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Water flow and pesticide transport in cultivated sandy soils

Experimental data on complications

Alterra report 2063
ISSN 1566-7197

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Commissioned by the Dutch Ministry for Agriculture, Nature and Food Quality, Research Theme BO-12-07-04: 'Risk assessment methodology for registration of plant protection products'.
Projectcode [BTG-4)

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Alterra-report 2063

Alterra Wageningen UR
Wageningen, 2010

Referaat

Leistra, M. and J.J.T.I. Boesten, 2010. *Water flow and pesticide transport in cultivated sandy soils; Experimental data on complications.* Wageningen, Alterra, Alterra-report 2063. 78 blz.; 36 fig.; 106 ref.

The risk of leaching of agricultural pesticides from soil to groundwater and water courses has to be evaluated. Complications in water flow and pesticide transport in humic-sandy and loamy-sandy soil profiles can be expected to increase the risk of leaching. Much of the precipitation water is intercepted by the crop canopy, after which stemflow and leafdrip lead to peaks in water load at the soil surface. Water infiltration at the soil surface can be highly non-uniform, e.g. due to differences in soil structure, presence of micro-depressions and water-repellency. Water flow in the soil profile is affected by sedimentation pattern, soil forming processes, differences in soil structure, antecedent soil moisture content, etc. The heterogeneous transport of pesticides in soils is reflected by the wide range of concentrations measured at the various depths. The leaching of substances from sandy soil profiles can occur in 'hot spots', which indicates that there are preferential flow and transport paths. A special situation is presented by fields with ridges and furrows (e.g. used for growing potatoes), in which much of the precipitation water can infiltrate in the furrow soil. In view of the conditions inducing preferential pesticide transport in sandy soils, the possibilities to describe/predict this type of transport by modelling should be investigated further.

Trefwoorden: anions, crop canopy, dyes, groundwater, infiltration, leaching, measurements, preferential flow, preferential transport, ridged fields, tracers, tube drains, water courses.

ISSN 1566-7197

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Alterra-report 2063
Wageningen, July 2010

Contents

Preface

The evaluation of the risk of leaching of pesticides to groundwater and water courses (e.g. via tube drains) is an important part of the registration procedures. In the first instance, leaching risk is estimated using computation models based on water flow through the whole soil matrix and chromatographic pesticide transport in soil (as a wave). The question rises whether these assumptions are justified. Water flow and pesticide transport in heavier loamy and clayey soils with large (visible) voids already receive much attention (drying cracks, worm holes, root holes, inter-aggregate voids). The situation with respect to sandy soils (humic-sandy and loamy-sandy) is less clear. On the one side, the idea is that water flow and pesticide transport in sandy soils proceed rather uncomplicated. On the other hand, there are measurements indicating that these processes can proceed in a highly complicated way in sandy soils.

The present report aims at giving a survey of how water flow and substance (pesticide) transport proceed in humic-sandy and loamy-sandy soils. The emphasis is on soils receiving the highest amounts of pesticide: regularly-cultivated agricultural and horticultural soils. Causes of heterogeneities in water flow and pesticide transport in such soils are discussed. Rapid (preferential) water flow and pesticide transport can be expected to increase the risk of leaching. The way in which the complications have to be accounted for in the framework of the registration procedures should be the topic of a subsequent study.

In principle, the term 'pesticides' includes groups of chemical compounds with various applications. Examples are: plant protection compounds, human health compounds, veterinary compounds, domestic compounds and industrial biocides. This report deals specifically with plant protection compounds. In the scientific literature it is common practice to use the term 'pesticides' for insecticides, fungicides, herbicides, etc. used to protect plants (mainly crops) in the field.

This research has been carried out in the framework of Research Theme BO-12-07-04 titled: 'Risk assessment methodology for registration of plant protection products', of the Dutch Ministry for Agriculture, Nature and Food Quality. The specific project No BTG-4 reads: 'Development and improvement of methods and tools for assessment of leaching to ground and surface water in the context of Dutch and EU registration of plant protection products'.

Summary

In the framework of the registration procedures, the risk of leaching of pesticides from agricultural fields to groundwater and water courses (e.g. via tube drains) has to be estimated. Often it is assumed that water from rainfall and sprinkler irrigation flows through the whole soil body (matrix flow). The pesticide is then assumed to move as a wave through the whole soil body, with the spreading of the distribution described by the dispersion coefficient (chromatographic transport). A lot of research dealt with complications in water flow and pesticide transport in loamy/clayey soils with large voids (cracks, biopores), often visible at the soil surface. Large (visible) voids can also occur in non-cultivated soils of other textural classes. The present study deals with water flow and pesticide transport in cultivated humic-sandy and loamy-sandy soils, without large voids. On the one side the idea is that water flow and pesticide transport in these soils proceed rather uncomplicated. On the other hand, certain research results indicate that there may be large complications in such soils. In the present study, the emphasis is on the nature and extent of the complications in water flow and pesticide transport in cultivated humic-sandy and loamy-sandy soils (not showing large voids).

The crop canopy has much effect on the distribution of rainfall and sprinkler irrigation over the soil surface underneath. A large fraction of the precipitation water is intercepted, after which stemflow and leafdrip lead to a high load of water on some places at the soil surface. It can be expected that water infiltration in soil is comparatively high at these places. A fraction of the pesticides sprayed on the plant surfaces can be washed-off with the precipitation water. Then places underneath the canopy with high loads of water and pesticide coincide. Flow paths through the canopy leading to locally high load of the soil surface are not directly dependent on soil type. Presumably, the pattern of water flow through the canopy is variable in time, dependent on crop development and weather conditions.

There are various potential causes of spatial variation in water infiltration at the soil surface. Heterogeneous wetting patterns resulting from the flow paths of precipitation water through the canopy have been measured in the soil. Infiltration capacity at the soil surface can be locally different because of differences in soil structure, in volume fraction of water and in water repellency. The infiltration capacity tends to decrease during the growing season due to the impact of precipitation on the soil and by soil settling. Microdepressions collect water when precipitation intensity exceeds infiltration capacity, which is followed by predominant infiltration from their bottom into the soil.

The volume fraction of water at a certain depth in the soil is often highly variable. This indicates that there is a pattern of wetter flow paths along which most of the water flows downward. The soil between the flow paths is comparatively dry and is wetted only slowly by lateral water flow from the flow paths. Water flow patterns were visualised by infiltrating solutions of weakly-adsorbed dyes. This type of experiment confirms that water can flow in an intricate pattern of flow paths through the soil. Water flow pattern will be affected by the textural layers formed by sedimentation in the past and by the obstacles resulting from soil-forming processes later on. Detailed soil profile descriptions (often missing) are very helpful in the interpretation of the results of field and lysimeter studies. Water outflow from sandy soil profiles (e.g. at one m depth) tends to show locations of high discharge (hot-spots).

The concentration of substances measured at a certain depth in sandy soils shows a wide variation. At the initial stages of infiltration, high concentrations can be expected to occur in the water flow paths. In between the flow paths, the concentration can be very low or even zero. The increased heterogeneity in concentration in the soil profile (as compared to the rather uniform application) also shows that there is lateral transport of

substance to local (preferential) flow and transport paths. Because of the heterogeneous transport pattern in sandy soils, preferential transport patterns can be easily missed by soil sampling. Local pesticide transport can be expected to lead to comparatively high leaching concentrations: much of the soil matrix is by-passed and time available for transformation in the bio-active top layers is shortened.

Measurements of the concentrations in the outflow from sandy soil profiles show different patterns. In some cases, the substance appeared roughly as a wave, as expected for chromatographic transport. In comparative studies for different soils, preferential leaching of solutes from sandy soils (e.g. to tube drains) was found to be distinctly lower than that for loamy/clayey soils. In other cases, distinct preferential (local) transport out of the sandy soil profile was measured. The comparatively new technique of water and solute sampling via a horizontal grid of suction cells in the subsoil showed a high variation in substance outflow. Major factors in this variation may be the heterogeneities in the soil profile and the water regime.

A particular situation is presented by fields with ridges and furrows, as used e.g. in growing potatoes. Precipitation water can flow along the soil surface from the ridges to the furrows, especially when falling at higher intensities. Pesticides sprayed on plants and soil can be carried along with this water. Thus the increased water load of the furrows can be accompanied by an increased pesticide load. Experimental work confirmed the surface-flow of water from the ridges to the furrows, the increased pesticide load of the furrows and the deeper movement of pesticide in the furrow soil. The comparatively low residence time of a pesticide in the furrow systems results in less time for transformation and thus to an increased risk of leaching. More experimental and modelling work is needed to develop and use a representative scenario that can be used in the procedure for evaluating the risk of leaching of pesticides from ridged fields.

1 General introduction

In many agricultural crops, pesticides are used in integrated systems of protecting the crops against pests and diseases. In the pesticide registration procedures, much attention is paid to the risk of leaching through the soil to groundwater and water courses (e.g. via tile drains). In the European Union, the concentration of a pesticide in groundwater should not exceed the drinking water limit of 0.1 μg/L. The limit values for pesticides in water courses may be also very low, in view of the extraction of drinking water and the risk of effects on aquatic organisms.

The risk of pesticide leaching from soil to groundwater is usually assessed using a combination of experiments and computations. Usually, experiments are carried out under uncomplicated conditions. In the process descriptions of computation models, usually simplifying assumptions are made. A common assumption is that water flow and pesticide transport in soil are rather uniform. Local differences in transport in soil are then described using a dispersion coefficient.

Heterogeneities in water flow and pesticide transport in soil can be expected to increase the risk of leaching to groundwater. Due to preferential flow and transport, a large fraction of the bio-active soil matrix is by-passed. Consequently, residence time of the pesticide in the soil zone with highest bioactivity is shorter than expected. Only limited time is available then for transformation of the pesticide to non-toxic compounds. Neglecting preferential transport may lead to under-estimation of pesticide leaching to groundwater and tile-drain water. More pesticide may be detected in the percolated water than expected on the basis of computations for simplified soil-plant systems. Thus it is important to study the extent in which preferential flow and transport occur in soil.

Preferential water flow and pesticide transport in loamy and clayey soils with distinct macropores (shrinkage cracks, inter-aggregate voids, earthworm burrows, root channels) already received much attention (e.g. Jarvis, 2007; Köhne et al., 2009). Large biopores up to the soil surface can occur in all soil types with minimal tillage (multi-annual crops, no-till cropping). The present survey concentrates on cultivated and cropped humic-sandy and loamy-sandy soils, usually showing no distinct macropores. The absence of clearly-visible macropes at the surface of sandy soils can give the impression that water flow and pesticide transport are rather uniform. The question arises whether this impression is justified.

In this study a survey is given of complications that can occur in water flow and pesticide transport in soil-plant systems. The study deals with soils that usually do not show distinct macropores, in particular with cultivated humic-sandy and loamy-sandy soils. Rainfall and sprinkler irrigation are partly intercepted by the crop, which leads to specific flow paths through the canopy to the soil surface (Chapter 2). Water infiltration at the soil surface in comparatively level fields is discussed in Chapter 3. Deviations from uniform water flow through sandy soil profiles have been observed and measured (Chapter 4). Measurements of tracers and pesticides in the soil profile (Chapter 5) indicate how their transport occurs. In studies with undisturbed soil columns or lysimeters and those on fields with a tile-drain system, the breakthrough pattern of substances was measured and evaluated (Chapter 6). Fields with ridges and furrows, e.g. grown with a potato crop, are vulnerable to redistribution processes at the soil surface (Chapter 7). Main lines in the nature and extent of the complications in water flow and pesticide transport in sandy soils are discussed in Chapter 8.

2 Stemflow, leafdrip and throughfall in the canopy

2.1 Survey of literature data

The crops in the field have an effect on the pattern in which the precipitation water (rainfall and sprinkler irrigation) reaches the soil surface. The rather uniform precipitation pattern is often modified to a more heterogeneous pattern. Three pathways of the precipitation water through the crop canopy are distinguished:

1. stemflow: the water is intercepted by the plants and flows along the leaves and down the stems to the soil around the stems;
2. leafdrip: the water is intercepted by the plants and drips at certain places from the leaves and other plant parts to the soil;
3. throughfall: the precipitation water is not intercepted by the plants, but falls directly on the soil surface.

A small fraction of the rainfall or sprinkler irrigation remains on the plant surfaces (e.g. 1 - 2 mm), where it gradually evaporates.

Steiner et al. (1983) sprinkler-irrigated maize fields and measured the stemflow of water by sealing funnels to the stems of the plants (Figure 2.1). The maize was sown in the end of May and the crop was well-developed during the measurements in the period end of July to beginning of September. In two years, stemflow was measured to be on average 41% and 47%, respectively, of the water reaching the top of the canopy.

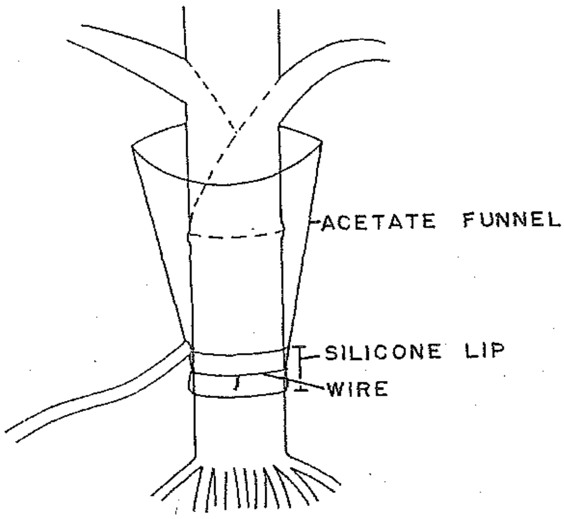


Figure 2.1
Stemflow catchment funnel attached to a corn stalk (Steiner et al., 1983; ©ASABE, with permission).

The stemflow of water in potato crops was measured by Jefferies and MacKerron (1985) using funnel-shaped collars. In one of the two measuring years, rainfall was supplemented by sprinkler irrigation. In the measuring period (end of June to beginning of August), the canopies were almost closed and the stems were erect.

Stemflow ranged from 17 to 87% of the water falling on the crop. The percentage of stemflow was found to be higher as precipitation intensity was lower. The authors expect that high wind speeds reduce the percentage of stemflow in the canopy.

While sprinkler-irrigating maize and soybean plants, the drop size distributions above and below the canopy were measured using a dye-paper technique (Armstrong and Mitchell, 1987). The cover percentages of the canopies were estimated to be 66% (maize) and 97% (soybean). Besides the drop sizes in the irrigation water (reflected in throughfall), a fraction of larger droplets was formed in the canopy. The formation of these larger droplets was explained by water interception by the plants, coalescence of the water on the leaves and local dripping from the leaves. The rainfall transformed by the canopy only wetted a limited fraction of the soil surface underneath the canopy (Figure 2.2), while another fraction was shielded by the canopy.

