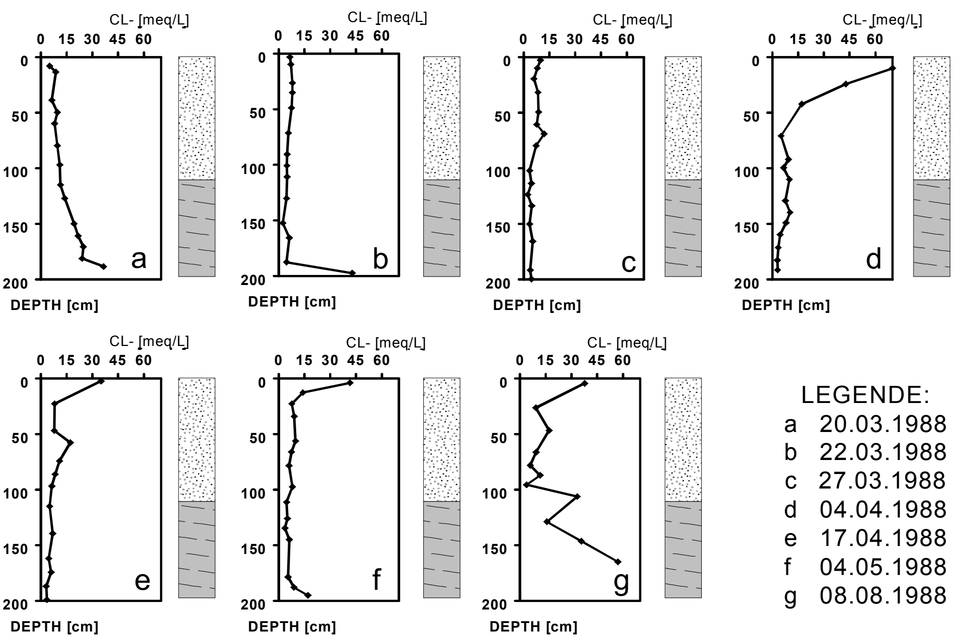


Fig.3.7 Changes of chloride concentrations in a sandy silt profile in the Jordan valley after irrigation

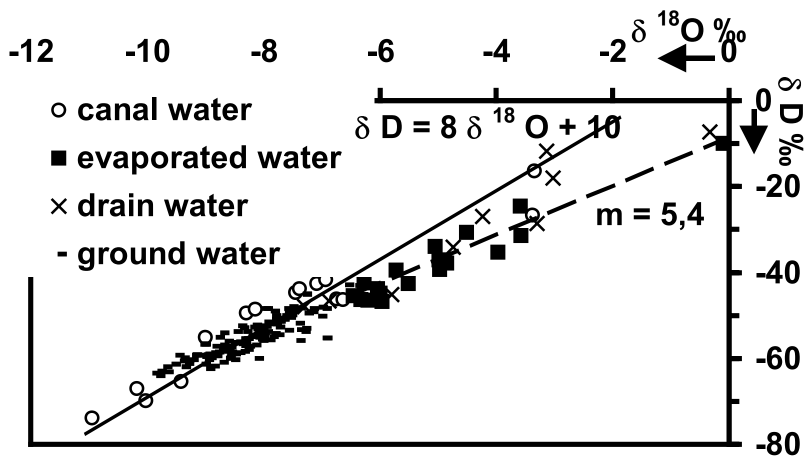


Fig.3.8 Stable isotope concentrations in channel and groundwaters of the study area in Pakistan.

3.1.3 THE CONTRIBUTION OF IRRIGATION AND CHANNEL WATERS IN THE AREA BETWEEN CHENAB AND RAVI, PUNJAB, TO GROUNDWATER LOGGING

In Pakistan almost all irrigation channels are ending blindly and unsealed. Stable isotope sampling of channel and groundwater (Fig.3.8) resulted in the following observations.

1) for channel waters no evaporation impact is observed; however, the ^{2}H excesses range between 18 (Mediterranean) and 9 (Monsoon),

2) groundwaters deeper than 3 m also show no evaporation and also a somewhat lower variability of the $\delta^{2}H/\delta^{18}O$ ratio than in channel waters; since the groundwater table was much deeper in former times (about 40 m), the actually missing evaporation impact indicates that channel water contributed predominantly to groundwater logging,

3) there is a strong evaporation impact as far as groundwaters are drained or become close to the land's surface.