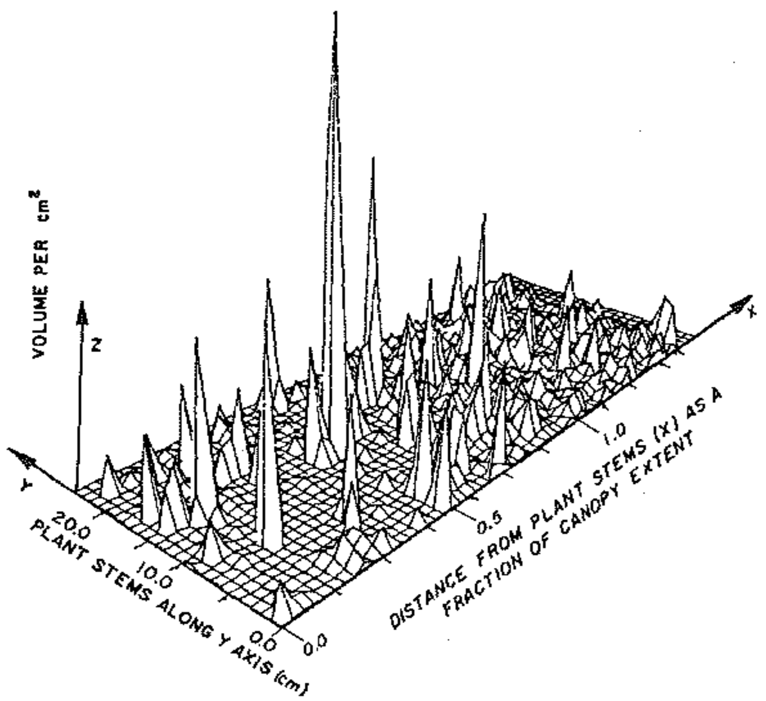


Figure 2.2
Spatial distribution of transformed rainfall (throughfall+leafdrip) underneath a soybean canopy (Armstrong and Mitchell, 1987; ©ASABE, with permission).

Parkin and Codling (1990) measured stemflow in a maize crop and the water distribution underneath the crop in natural rainfall conditions (eight events). In the measuring period (mid July to beginning of September), plant height increased from 0.7 m to 2.0 m. They found the stemflow to range from 19 to 48% of the rainfall. A field strip including the plant row (25% of the surface area) received 42% of the total rainfall. After a rain shower, soil moisture content in the plant row was measured to be higher than that between the rows. The authors point to the increased risk of the leaching of agrochemicals in the row strip.

While maize and sorghum crops received 64 mm of simulated rainfall in one hour, stemflow of water was collected via funnels mounted around the stems (Bui and Box, 1992). The heights of the crops were 1.0 to 1.7

m (maize) and < 1.2 m (sorghum). The amounts of stemflow were found to be on average 44% (maize) and 31% (sorghum) of the simulated rainfall. Stemflow increased with increasing crop development.

During sprinkler irrigation under low-wind conditions of a fully-developed maize crop, stemflow and throughfall+leafdrip through the canopy were measured (Lamm and Manges, 2000). Stemflow was collected with tubes around the stems and throughfall+leafdrip was collected in pans underneath the canopy between the plant rows. At a typical 0.2 m plant row spacing, the average stemflow was 53% of the 25 mm irrigation gift. Stemflow percentage decreased when plant row spacing was increased from 20 to 40 cm (lower soil cover). The authors expect that windy conditions reduce stemflow.

Throughfall+leafdrip of water from rainfall and sprinkler irrigation in fields with well-developed maize crops was measured by Dolan et al. (2001). Stemflow was calculated from the difference between above-crop precipitation and throughfall+leafdrip measured underneath the crop between the rows. The range of stemflow found in 21 rainfall and/or irrigation events was 30 to 66% of the above-crop precipitation. Stemflow tended to increase with the development of the maize plants. Throughfall+leafdrip tended to be highest midway between the rows, because of the contribution of leaf-drip from overhanging leaves.

Throughfall+leafdrip resulting from natural rainfall through various stages of a maize crop was measured by Hupet and Vanclooster (2005) using series of rectangular boxes. Stemflow was calculated from: 'rainfall minus (throughfall+leafdrip) minus interception' remaining on the crop. In a series of seven rainfall events, stemflow ranged from 12 to 66% of the incident rainfall. The spatial variation in throughfall+leafdrip of water to the soil surface under the canopy was high.

2.2 Discussion and conclusions

By far most of the measurements on stemflow in agricultural crops have been carried out for maize. Stemflow in that crop was measured to range from 12 to 66% of the precipitation above the crop. Plant structure of maize promotes stemflow: broad leaves sloping like a gutter to the stems. In some other crops, stemflow was found to range from 17 to 87% of the precipitation.

Various factors are mentioned to affect stemflow through canopies in practice:
– plant structure, e.g. long strip-formed leaves sloping to the stems increase stemflow;
– increasing crop development and soil cover increase stemflow;
– increasing wind speed decreases stemflow;
– increasing precipitation intensity decreases stemflow;
– subsidence and senescence of the canopy later in the growing season decrease stemflow.

Throughfall+leafdrip through the canopy, the latter following interception and coalescence on the leaves, is highly irregular. So both stemflow and throughfall+leafdrip via the canopy result in large local differences in water supply to the soil surface.

Pesticides sprayed on a crop can be partly washed-off by rainfall and sprinkler irrigation (Leistra, 2005). It can be expected that local differences in pesticide load of the soil run parallel to the differences in water supply: highest pesticide load of the soil on places where water supply is also highest. In growing systems in which pesticides are applied with the irrigation water, peaks of pesticide load to the soil can be expected to coincide with peaks in water supply.

3 Infiltration at the soil surface

3.1 Introduction

The patterns of water flow through the crop canopy have been discussed in Chapter 2, with only little attention to the resulting wetting patterns in soil. In Chapter 7, water flow through the canopy and the resulting wetting patterns in soil will be discussed for the special case of fields with ridges and furrows. The present Chapter deals with the infiltration of water in the soil of comparatively level fields (without ridges and furrows), both for temporary fallow and crop-grown fields. The focus is still on regularly-cultivated fields with humic-sandy and loamy-sandy soils, without distinct macropores. However, some aspects of water infiltration at the soil surface are common for various soil types, so results for other soil types are included in this Chapter if relevant.

Three mechanisms for differences in rate and extent of water infiltration at the soil surface are distinguished:
1. infiltration of water from flow pathways in the canopy;
2. differences in infiltration capacity;
3. surface-flow of water to (micro-)depressions.

3.2 Infiltration of stemflow and leafdrip

The volume fractions of water in the soil of a field with maize grown in rows (distance 0.8 m) were measured by TDR probes (Van Wesenbeeck and Kachanoski, 1988). In dry periods in the growing season, the soil in the rows (0.2 m deep) dried more rapidly than that between the rows due to the higher water uptake by the comparatively dense root systems in the rows. However, water recharge to the row soil by subsequent rainfall was higher than that to the soil between the rows. This was ascribed to the flow of a substantial fraction of the rainfall along the leaves and stems to the rows (stemflow).

The pattern of infiltration of rainwater in a humic-sandy soil used for growing maize was studied by Dekker and Ritsema (1997) and Dekker (1998). As a result of interception of rainwater by the plants followed by stem flow, the soil near the stem feet in the rows was wetted most (Figure 3.1). Another fraction of the intercepted water dripped from overhanging maize leaves to places between the rows. Small depressions in the soil surface collected water for subsequent local infiltration. Various actually water-repellent places in the topsoil, between the wetted places, remained rather dry.

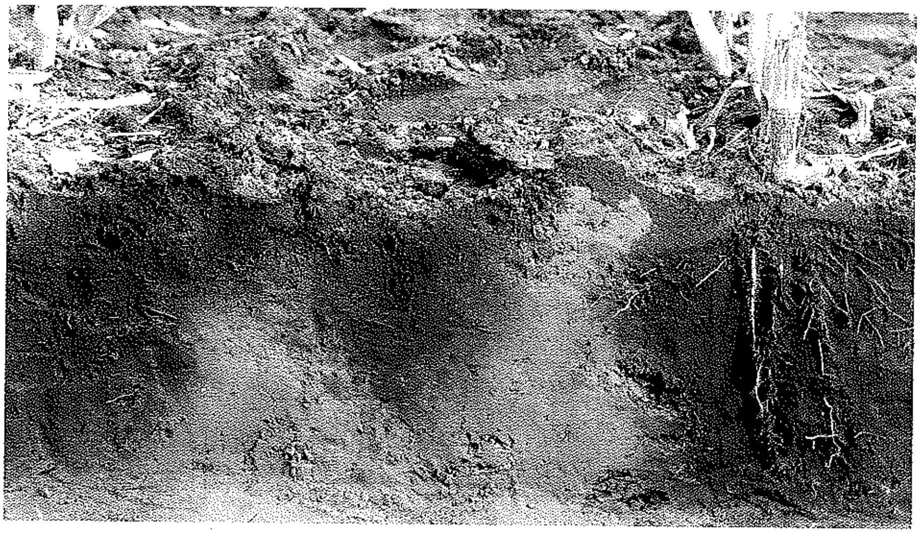


Figure 3.1
Soil moisture pattern (darker = wetter) in a potentially water-repellent humic-sandy soil measured just after maize harvest (Dekker, 1998; with permission).

Soil moisture in a field with silty-loam soil, grown with soybeans in rows at a distance of 0.5 m, was measured in detail via TDR (Timlin et al., 2001). In some periods, rainfall was supplemented by sprinkler irrigation. Under moist soil conditions, water uptake by the well-developed crop from the soil near the rows was higher than that from the soil between the rows. Precipitation caused a higher increase of soil water near the rows than between the rows, which was ascribed to interception by the well-developed canopy followed by stemflow. Towards the end of the growing season, the differences in soil wetting vanished due to crop senescence (flatter stems).

3.3 Differences in infiltration capacity

The impact of the drops from rainfall and sprinkler irrigation may destroy the structure of the top layer of the soil and form a crust. Morin and Benyamini (1977) simulated 70 mm of rainfall on a recently-cultivated bare loamy-sand soil (seedbed preparation). The water-infiltration rate in the soil rapidly decreased in time to low values, thus causing runoff. The rate of infiltration in the soil covered with a straw mulch remained much higher than that in the bare soil.

The rate of water infiltration in a loam soil was measured by Vieira et al. (1981) in a grid of 1280 points in an arable field. They used ring-infiltrometers and the infiltration rate was measured after 36 hours of ponding. The average rate of infiltration was 7 mm/hour, while the variation in the rate was great. By using kriging techniques for spatial interpolation, they constructed a contour map of the infiltration rate (Figure 3.2). It gives an impression of the spatial variation in a field of the rate of water infiltration resulting from ponding, e.g. due to intensive rainfall or sprinkler irrigation.

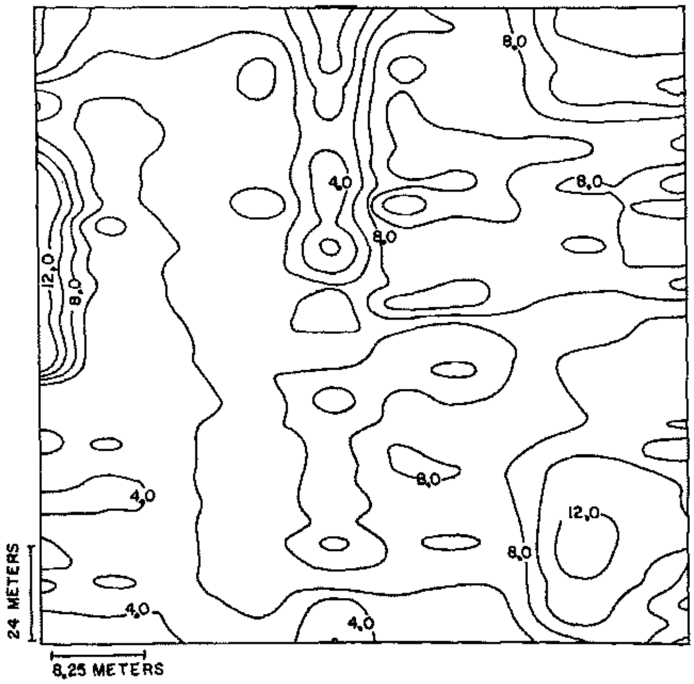


Figure 3.2
Contour map based on 1280 measured and 800 kriged values of water infiltration rate (mm/hour) under ponding. Contour interval is 2 mm/hour (Vieira et al.,1981; ©SSSA, with permission).

Various sandy soils become water-repellent (hydrophobic) when dried below a certain threshold moisture content (e.g. Dekker et al., 1999). Actual water-repellency in cultivated top layers mainly occurs near the dried soil surface. The repellency impedes water infiltration and thus causes surface-flow of water along the soil surface down the micro-relief. After this, the water infiltrates locally, e.g. at depressions in the micro-relief (depression-focused infiltration) and at places with a higher hydraulic conductivity.

3.4 Role of (micro-)depressions

When the precipitation intensity exceeds the infiltration capacity of a soil, micro-depressions in the soil surface are gradually filled with water (Gayle and Skaggs, 1978). The water in a filled micro-depression flows to neighbouring micro-depressions (local overland flow), thus forming larger puddles. Especially in sloping fields, this can ultimately result in large-scale overland flow (runoff). When precipitation ceases, the remaining water continues to infiltrate in the micro-depressions, thus in a heterogeneous pattern. Surface storage of precipitation water is highest shortly after the main cultivation (e.g. ploughing). The soil surface tends to level-off in the course of the crop growing season due to precipitation and settling.

Factors affecting water infiltration into bare soil surfaces were described by Moore and Larsson (1979) and Moore et al. (1980). When the precipitation rate exceeds the infiltration rate, the roughness of the soil surface provides storage capacity to the excess of water. The start of large-scale surface runoff is delayed by this storage. The extent of surface storage is estimated on the basis of micro-relief measurements. The collection of water in micro-depressions means that the infiltration is higher at these places. Both the micro-relief and the hydraulic conductivity at the soil surface are decreased by continuing intensive precipitation.

A review on the effect of tillage and rainfall on soil-surface roughness was presented by Zobeck and Onstad (1987). This type of research started with manual measurements (e.g. using pins), but later on computer-controlled sensor measurements were developed. The highest roughness produced by primary tillage (e.g. ploughing) is usually reduced by secondary tillage (e.g. harrowing). The impact of rainfall and sprinkler irrigation reduces roughness of the soil surface.

There may be comparatively large soil surface depressions in undulating fields. Derby and Knighton (1995) measured the depth of the water table in a transect through such a surface depression, about 100 m in diameter and up to one m deep. After spring thawing of snow and after intensive precipitation in summer, they found a mound in the water table underneath the depression in a sandy soil (Figure 3.3). Following chloride tracer application to the soil surface in November, they measured a large chloride peak in the tile-drain effluent from a field section with a depression. On the contrary, chloride leaching to the tile drain of a level section of the field was low in this period. These measurements confirmed that, under ponding conditions, groundwater recharge and solute transport are focused in topographical depressions in undulating fields.

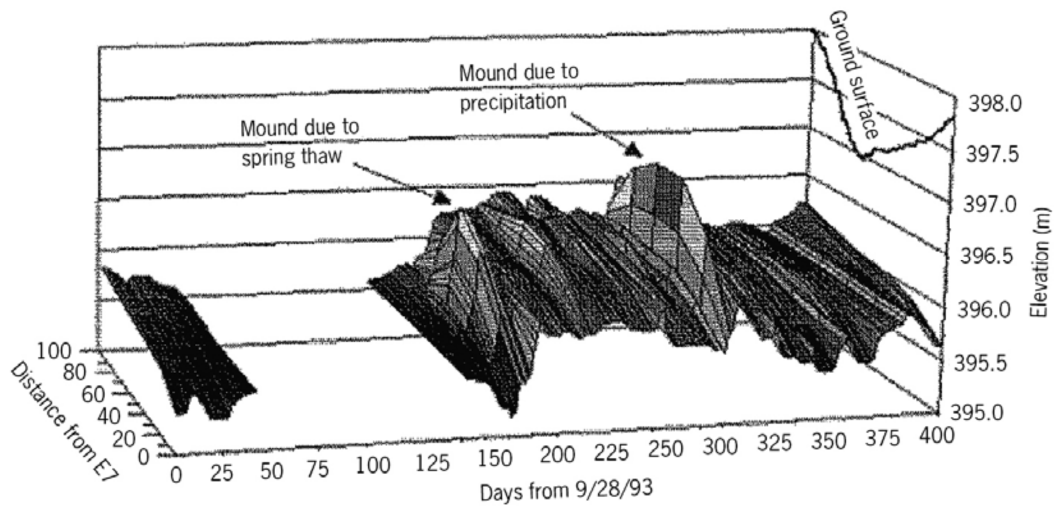


Figure 3.3
Water table elevation in a transect through a depression in the soil surface, as a function of time. Groundwater mounds formed under the surface depression (Derby and Knighton, 1995).

The herbicides atrazine and alachlor were sprayed on the soil surface of corn fields with silt-loam soil (Edwards et al., 1997). After this, the fields received rainfall simulation at 50 mm/hour. Water flown to micro-depressions at the soil surface was sampled and analysed for the herbicides. Concentrations in the order of several mg/L were measured in the first water sampled. The concentrations for the cultivated soil plots decreased rapidly in the first 30 min after irrigation to less than 10% of the initial concentration. Plots sprinkler-irrigated later after spraying, following some small rain showers, contained much lower concentrations in the micro-depression water than plots irrigated immediately after spraying.

Larsson et al. (1999) applied an anionic dye with sprinkler-irrigation water to the surface of a loamy-sand soil used for growing cereals. They sprinkled 40 mm of dyed water at a low rate (2.7 mm/hour). They observed surface-flow of dye-coloured water to micro-depressions in the soil surface. This was the result of water-repellency and micro-topography of the topsoil. After the micro-depressions had drained in about one hour, dye-coloured infiltration patterns were visible on horizontal cross sections uncovered by excavation (Figure 3.4). This type of preferential flow is expected to be highest when the topsoil is dry and water-repellent.

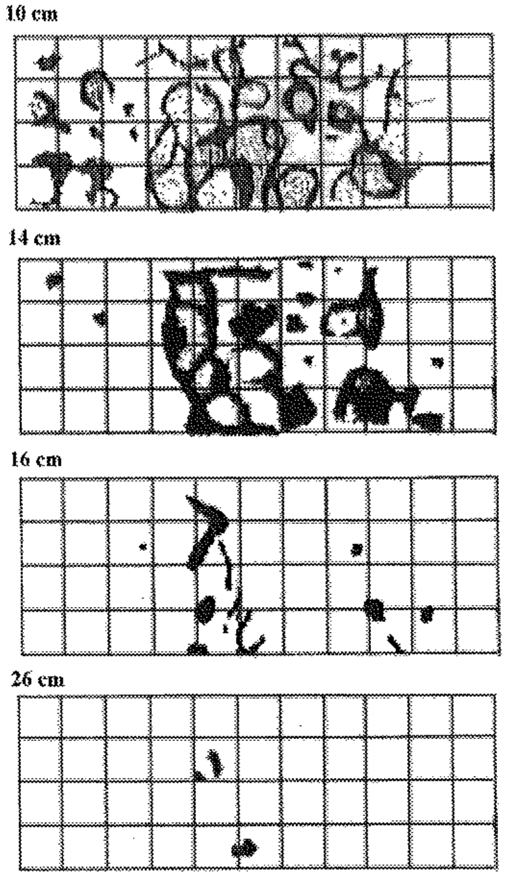


Figure 3.4

Dye-tracing patterns in horizontal cross-sections (0.1 to 0.26 m deep) resulting from 40 mm sprinkler irrigation of water with dye on a loamy-sand soil with infiltration in micro-depressions (Larsson et al., 1999; ; ©Elsevier, with permission).

Govers et al. (2000) reviewed the effect of soil surface roughness on water infiltration. They distinguished 'random roughness' at the scale of structural elements and 'oriented roughness' caused by farm implements. When the rate of precipitation exceeds the rate of infiltration, water can be stored in depressions in the soil surface. Surface roughness data were used to calculate surface storage capacity. Both random roughness (and thus storage) and infiltration capacity decreased with continuing precipitation. Surface storage leads to a comparatively high infiltration of water from the depressions into the soil.

Scorza Junior et al. (2002) described a conceptual approach and a numerical model for the storage of precipitation water in microdepressions at the soil surface. As soon as the precipitation intensity exceeds the infiltration capacity of the soil, puddles are formed in the microdepressions. The depressions are characterised by their bottom level, their maximum water storage and their inflow/outflow threshold. When precipitation continues, the smaller puddles combine into larger puddles. Ultimately, overland flow can occur, especially in sloping fields. Scorza Junior et al. (2002) also discussed surface flow to macropores, which does not seem to be relevant for cultivated sandy soils.

3.5 Discussion and conclusions

The flow of water along pathways in the crop canopy (Chapter 2) leads to places of high water supply to the soil (this Chapter). Examples of such places are the soil around the stem feet of the plants (stemflow) and the soil midway between the rows (leafdrip from overhanging leaves). Other places in soil remain comparatively dry due to shielding effect of the canopy.

The large variation in infiltration capacity at the soil surface could be a common phenomenon for various soils. Such differences are important under intensive rainfall or sprinkler irrigation leading to ponding. The infiltration capacity decreases in time due to the impact of precipitation and settling. The infiltration capacity is particularly low for actually water-repellent soil surfaces.

Soil surfaces have a certain roughness, with (micro-)depressions available for temporary storage of precipitation water. This leads to a pattern of local infiltration of the water from the depressions. Surface storage tends to decrease in the course of the growing season of the crop.

Crop development, soil surface condition (structure, moisture content), precipitation intensity/duration and wind speed/direction change in the course time, so the pattern of water infiltration in soil can be expected to change accordingly in an intricate way. It is regrettable that, in most publications on field studies, a description of the water-infiltration pattern in the course of time is missing.

4 Water flow in the soil profile

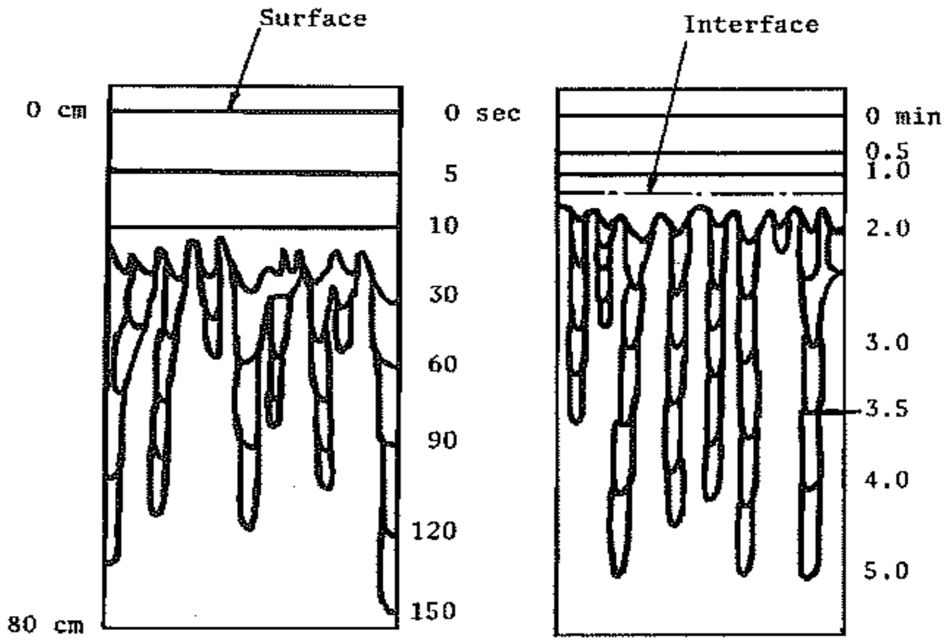
4.1 Introduction

Much research has been carried out on water flow and substance transport in water-repellent sandy soils with permanent vegetation, such as permanent grassland and nature areas. An example is the research on water flow and bromide transport in potentially strongly water-repellent dune-sand soil with permanent grass vegetation in Ouddorp (NL). When rainwater falls on the field after a dry period, a thin humous top layer is wetted rather uniformly (distribution layer) (Ritsema and Dekker, 1995). The water in this layer flows horizontally (distribution flow) until it flows via a pattern of fingers through the water-repellent intermediate layer to the wettable subsoil with water table. The soil in the intermediate layer between the flow paths remains rather dry. The result is a very wide variation in volume fraction of water per depth (Ritsema et al., 1993; Ritsema and Dekker, 1994). The flow paths tend to be formed on the same places in subsequent rainy periods (recurrent flow paths) (Ritsema et al., 1997). Presumably, such non-tilled sandy soils with permanent grass vegetation represent rather extreme cases of water-repellency. Nevertheless, this research yields interesting background information for the present study, so it is summarised in Appendix 1. Regular soil tillage disturbs the recurrent flow paths in the top layer. Further, the water-repellency of tilled agricultural soil is often lower than that of non-tilled soil (Dekker, 1988). The present study is focused on water flow in regularly-tilled sandy soils, used for growing arable and horticultural crops.

The conventional idea is that water flows rather uniformly through cultivated sandy soils, be it at somewhat different rates in a horizontal cross-section. Cultivated sandy soils do not show large structural elements and large voids (cracks, macropores, etc.) at their surface. This can create the impression that water flow proceeds rather uncomplicated in sandy soils. The first section in this Chapter discusses direct experimental data on water flow in sands and sandy soils, together with data on the outflow of water from sands and sandy soils. The second section discusses the visualisation of the flow paths of water in sandy soils using dyes. It is attempted to draw some conclusions on the degree of complexity of water flow in cultivated sandy soils.

4.2 Soil moisture and outflow measurements

Ponded water infiltration in a dry homogeneous coarse-sand layer occurred with a stable water front in the form of a horizontal plane (Diment and Watson, 1985). After ponding had stopped, water redistribution occurred via a pattern of fingers (Figure 4.1A). The tendency of finger formation became less as the sand was finer: the redistribution front became more wavy. The tendency of finger formation in the coarse sand decreased with a slight increase in volume fraction of water (wavy wetting front). When a dry fine-sandy top layer is underlain by a layer with dry coarser sand (which has a higher saturated hydraulic conductivity), the water front became unstable underneath the top layer (Figure 4.1B). The saturated hydraulic conductivity of the coarser-sandy layer below was higher than needed for the conduction of the water supplied from above. Just below the interface of the layers (induction zone), the water started to flow in a pattern of fingers through the coarser-sandy layer. Again the tendency of finger formation in the coarse sand became much less at a slight increase of volume fraction of water (wavy wetting front). This was explained by greater lateral water flow.



A Infiltration-redistribution **B** Infiltration in two layers

Figure 4.1
*Wetting pattern from water infiltration in a homogeneous dry sand with infiltration stage followed by redistribution stage (**A**). Wetting pattern from continuous water infiltration in a dry fine-sandy top layer underlain by a dry coarser-sandy layer (**B**) (Diment and Watson, 1985).*

Lysimeters filled with sand (1.0 m high) were each provided with 30 cylinders (0.1 m high) at the bottom for the collection of water flowing out of the sand (Hendrickx and Dekker, 1991). In the winter period, cumulative natural rainfall on the lysimeters was 403 mm. Two of the 30 cylinders (free drainage) discharged about 60% of the total volume of water flowing out. Various other cylinders did not show any drainage at all or low drainage. At the end, the wetted areas on horizontal cross sections at 0.2 m depth in soil were 7 to 22% (in wettable sand) and 12% (in water-repellent sand) of the total area. So preferential water flow was found to occur in both wettable and water-repellent sand under natural rainfall.

Soil moisture contents were measured in an experimental field (Vredepeel (NL)) with humic-sandy soil used for arable farming (Hamminga et al., 1994; Ritsema and Dekker, 1995; Ritsema et al., 1998). The soil (grown with winter wheat) was sampled at seven times in the period from November 1990 to March 1992. The variation in the 16 volume fractions of water measured per depth at each time was high, most so for depths around 0.4 m (Figure 4.2). This indicates that there was a pattern of wetter flow paths with drier soil regions in between them. The soil in the lowest part of the experimental field (maximum height difference of 0.27 m) contained comparatively high moisture contents.

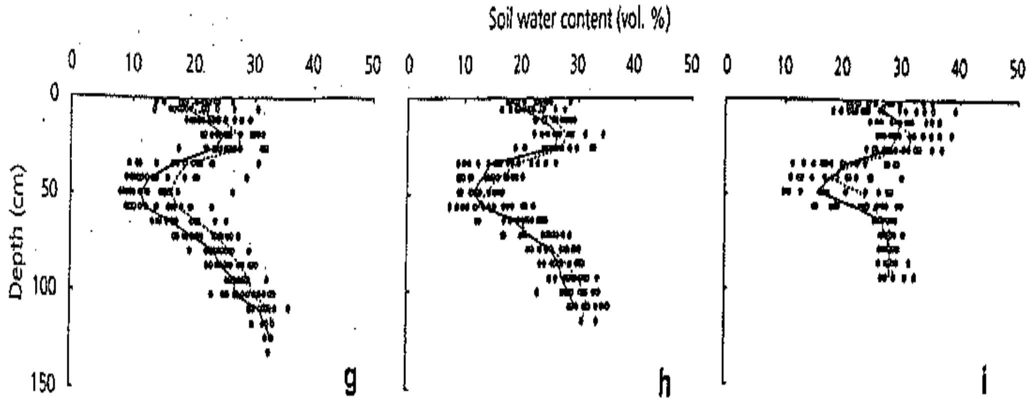


Figure 4.2
Measured volume percentages of water in the humic-sandy soil of the Vredepeel experimental field at 1, 22 and 42 days after 22 November (Ritsema and Dekker, 1995).

4.3 Visualisation of flow paths

Water containing dye infiltrated by ponding in a top layer of dried fine sand on top of a layer of dried coarser sand (Glass et al., 1988). The water flowed uniformly through the fine-sand layer on top, but it started to flow in fingers in the coarse-sand layer underneath (Figure 4.3). Only gradually, the water flowed laterally from the fingers into the surrounding dry sand. In the second infiltration period for the system (after water drainage), the water followed the same flow pathways as in the first period. When the water content in the system was increased from below, the infiltration front became wavy (lower instability). Variation in water outflow at the bottom of the system (3 cm wide collector sections) was highest with infiltration in the driest sands (flow most unstable).

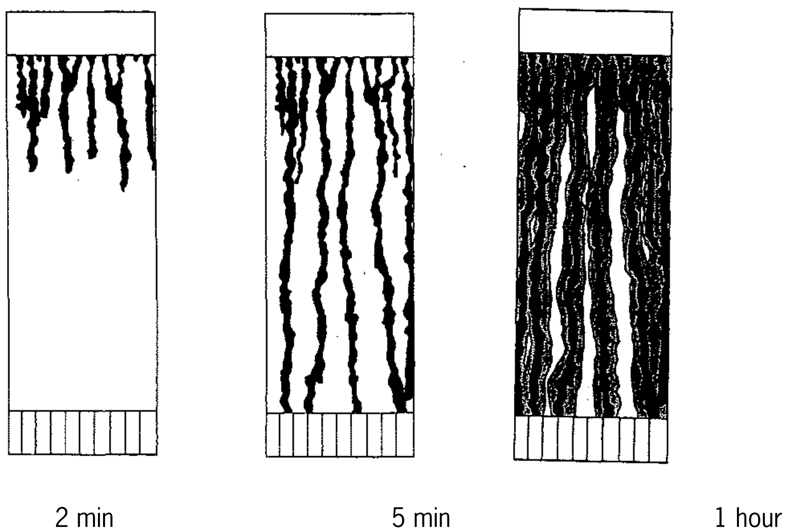


Figure 4.3
Fingered flow of dyed water in coarser dry sand overlain by finer dry sand (Glass et al., 1988; ©Elsevier, with permission). Dimensions of the system: 1 m high and 0.3 m wide. Ten collector sections (each 0.03 m wide) at the bottom.

Rhodamine dye was sprayed four times (at 10-day intervals) as a band in furrows on a potato field with sandy soil (Kung, 1988, 1990a). Rainfall was supplemented by sprinkler irrigation (total precipitation of 275 mm in 80 days). After potato harvest (2.7 months after the start of the applications), pits were excavated to study the dye-coloured flow patterns on vertical and horizontal cross-sections of the soil. First the dye plumes (red) moved downward from the furrow through the sandy soil with little lateral spreading. At textural layer transitions in the soil profile below 1 m depth (e.g. silty/clayey layers), the solution started to move in more horizontal direction along the inclined layer transitions (sheet or funnel flow). Coarse-sandy layers or wedges also impeded vertical water flow, because of the water-entry pressure needed. At locations in the soil profile with discontinuities (e.g. previous root penetrations), the dye moved in almost vertical direction (column flow). The number of flow paths decreased with depth. Between 1.5 and 2.0 m depth, only about half of the soil matrix was coloured (both by vertical flow and lateral flow by capillary suction) and in deeper layers the fraction coloured was even less.

Ten sprinkler-irrigation gifts (total of 100 mm) of iodide-ion solution were applied in two days (April) to moist plots of bare loamy-sand soil (Hupselse Beek catchment, NL) used for arable farming (Van Ommen and Dijksma, 1988; Van Ommen et al., 1989b). Horizontal cross-sections of the soil were uncovered by excavation and the flow patterns were visualised by spraying chloride and starch (gives blue colour with the iodine formed). The top layer (more than 0.26 m thick) of the arable soil was uniformly coloured. In the sandy soil zone between 0.40 and 0.55 m depth, colour pattern was highly irregular showing distinct flow paths (Figure 4.4).

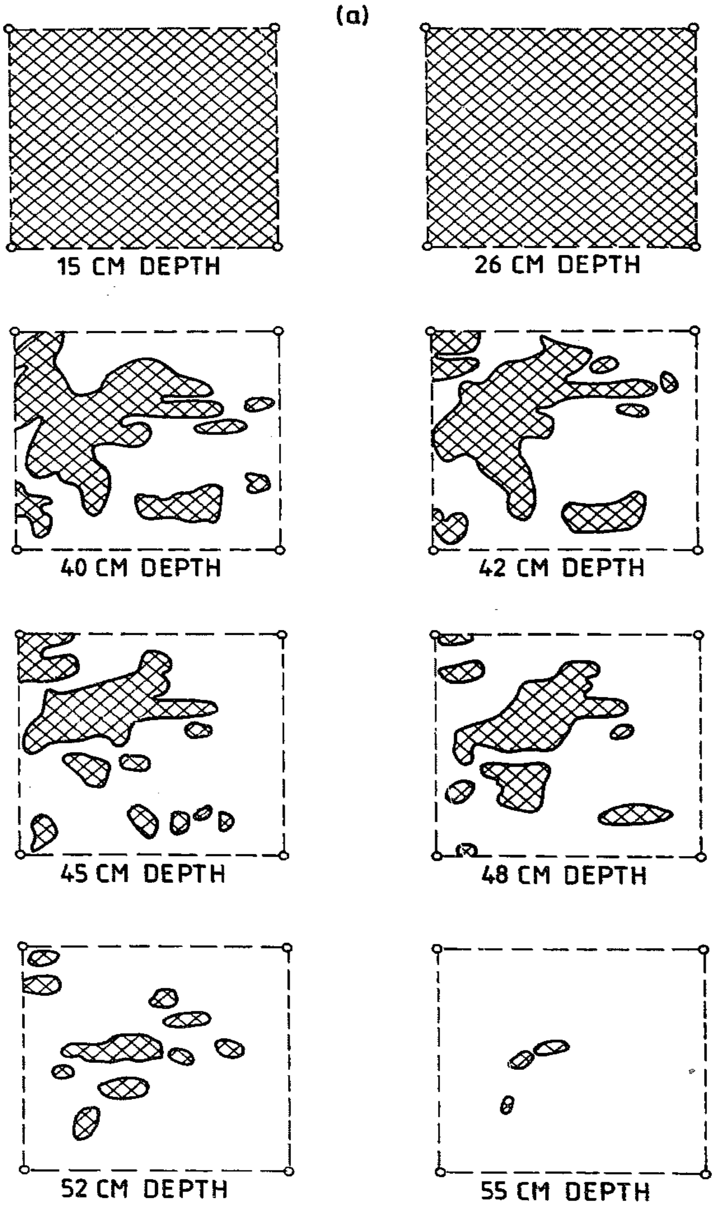


Figure 4.4

Horizontal cross sections showing the presence of iodide in the flow paths at different depths in sandy soil (Van Ommen et al., 1989b; ©Elsevier, with permission).

Ghodrati and Jury (1990) sprayed an anionic dye on the surface of field plots with loamy-sand soil. The plots were sprinkler-irrigated at a rate of 5 mm/hour up to 100 mm water layer, distributed over a period of five days. The flow patterns were observed on vertical and horizontal cross sections of the soil. Movement of the dye in the cultivated top layer (about 0.3 m) was rather uniform, but below that movement showed a finger-like pattern (Figure 4.5). Nevertheless, averaging the concentrations per depth resulted in a convection-dispersion type of substance distribution with depth (wave form) (Figure 4.6).

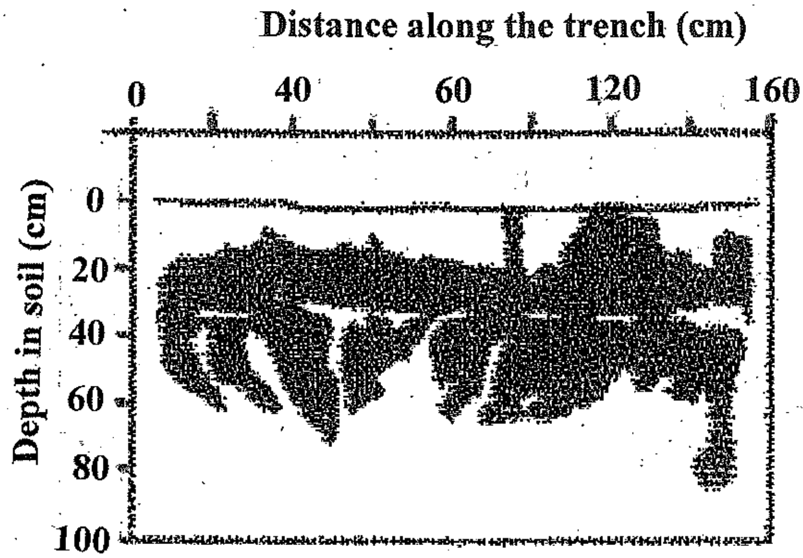


Figure 4.5
Vertical distribution patterns of the dye resulting from sprinkler irrigation on cultivated loamy-sand soil (Ghodrati and Jury, 1990; ©SSSA, with permission).

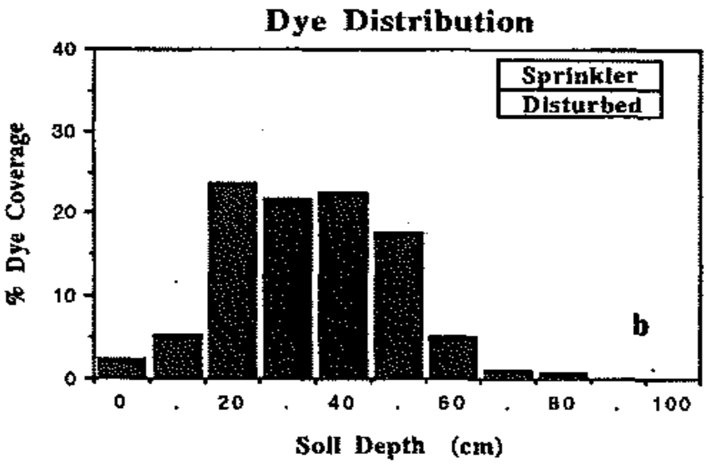


Figure 4.6
Distribution of a dye in with depth in loamy-sand soil obtained by averaging the results of observation per depth (Ghodrati and Jury, 1990; ©SSSA, with permission). Sprinkler irrigation on cultivated loamy-sand soil.

Fourteen bare field plots with divergent soils were sprinkler irrigated with 40 mm water in a period of 8 hours (Flury et al., 1994). The top soils had been cultivated by ploughing, harrowing and spading. The water was coloured with a dye showing low adsorption to soils. At one day after irrigation, a trench was dug in the plot and the colour patterns on the trench wall were recorded. A sandy soil was rather uniformly coloured and this was restricted to a top layer of around 0.15 m. The amount of irrigation water was too small to move the dye out of the top layer. The structured soils, containing macropores, showed deep penetration of the dye (e.g. to 0.8 m depth) in a very irregular pattern.

A dye-tracing experiment was carried out for undisturbed monoliths of loamy-sand soil (Mellby), about one m long, taken from an arable field (Bergström and Shirmohammadi, 1999). A layer of 100 mm of water with dye was infiltrated by ponding or by dripping via many tubes (80 mm/hour). Soil staining by the dye was recorded at horizontal cross sections at depth intervals of 0.1 m. Staining in the top 0.2 m of the loamy sand was homogeneous, but below that only a fraction of the soil was stained. Water flow through the loamy sand soil proceeded more heterogeneously with increasing depth. However, dye transport in the loamy-sand soil was much less heterogeneous than that in a clayey soil monolith with macropores.

Sandy and loamy-sandy field plots were sprayed with ammonium-carbonate, after which they were sprinkler-irrigated at 23 mm/hour to a total of 120 mm water layer (Wang et al., 2002). The increase in pH (above pH 8) on excavated vertical cross sections of the soil profiles was detected by spraying pH-indicators. The top layer of the soils was wetted rather uniformly. Below that the water infiltration front showed a fingered (sandy soil) or wavy (loamy sand soil) pattern.

Wang et al. (2003) sprayed dyes on the surface of plots in fields with sand and loamy-sand soils, after which the plots were sprinkler-irrigated. The coloured flow patterns were studied on the walls of excavated trenches. The flow patterns were found to be comparatively stable in the water-infiltration stage. However, fingered flow started at the end of the infiltration stage and the extent of fingering increased with time during water redistribution. In non-cultivated soil fingering started at the soil surface, whereas in cultivated soils it started below the cultivated layer of about 20 cm (Figure 4.7). So tillage of sandy soils can prevent preferential water flow in the cultivated top layer, but not below it. When the top layer of the soil was removed, unstable water flow developed in the remaining part of the soil profile. Water flow in one of the sandy soils was stable; the reason for this was not clear. The tracer bromide ion, which had also been sprayed on the soil surface, was measured to be concentrated in some positions in the soil profile.

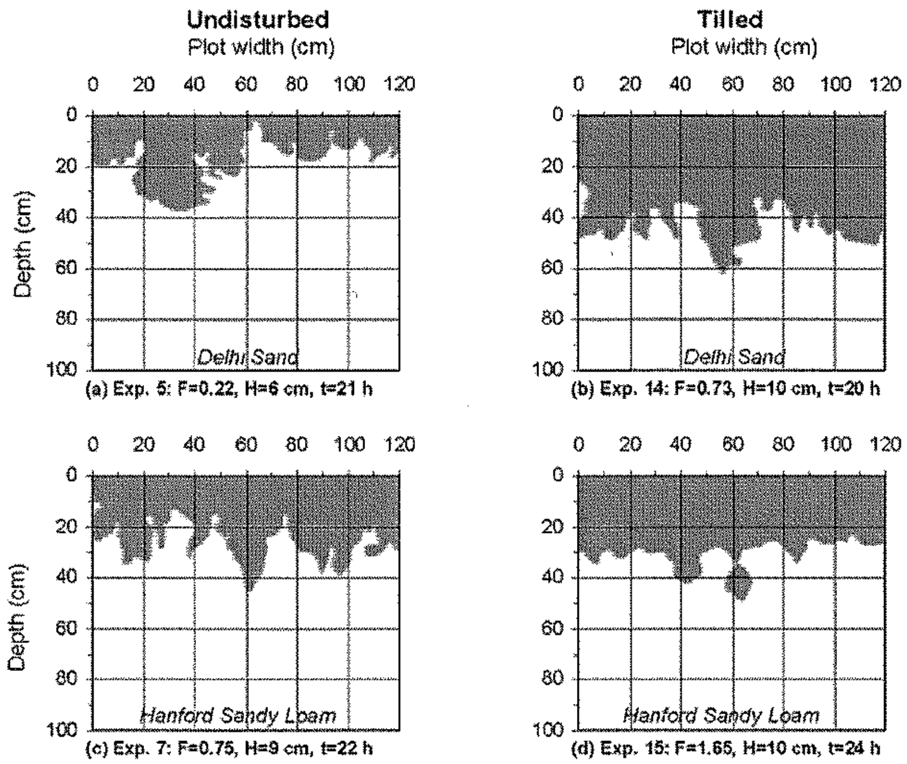


Figure 4.7
Dye-coloured water flow patterns in two sandy soils (Wang et al., 2003). Left: non-tilled soils; right: tilled soils.

An agricultural field with loamy-sand soil was left uncultivated for four years; it was only cleared of vegetation and leveled. The soil (without apparent structure) was irrigated by ponding (11.9 mm/d) of a solution of a dye, on three consecutive days (Öhrström et al., 2004). The coloured patterns were studied on vertical cross-sections of the soil. Water flow in preferential flow paths started already at the soil surface. The dye coverage decreased rapidly from 100% at the soil surface to 35% at 0.2 m depth. Preferential water-flow paths occurred at the same locations for each irrigation gift; the initially wetter locations were most active in water and solute transport. Distribution of bromide ion (applied in the same water) at various depths was also very heterogeneous, with the higher concentrations coinciding with the dyed places. Some horizontal flow between 0.3 and 0.5 m depth increased the dye coverage.

4.4 Discussion and conclusions

In dry homogeneous sand layers, water may flow in a fingered pattern. A first stage of ponded water infiltration with a stable wetting front can be followed by a redistribution stage with fingered flow. Stable flow due to ponding on a dry finer-sandy top layer can be followed by fingered flow in a dry coarser-sandy layer underneath. As the initial volume fraction of water in the sands increases, the water flow pattern changes from a fingered to a more wavy pattern (less unstable).

Measurements on soil moisture content in sandy soils in the field show a wide range of values per depth. This indicates that there is a pattern of wetter flow paths with drier soil places between them.

Irregular and incomplete wetting of the soil is found to be a rather common phenomenon in practice. Van Dam et al. (1990) attempted to simulate water flow in sandy soils with a model, using hydraulic relationships measured in the laboratory. Comparison between computed and measured water distributions in soil was poor. A main reason is that the moisture retention curve is measured in the lab for thoroughly-wetted soil cores. The moisture retention curve for the field soil had to be obtained by inverse modelling on the basis of the field-measured soil moisture profiles. Simulation of soil moisture was sensitive to the moisture retention curve, whereas the value of the saturated hydraulic conductivity had little effect.

The water supplied to a lysimeter or tray filled with sand was found to flow from the bottom in a highly variable pattern.

Sedimentation layers with different texture (sand, silt, clay) can lead to a complicated water-flow pattern in soil. Fine-textured layers may have low water-permeability, so water tends to flow more horizontally along (often inclined) interfaces (funnel flow). At more-permeable disturbances in low-permeable layers, water may start to flow in more downward direction (column flow). Coarse-sandy layers and wedges may also act as a barrier for water flow, when the water-entry value of the coarse sand is not exceeded.

Regularly-cultivated top layers of sandy soils often allow rather uniform water flow. Flow in a finger-like pattern may then start underneath the cultivated top layer. However, an agricultural soil not cultivated for some years showed a finger-like flow pattern starting at the soil surface.

In general, water flow in sandy soils can become unstable due to an increase in (saturated) hydraulic conductivity with depth. If there is a dense plough layer with low hydraulic conductivity, unstable water flow could start just below this layer.

A fingered flow pattern of water in field soils implies that the average values of the volume fraction of water per depth are lower than expected from water-release curves determined in the laboratory.

The actual hydraulic conductivity in soil increases strongly with increasing volume fraction of water. The differences in volume fraction in water in soil are dependent on the wetting/drying history of the location. Water from a new precipitation event tends to flow through the wettest places in the soil profile left after the previous event (recurrent flow paths). Local actual hydraulic conductivity in soil changes in time, in combination with the volume fraction of water.

5 Substance transport in the soil profile

5.1 Introduction

Some field studies dealt with the movement of bromide-ion in water-repellent sandy soil with permanent grass vegetation. This represents a rather extreme situation of water-repellency, as compared to that in regularly-tilled sandy soils. Nevertheless, this research delivers interesting background information, which is summarised in Appendix 1. In the present study, the emphasis is on substance transport in tilled humic-sandy and loamy-sandy soils used for growing arable and horticultural crops, which are often less water-repellent than non-tilled soils.

5.2 Anions

Bromide-ion tracer was applied (December) to a strip of bare arable land with loamy- sand soil (Hupselse Beek catchment, NL) (Van Ommen and Dijksma, 1988; Van Ommen et al., 1989a). Rainfall in the study period of 190 days was 480 mm. At four times, ten soil cores were taken down to 0.7 m depth and separated into layers for the analysis of bromide. Bromide-ion concentration per depth showed a wide range of values (Figure 5.1). Further, the spreading in the distribution of bromide with depth in the profile was rather wide (averaged dispersion length in convection-dispersion equation of 6.2 cm). After 193 mm of estimated water percolation, substantial leaching of bromide from the top 0.7 m of the profile had occurred. The concentration of bromide measured in the upper groundwater was highly variable. The authors concluded from their results that preferential transport occurred in this soil.

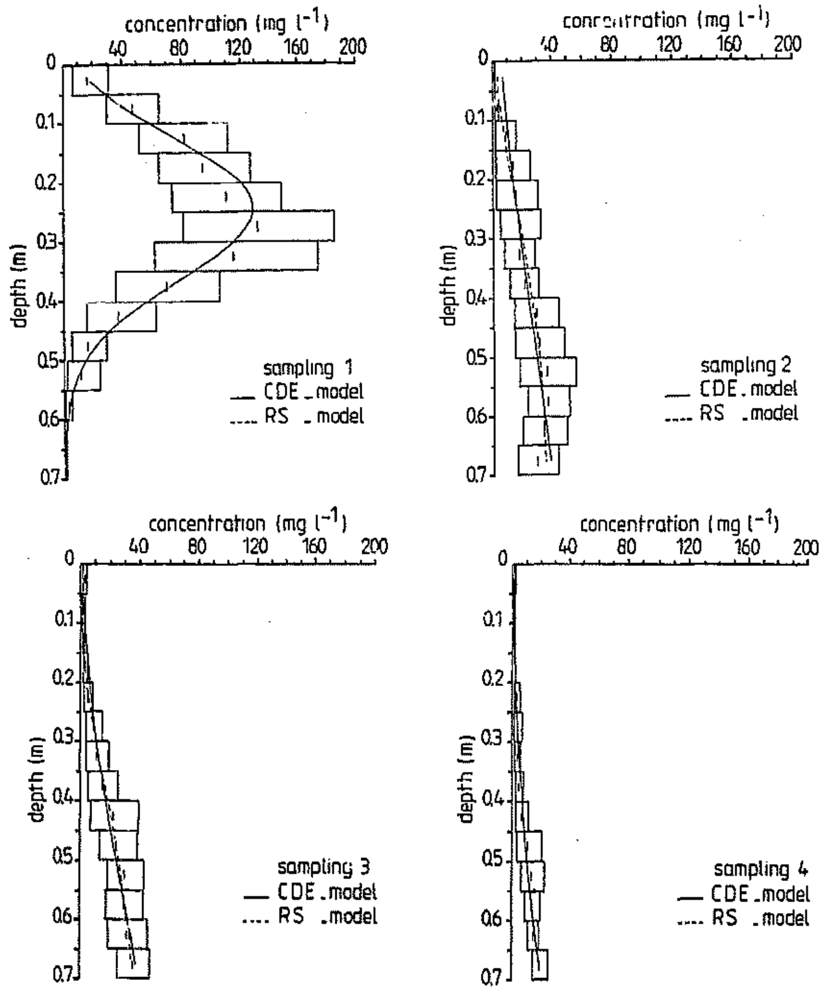


Figure 5.1
Concentration profiles of bromide-ion (applied in December) in arable loamy-sand soil after 70, 167, 225 and 305 mm drain discharge (Van Ommen et al., 1989a; ©Elsevier, with permission). With confidence intervals of 90%.

Water flow and transport of bromide-ion in a potentially water-repellent humic-sandy soil near Vredepeel (NL) were studied (Hamminga et al., 1994; Ritsema and Dekker, 1995; Ritsema et al., 1998). After spraying bromide-ion on the arable field in November (shortly after sowing winter wheat), 20 soil cores were taken at seven times in a period of 1.3 years. The range in volume fraction of water at a certain depth was high, which indicates that water flow was non-uniform (Chapter 4). Similarly, the concentration of bromide-ion at a certain depth on the sampling times showed a wide range (Figure 5.2), indicating that preferential transport occurred. In a fraction of the soil samples, bromide concentration was (almost) zero, while the measuring depth was well within the main concentration wave. In the first period, wetter soil cores (within the flow paths) contained more bromide-ion than the drier cores (outside the flow paths). The spreading in the amount of bromide measured per core was distinctly greater than the spreading in the application. This was ascribed to lateral water flow and bromide transport in the upper part of the soil profile to preferential flow paths. Incidental high concentrations of bromide were measured in the groundwater before the main concentration wave appeared. The general picture is that there was a very heterogeneous pattern of pathways for water flow and bromide transport in the soil.

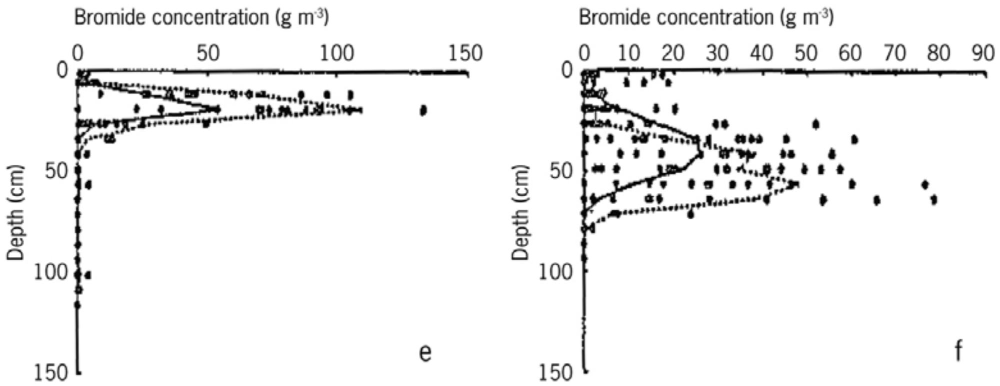


Figure 5.2
Concentrations of bromide ion in the Vredepeel humic-sandy soil measured at 22 and 42 days after application on 22 November (Ritsema and Dekker, 1995).

A pulse of chloride ion was sprayed on a cultivated sandy soil with a highly variable thickness of the B horizon (Van Wesenbeeck and Kachanoski, 1994). The depth of the transition between the B and C horizons mainly varied between 0.5 and 1.5 m depth, typically at horizontal distances of 1 to 1.5 m. The field plot was trickle-irrigated with 131 mm of water (rate of about 40 mm/d; position of the tricklers was changed at random). Soil cores were taken in the walls of trenches and analysed for chloride ion. Chloride transport in the B horizon tongues (concentration peak at 0.85 m depth) was distinctly deeper than that in the no-tongue C-horizon areas (concentration peak at 0.55 m depth). It was concluded that the tongue areas are the zones of preferential water flow and substance movement in the soil profile. Possible causes were a textural transition (thin Bt clay-enrichment horizon) and differences in hydraulic conductivity.

A soil monolith of loamy-sand soil (1 m high; 0.8 m diam.) was taken in a cylinder and placed on a column of sand (0.8 m high; unsaturated outflow) (Vanclooster et al., 1995). A pulse of chloride ion was applied to the soil surface of the monolith, after which rainfall was simulated at a rate of 10 mm/day. The concentrations of chloride in soil solution at various depths (breakthrough curves) were measured by TDR probes installed horizontally into the monolith. Some of the chloride moved very rapidly to a depth of about 0.7 m in soil (Figure 5.3). Below that depth, breakthrough of chloride started later. After five days with 50 mm of simulated rainfall, 35% of the applied chloride ion had moved below a depth of 1.8 m. The authors concluded that preferential water flow and solute transport occurred in the loamy-sand soil.

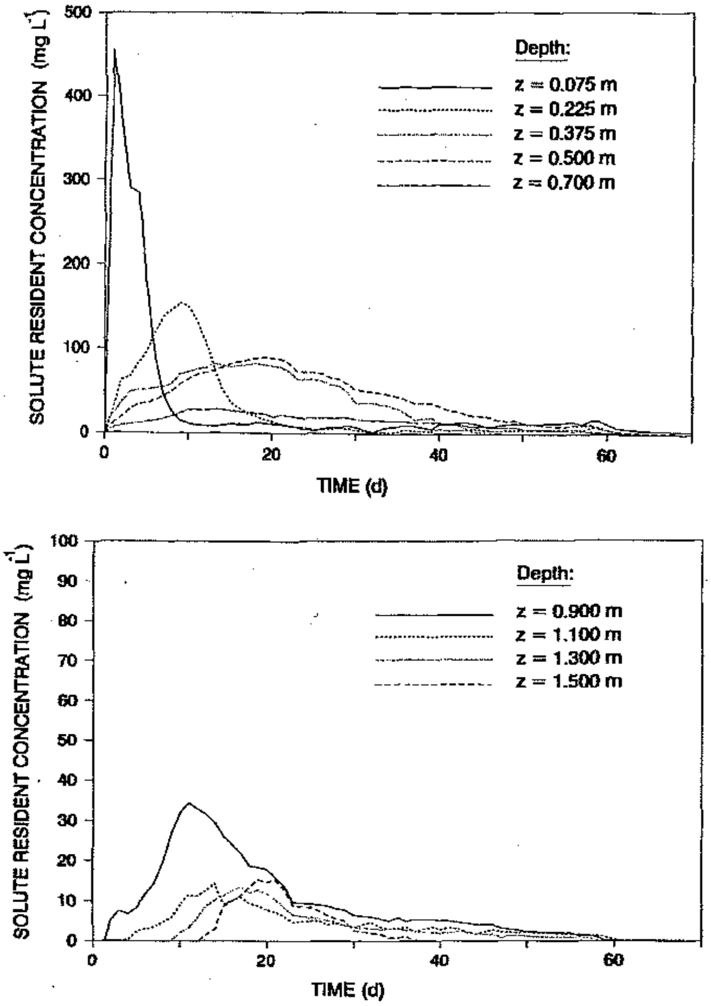


Figure 5.3
Chloride breakthrough curves measured by TDR probes at various depths in a loamy-sand soil monolith (Vanclooster et al., 1995; ©SSSA, with permission).

Bromide ion was sprayed on a fine-sandy soil in strips along orange-tree rows in an orchard (Florida) in June (Foussereau and Graham, 1997). Cumulative rainfall in the 57-days soil sampling period was 290 mm. Bromide ion roughly moved as a wave through the soil profile, with a wide variation in concentration at the measuring depths. The spreading of bromide distribution with depth in the soil was great. The amount of bromide measured in the soil profile at the sampling times (six cores) was highly variable, presumably due to its heterogeneous distribution in soil. The time of arrival of bromide ion in the groundwater and the concentration levels in this water (in sampling period of 700 days) were highly different for the two sampling tubes in the treated area.

A large number of soil columns was taken from the 5 to 15 cm layer of two arable fields with sandy-loam soil (23 columns) and loam soil (35 columns) (Lennartz et al., 1997). In the laboratory, the leaching of a short pulse of bromide ion through each of the columns (diameter 5.7 cm) was measured under simulated rainfall (four needles; flux around 8 mm/day). A pressure of minus 30 hPa was maintained under the suction plate at the bottom of the columns (unsaturated flow). About three quarters of the soil columns delivered classical breakthrough curves for bromide-ion, be it with a substantial fraction of stagnant water (Figure 5.4). The other one-quarter of the soil columns showed early breakthrough of bromide-ion, with the peak at about 0.2 pore volumes of effluent, due to preferential flow.

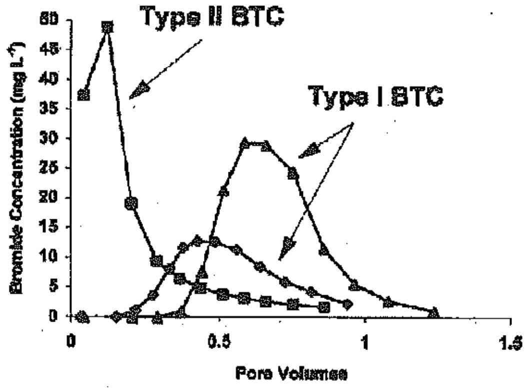


Figure 5.4
Measured breakthrough curves of bromide ion: Type I = classical breakthrough; Type II = preferential breakthrough (Lennartz et al., 1997).

Bromide ion was sprayed on the surface of two field plots with loamy-sand soil (Jene, 1998). At 182 days (with 367 mm rainfall) and 308 days (with 743 mm rainfall) after spraying, soil cores were taken to a depth of 1.3 m. The ten (Plot 1) and five (Plot 2; combination of two subsamples) measured concentrations per depth were highly variable. After 308 days, the amount of bromide ion measured in the separate cores ranged from 4% to 75% of the dosage. It was concluded that much lateral redistribution had occurred from a rather uniform distribution in the top layer to a highly non-uniform distribution in the deeper layers.

A solution of bromide ion was sprayed on an arable field with loamy-sand soil (South-West Sweden) in October (Larsson et al., 1999). The application was measured to be rather uniform. Long soil cores (0.9 m) were taken at three times after application, until March. The concentration of bromide ion per measuring depth showed a wide range. The amount of bromide ion measured per soil column (after 28 mm of rainfall) was much more variable than the application at the soil surface. This indicates that there was lateral redistribution of the bromide, at or near the soil surface, to preferential flow paths in the soil profile. One of the possible mechanisms was redistribution at the soil surface due to water repellency and flow to micro-depressions.

Soil columns (on average 20 cm long, 15 cm diam.) were taken from sandy Ap and E horizons and used in leaching experiments in the laboratory (Shaw et al., 2000). A pulse of bromide ion was applied and steady-state water flow was maintained (no details). Solute transport parameters were estimated by evaluating the breakthrough curves with models. The sandy soil columns had a high ratio of mobile/total volume fraction of water (on average 0.86). The rate of exchange of solute between the mobile and immobile regions was rather high. Preferential water flow and bromide transport were smaller in the sandy horizons than in more loamy/clayey (deeper) horizons in the same soil profile, with e.g. subangular structure.

Multi-compartment solution samplers (32.5 x 32.5 cm) were installed horizontally at 0.25 and 0.31 m depth in a field with humic-sandy soil at Vredepeel (NL) (Bloem, 2008; Bloem et al., 2009). The grass-grown soil was characterised as hydrophilic, without obvious causes of preferential flow. Under-pressure in the 100 suction cells (each 31 x 31 mm) was adjusted to the moisture pressure in the surrounding soil in the field, measured by tensiometers. Chloride solution was trickled on the soil surface with short-cutted grass (mid-December), after which the soil was exposed to natural rainfall. Water drainage from the soil was non-uniform (Figure 5.5): 25% of the drainage water passed through about 6% of the cross-sectional area. The most productive suction cells generated about seven times the mean drainage water. Leaching of chloride ion from the soil was heterogeneous (Figure 5.5). Nevertheless, chloride leaching summed for all suction cells showed roughly the form of a wave (Figure 5.6). The authors concluded that there was a great deal of chloride exchange between the stream tubes in soil, resulting in dispersion-type of transport.

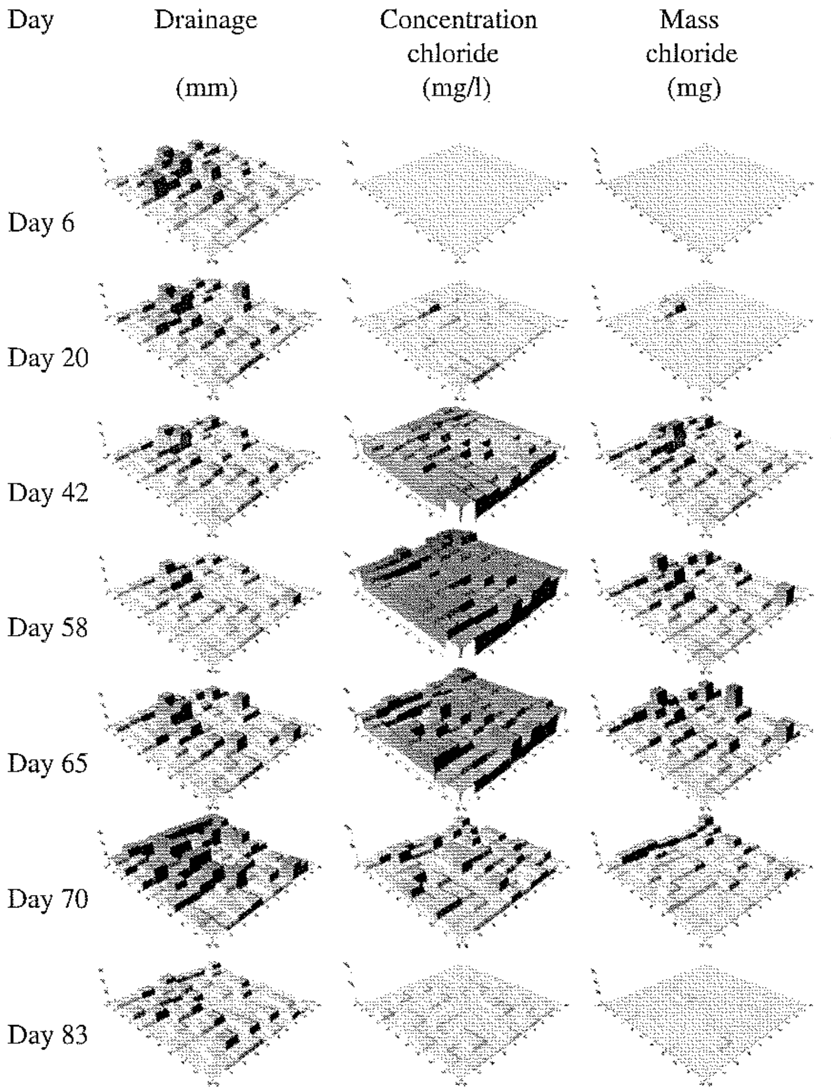


Figure 5.5
Water drainage, chloride concentration and mass of chloride collected by each of the suction cells in the multi-compartment sampler with porous-steel plate installed at 0.31 m depth. (Bloem et al.,, 2009; ©Elsevier, with permission). Series of days in the experimental (winter) period.

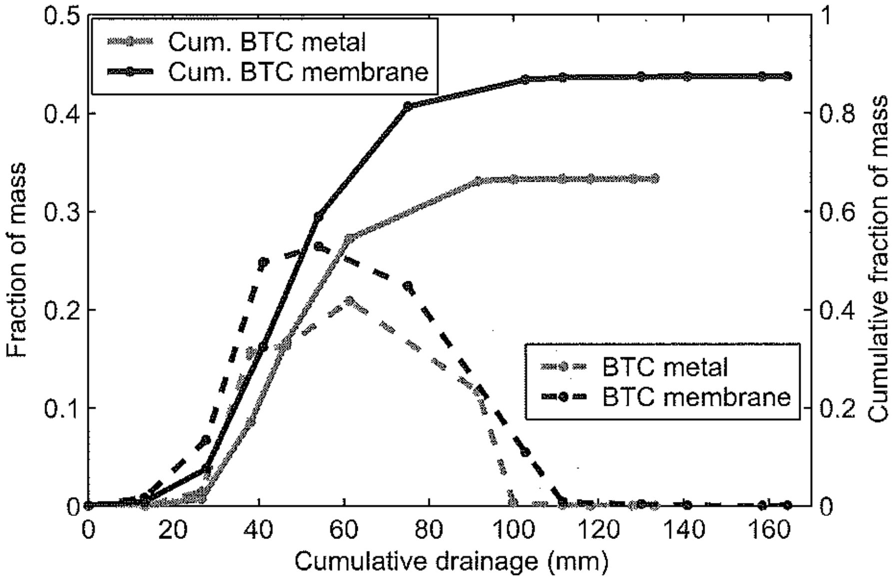


Figure 5.6
Breakthrough curves for the whole multi-compartment samplers obtained by summing the amounts of chloride collected in the suction cells (Bloem, et al., 2009; ©Elsevier, with permission). Porous-metal plate at 0.31 m depth and polyamide membrane at 0.25 m depth.

5.3 Pesticides

The herbicide napropamide was applied to the surface of a regularly-cultivated field with loamy-sand soil (0.5 to 1.0% organic matter) in August (Jury et al., 1986). The field (California) was first sprinkler-irrigated (5 mm/hour) with 30 mm of water (shortly after spraying) and subsequently with 230 mm of water (daily applications during two weeks). At the end of this period, the soil was sampled by coring down to 3 m depth. The highest concentrations of napropamide (rather strongly adsorbed) were measured in the top 0.1 m of the soil profile (Figure 5.7). However, a fraction of the herbicide penetrated to greater depths with peaks at e.g. 0.8 m, while the maximum penetration depth was 1.8 m. It was concluded that preferential water flow and herbicide transport occurred in this profile without visible macropores.

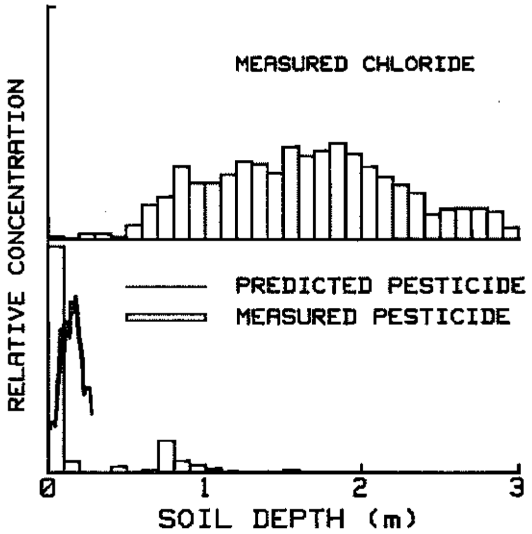


Figure 5.7
Movement of the herbicide napropamide in a loamy-sand soil profile (Jury et al., 1986). Line = movement estimated from the combination of chloride movement and adsorption of napropamide.

In a field study on loamy-sand soil (0.68% organic C in top layer), the herbicides bromacil, napropamide and prometryn were sprayed on bare plots of 1 m^2 (Jury et al., 1988). The plots were sprinkler-irrigated for several hours per day to a total of 100 or 180 mm of water. Bromacil (weakly adsorbed) moved in a kind of wave through the soil profile (Figure 5.8). This movement tended to be greater than simulated with a computation model. The highest concentrations of napropamide and prometryn (both rather strongly adsorbed) were still present in the top layer. However, a fraction of these herbicides moved to greater depths. The latter movement was much deeper than simulated by the model. A 3-day delay of sprinkler irrigation after spraying did not have a distinct effect on the movement of the herbicides.

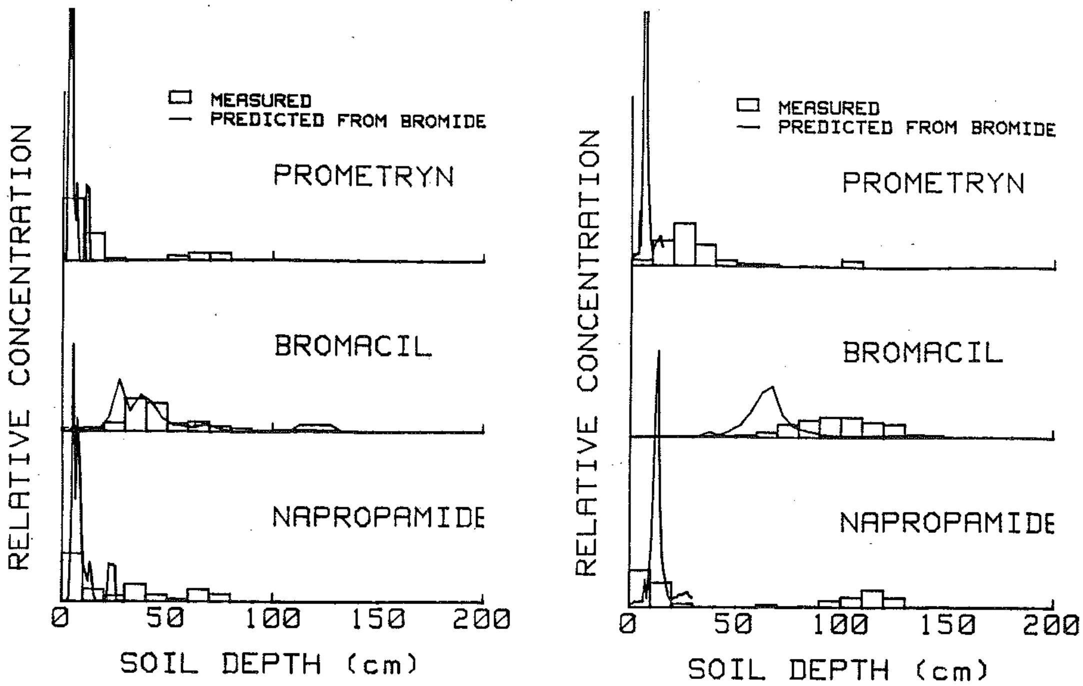


Figure 5.8
Movement of three herbicides in a loamy-sand soil after 100 mm (left) and 180 mm (right) of sprinkler irrigation (Jury et al., 1988).

Bromide ion and atrazine were sprayed on the bare surface of loamy-sand soil plots (0.71% organic matter; unstructured) in California, which were irrigated by one of three methods (Troiano et al., 1993). The three levels of irrigation were in the range from 190 to 560 mm and these were applied in a period of about 40 days. After this, the soil was sampled (four cores per plot) in 0.15 cm increments to a depth of 3 m. The extent of movement of the substances was lowest for sprinkler irrigation, intermediate for basin irrigation and highest for furrow irrigation (the latter with water flow through only half of the plot surface). The substances moved to greater depths as more water percolated through the soil profile, as expected. Bromide ion moved in a broad wave through the soil profile. In most cases, atrazine was distributed throughout a large fraction of the sampled soil profile (3 m deep).

The movement of bromide ion and three herbicides in a loamy-sand soil and in a silt loam soil (Switserland) was studied by Flury et al. (1995) in bare cultivated fields. The cumulative amounts of sprinkler irrigation were: 30 mm (after eight hours), 60 mm (day 2) and 90 mm (day 3). In the loamy-sand soil, the substances showed chromatographic (matrix) transport behaviour in the top 0.3 m of the soil profile (Figure 5.9). Herbicide movement was greatest for the most weakly adsorbed triasulfuron. It was lower for atrazine and terbuthylazine, which are moderately adsorbed. In the silt-loam soil, on the contrary, there was deep and irregular movement of the substances, to a maximum of e.g. 1 m depth, due to preferential transport through macropores. In this soil too, herbicide movement decreased in the sequence triasulfuron > atrazine> terbuthylazine, thus movement was lower as adsorption to the soil was greater.

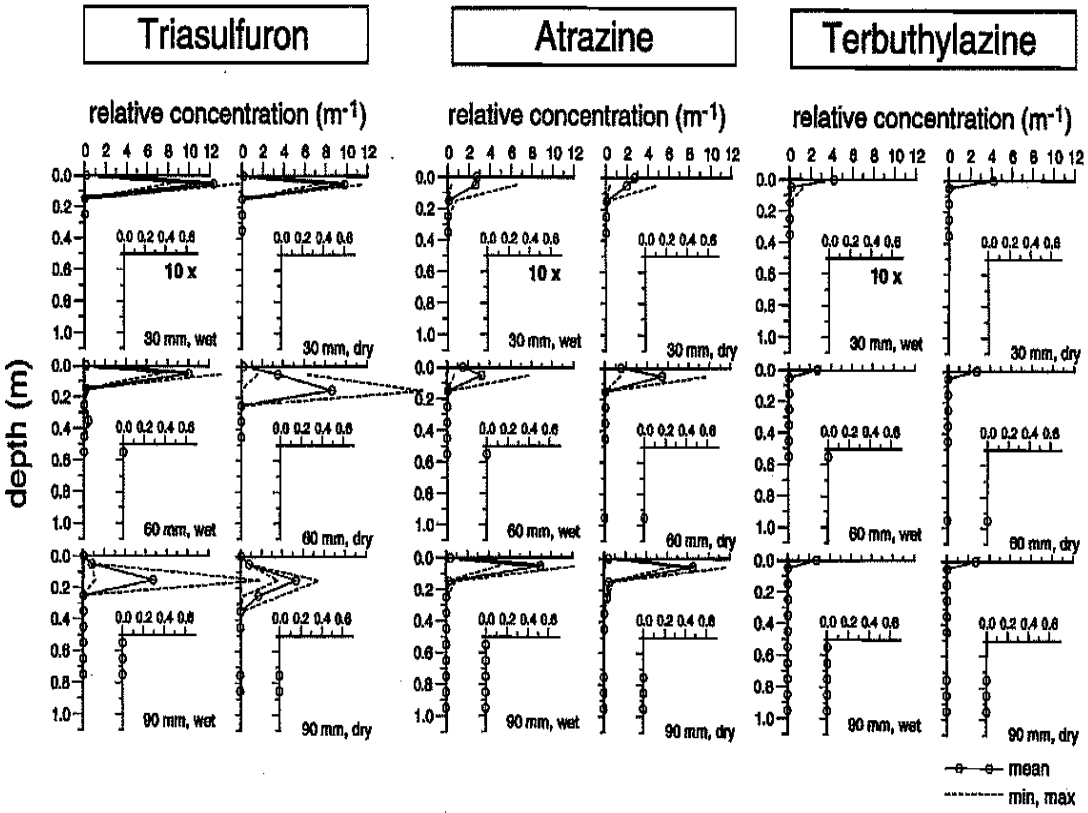


Figure 5.9
Concentration of triasulfuron, atrazine and terbuthylazine versus depth in a loamy-sand soil under sprinkler irrigation (Flury et al., 1995). Initially wet and dry soil condition. The insets show the concentrations at depths 0.5 - 1.1 m in ten-fold resolution.

Two soil columns were taken from each of the A-horizon and B-horizon of a loamy-sand-on-sand tree-nursery soil (Meyer-Windel and Lennartz, 1995). After application of bromide ion and some herbicides to the soil surface, the columns were subjected to steady-state or transient simulated rainfall. Steady-state water flow through the soil columns of both horizons caused the convection-dispersion type of transport (roughly in a wave) for bromide ion, atrazine and chlortoluron. With transient water flow through the A-horizon columns, bromide ion, isoproturon and terbuthylazine were detected already in the first mm of leachate. It was concluded that preferential water flow and solute transport occurred. The adsorption of the herbicides retarded the breakthrough of the subsequent part of the distributions in the columns.

The transport of bromide ion and simazine in an undisturbed loamy-sand soil block (0.5 to 0.7% organic C) was studied by Poletika et al. (1995). A grid of 64 capillary-wick solution samplers (0.5 m long) was installed in a horizontal cross-section of 0.8 x 0.8 m, at 0.3 m depth below the soil block. Bromide ion and simazine were sprayed on the soil surface, after which the soil was sprinkler-irrigated at about 20 mm/day for 10 days (total of 197 mm). The breakthrough curve of bromide ion had the form of a wave and could be simulated by a convection-dispersion transport model. Only small amounts of simazine leached from the soil block. At the end of the experiment, simazine was distributed as a wave with depth in the soil block. It was concluded that substance movement in this soil did not show characteristics of preferential transport.

Lennartz (1999) took 99 soil cores (diam. 5.4 cm) from the 5 to 15 cm layer in an annually-tilled field with sandy-loam soil. After applying bromide-ion and two herbicides, the columns were trickled (four needles) at a rate of 5.8 mm/day. Water flow from the columns was collected at minus 30 hPa (unsaturated flow) and the breakthrough curves were measured. Seven of the 99 columns showed preferential bromide transport, with the peak appearing at about 0.2 pore volumes of effluent. The peaks of isoproturon and terbuthylazine also appeared early from these columns (Figure 5.10). Most of the peaks of bromide in the effluent appeared after about 0.55 pore volumes of effluent (matrix transport, with an immobile domain). Most peaks of isoproturon appeared at 2 to 3 pore volumes of effluent. Terbuthylazine (most strongly adsorbed) was retained to the highest extent in the matrix-flow columns. When a second experiment was done with the columns, the same type of transport (preferential or matrix) was found as in the first experiment.

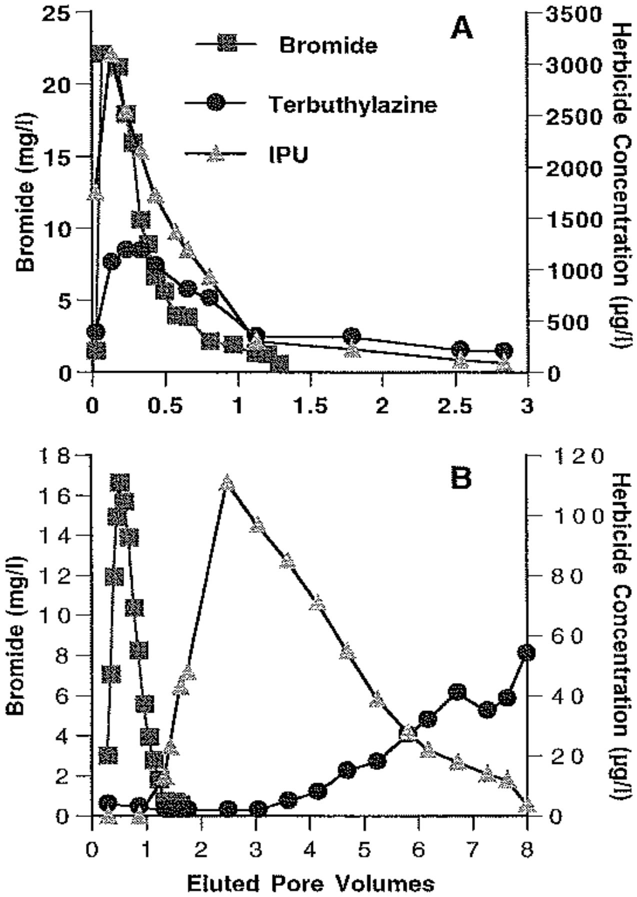


Figure 5.10

*Breakthrough curves measured for bromide-ion, terbuthylazine and isoproturon leached through soil columns taken from of the 5-15 cm layer of a cultivated sandy-loam soil (Lennartz, 1999; ©Elsevier, with permission). **A**. Preferential transport. **B**. More chromatographic transport, with a fraction of stagnant water.*

The herbicide bentazone was sprayed (22 November) on the surface of a humic-sandy soil (Vredepeel NL), recently sown with winter wheat (Boesten and Van der Pas, 2000). The weather and soil conditions on the experimental field were monitored in detail. The soil profile was sampled down to about 1 m depth, at four times in a period of 1.3 years. In each of the four field sectors, four soil cores were taken and the samples per depth were combined (so four samples were analysed per depth and per time for the whole field). In the first winter period, bentazone already showed substantial downward movement in the soil profile, with presumably some leaching below 1 m depth. The ranges in the concentration of bentazone measured per depth were very wide (Boesten and Gottesbüren, 2000), indicating that transport occurred in a complicated way.

5.4 Consequences for soil and soil solution sampling

Preferential transport presents problems with respect to representative sampling of the soil solution. The concentration measured by suction sampling per depth was highly variable (Kung et al., 1990b; from Brasino, 1986, unpublished PhD thesis). Aldicarb was measured earlier and at higher concentrations in the deeper groundwater than in the less deep soil solution (suction sampling). Further, the concentration in groundwater was highly variable.

A field plot of loamy-sand soil was scanned by ground penetrating radar (GPR) to map the location of layers in the soil profile (Kung and Donohue, 1991). Four suction samplers were installed in the water-unsaturated zone at 1.85 m depth, at the lower end of inclined layers. Another four suction samplers were installed at random at 1.5 m depth. Bromide-ion was sprayed uniformly on the bare soil surface, after which the plot was sprinkler-irrigated twice a week (amount not given). Soil solution samples were taken twice a week in a 80-day period and the bromide concentrations were measured. The samplers installed at the lower end of inclined layers using the GPR scans yielded greater water volumes and higher bromide concentration peaks than the samplers installed at random. Presumably, fingered water flows were intercepted by the interface of inclined layers and funnelled to their lower end.

When taking soil samples via coring, highly different concentrations are encountered at a specific depth. The pattern was illustrated by Flury (1996) in a picture (Figure 5.11). Soil corings at two positions in a heterogeneous pesticide distribution yields highly different results per depth and an irregular course of the concentration with depth. Concentrations moving locally to greater depths in the soil can be easily missed by soil coring.

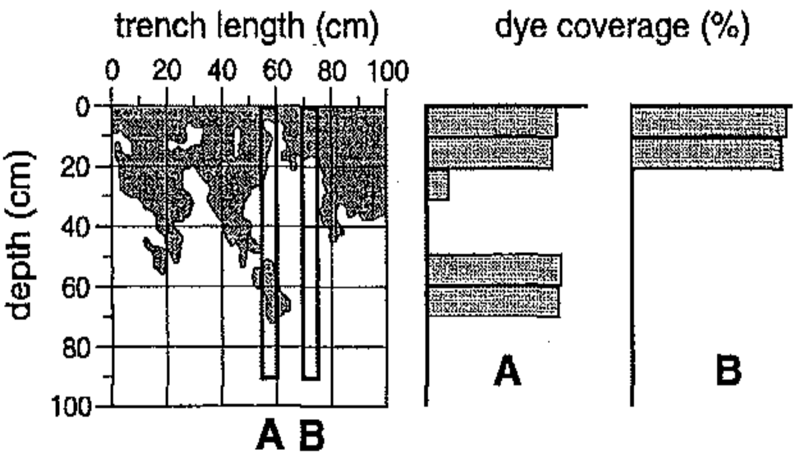


Figure 5.11
Effect of the heterogeneous distribution of a dye on the depth profile obtained by soil coring (Flury, 1996; ©ASA, with permission).

5.5 Discussion and conclusions

The heterogeneous water flow and substance transport in soil present problems with respect to representative soil and soil solution sampling in the profile. There is a wide variation in measured concentration per depth, irrespective of the number of samples taken. Localised pathways of preferential flow and transport can be easily missed in soil and soil solution sampling.

When sandy soils are sampled by coring, the measured distribution of the substance with depth in the soil may have roughly the form of a wave. However, the range of the concentrations measured at a certain depth within the wave area is often very wide. At some locations in the soil profile, hardly any substance is present or the concentration is even zero. In the infiltration stage, this is often accompanied by a low volume fraction of water at these locations (Chapter 4). This indicates that water flow and substance transport in sandy soils proceed very heterogeneously. There is a pattern of local pathways of preferential flow and transport, while other parts of the soil profile are by-passed.

A substance may move roughly in a wave through the soil profile. Besides a wide spreading in the concentration per depth, there is often a wide spreading of the distribution with depth in the soil. The question rises then whether the average movement can be described by a chromatographic-transport model based on the convection-dispersion equation. Possibly a high value has to be taken for the dispersion length. One should realise that such a simulation test deals with the measured part of the distribution in the soil profile and that preferential transport can have been missed by the soil sampling.

The horizontal distribution of a substance in the soil profile, as derived from the amounts measured per soil core, is often much wider than the variation in substance application at the soil surface. This indicates that a lateral (horizontal) transport component exists to localised (preferential) flow and transport paths. Breakthrough curves measured for many soil columns from the top layer of a field confirm the existence of places in soil where fast preferential flow and transport can occur.

There is an interesting relationship between the build-up of the soil profile on the one side and water flow and substance transport on the other hand. As the result of sedimentation, many soils consist of layers with different texture. Silty/clayey layers may have a low water permeability. Such layers are often inclined and they are disturbed at some places. Soil-forming processes may have led to (additional) layering, e.g. different types of B horizon (enrichment of e.g. clay, iron oxides, humic substances). Such layering can show an erratic pattern and the layers can be locally disturbed. Man-made layers, like a dense plough layer, may also have an effect on the flow and transport pattern. Soil profile descriptions are very useful for the interpretation of the results of transport studies. Unfortunately, such descriptions are seldom included as part of a field study.

In some studies, substance transport showed a distinct bimodal pattern. A fraction of the substance moved rapidly along preferential flow paths, while another fraction moved slowly through the soil matrix. The separation of these fractions showed up most clearly for substances showing distinct adsorption and it was induced by high sprinkler-irrigation rates.

Heterogeneous water flow and substance transport in the soil profile can result from processes at the soil surface. Examples are stemflow and leafdrip (Chapter 2), differences in infiltration capacity at the soil surface (Section 3.3) and water flow along the soil surface to microdepressions (Section 3.4). High precipitation intensities can be expected to promote the onset of heterogeneities in flow and transport at the soil surface.

In some of the studies, water flow and substance transport in the cultivated (level) sandy top layer were quite uniform. Heterogeneities in flow and transport may then start below the cultivated top layer.

6 Measured outflow (flux) concentrations

6.1 Introduction

Reviews were presented on pesticide and tracer transport to subsurface tube drains in humid regions of North America (Kladivko et al., 2001) and in Europe (Brown and Van Beinum, 2009). Nearly all field studies had been carried out for heavier **loamy and clayey** soils containing macropores (cracks, biopores). In the present chapter, the emphasis is on leaching of pesticides through cultivated **sandy** soils, e.g. to the subsurface drainage systems. Main objective is to get information on the way pesticides are transported in sandy soil profiles.

6.2 Lysimeter and column studies

The nematicide aldicarb was mixed into the top layer (9.5 cm) of a further undisturbed humic-sandy soil column in mid-May (Smelt et al., 1983). The soil columns were installed in the field under natural rainfall conditions and the outflow was collected via a filter piece at the bottom. In June, with much rainfall (107 mm), low amounts of the weakly-adsorbed oxidation products of aldicarb (corresponding to 0.03, 0.04 and 0.21% of the dosage) leached from three of the six grass-grown soil columns (0.8 m long). Substantial leaching from the grass-grown columns started in December. Substantial leaching from bare humic-sandy soil columns (0.6 m long) started in July-August, when about 90 mm of water had flown from the columns. In these cases, preferential transport of the substances seemed to be restricted to a small fraction of the dosage.

Six undisturbed columns of sandy soil (diam. 0.295 m; length about 1 m) were placed in a lysimeter station (Sweden) and sown with spring barley (Bergström, 1992). The top layer of the soil contained 1.5% organic matter. In June, bentazone was sprayed on the young barley plants. Together with the supplementary sprinkler irrigation, precipitation (June to April) was 69 mm above the average. Little water drained in the growing season; drainage started in the autumn. Leaching of bentazone started by the end of August, with the first drainage water. The highest concentrations up to 4.2 µg/L were measured around the end of September. The authors suggested that preferential water flow and herbicide transport occurred in the sandy soil. In the period November to April, the concentration in the drainage water mostly ranged from 0.1 to 1.0 µg/L. Total leaching of bentazone in the period June - April was around 0.14% of the dosage.

Chloride tracer, dichlorprop and bentazone were applied in June to monoliths of a sandy-loam-on-sand soil profile (depth about 1 m; grown with spring barley) in lysimeters (Bergström and Jarvis, 1993). In two water regimes, natural rainfall (Sweden) was supplemented by irrigation, to average and worst-case water supply, respectively. Chloride started to leach from the sandy soil with average precipitation in the first effluent appearing in September. Under worst-case water supply to the sandy soil, chloride appeared after about 40 mm of water percolation and it leached roughly in a wave. Water flow in the sandy soil seemed to be more unstable under the average-precipitation condition. Dichlorprop appeared in the first leachate from the sandy soil in September, both for average and worst-case water supply. It was concluded that preferential water flow and substance transport occurred in the sandy soil profile. However, preferential movement was less pronounced in the sandy soil than in a clayey and in a peaty soil. Leaching of dichlorprop from sandy soil was higher at the worst-case water supply, as expected. In case of the sandy soil, bentazone in the percolation water for average water supply was below detection level, while it was sometimes above this level at worst-case water supply. Preferential transport of bentazone in the sandy soil was also less pronounced than that in the clayey soil.

Undisturbed soil columns (0.8 m long, 0.2 m diam.) were taken in triplicate from two sand soils and trickled with liquids containing bromide ion, atrazine and metolachlor (Wietersen et al., 1993). Simulated rainfall of 628 mm was applied in a period of 156 days, at a rate of 7.3 mm/hour. Total drainage from the columns of the two soils was 335 and 443 mm, respectively. Distinct leaching of bromide ion started after about 30 mm of water drainage and the peak concentration appeared around 100 mm of drainage (Figure 6.1). Distinct leaching of atrazine from one of the soils started after about 200 mm of drainage, to a total amount of 5.65% of the dosage. Cumulative leaching from the other soil was only 0.08% of the dosage. Distinct leaching of metolachlor from one of the soils started after about 280 mm of drainage and cumulative leaching was 0.94% of the dosage (Figure 6.1). Leaching from the other soil was only 0.007% of the dosage. These results do not show signs of fast preferential leaching of the substances from the sand soils.

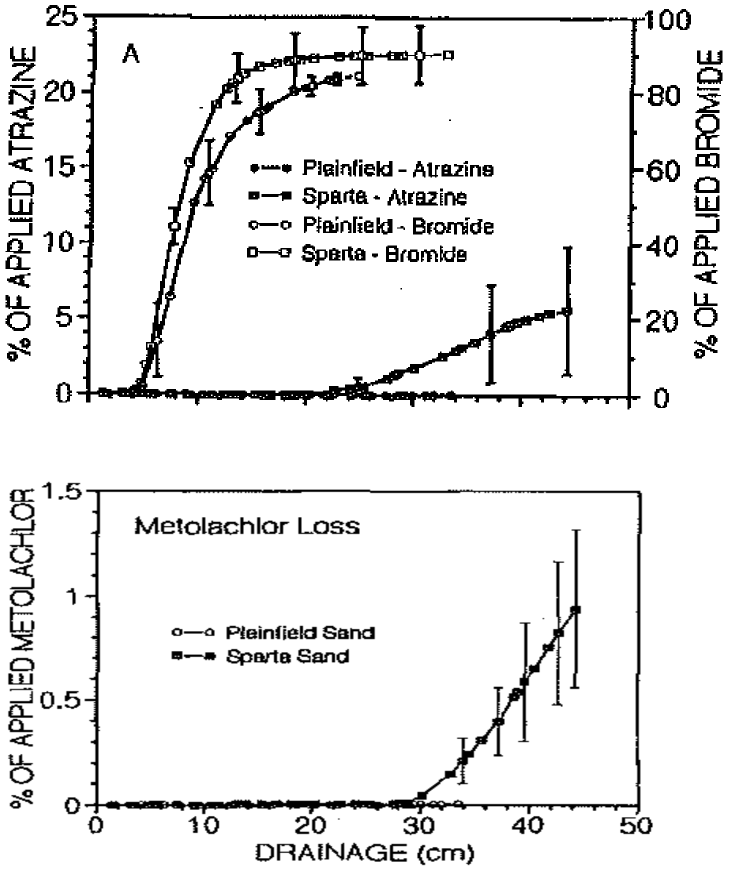


Figure 6.1
Cumulative leaching of bromide ion, atrazine and metolachlor from undisturbed columns of two sand soils (Wietersen et al., 1993; ©ASA, with permission).

Bentazone was sprayed (June) on barley-grown undisturbed monoliths of a sandy soil in lysimeters (about 0.3 m diam. and 1 m long) (Bergström et al., 1994; Jarvis et al., 1994). Deficits in rainfall (Sweden) were compensated by watering. The herbicide (weakly adsorbed) was measured already in the drainage water in the autumn. This early leaching was not simulated with the one-flow-domain option of the MACRO model, using a low value of the dispersion length. It was concluded that preferential transport of bentazone in the sandy soil occurred. The amount leached from autumn to spring corresponded to 0.15% of the dosage. Preferential transport was less in the sandy soil than in the loamy/clayey soils.

Undisturbed soil columns (length 1.1 m; diam. 0.295 m) were taken from a field with sandy soil and placed in a lysimeter station (Saxena et al., 1994). Tritiated water and chloride ion were applied in Mid-August, after which the columns were exposed to natural conditions (Sweden). The breakthrough of tritiated water and chloride occurred in the classical convection-dispersion manner, starting after about 100 mm of water had drained (Figure 6.2). The approximately symmetrical breakthrough curves could be simulated with a convection-dispersion model, although simulated breakthrough was somewhat later than measured. Correspondence was better when it was assumed that a fraction of 0.8 of the water phase in soil was mobile.

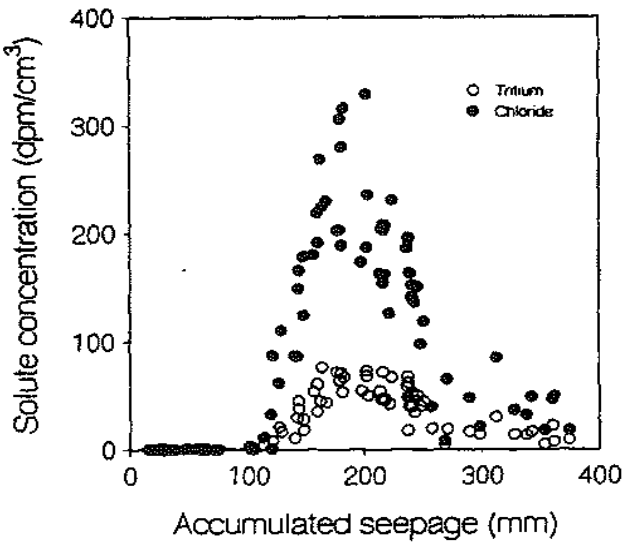


Figure 6.2
Breakthrough curves of tritiated water and chloride ion from sandy soil columns in a lysimeter station (Saxena et al., 1994; ©Elsevier, with permission).

The herbicide bentazone was sprayed (in or around April) on winter wheat grown on indisturbed monoliths of two loamy-sand-on-sand soils in lysimeters (1 m^2 surface area, 1.2 m high) (Becker-Arnold et al., 1995). Organic carbon contents in the top layer of the two soils were 0.9 and 1.5%. Rainfall on the lysimeters (at two locations in Germany) was supplemented (if needed) by sprinkler irrigation to attain at least 800 mm precipitation per year. The annual mean concentrations (in two years) of bentazone (weakly adsorbed) in the leachate were below 0.1 µg/L. The authors concluded that preferential transport of the herbicide did not occur.

Monoliths of undisturbed loamy-sand soil were collected in three cylindrical lysimeters (inner diam. 1.0 m; length 1.3 m) and placed in a lysimeter station (Germany) under natural conditions (Jene, 1998). Bromide ion and ^{14}C-labeled benazolin-ethyl were sprayed on the cultivated and leveled soil in November. Rainfall was supplemented by sprinkler irrigation to attain at least 800 mm precipitation per year. Bromide ion started to leach from the lysimeter soil at 69 days after application (Figure 6.3), with 140 mm rainfall and with 80 mm of water drained. The flux concentrations of benazolin averaged over 2 years amounted to 0.4, 1.3 and 3.8% for the three lysimeters taken from the same field. This difference was mainly ascribed to a difference in transformation rate. The transformation products of benazolin-ethyl showed little retardation effect of their (weak) adsorption on leaching.

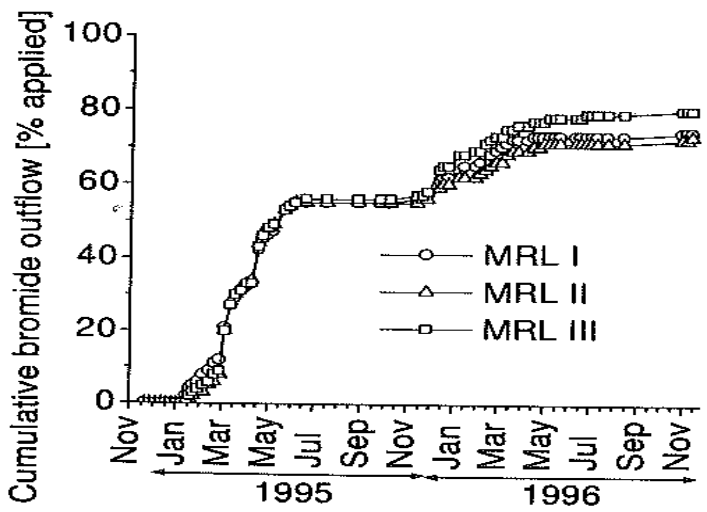


Figure 6.3
Cumulative leaching of bromide ion from loamy-sand lysimeter soil in two experimental years (Jene, 1998).

Soil columns (diam. 14.7 cm; length 29 cm) taken from a sand subsoil received simulated rainfall at steady state (Meyer-Windel, 1998). A pulse of bromide ion was applied to the top of the columns and the course in time of its breakthrough from the columns was measured. The maximum concentration in the breakthrough curve appeared distinctly before one pore volume of effluent. A fraction of 0.20 to 0.30 of the water-filled pore volume did not participate in bromide transport (immobile water).

Duplicate undisturbed soil columns (0.8 m diam., 1.05 m long) were taken from four mineral soil types in arable fields and placed in a lysimeter station (Brown et al., 2000). In the autumn of two successive years the soils were cultivated to 0.15 m depth, sown with winter wheat, and then sprayed with bromide ion and the herbicide isoproturon. The lysimeters were exposed to natural rainfall (England; two springs with half the average rainfall) and the drained water was collected for chemical analysis. The sandy soil (0.7% organic C in the top layer) showed later breakthrough of bromide ion than the loamy and clayey soils. Accumulated leaching of isoproturon from the sandy soil was 0.04 and 0.07% of the dosage, respectively, which was lower than leaching from the loamy/clayey soils. The results showed the effect of more preferential substance transport in the loamy/clayey soils with a distinct pattern of cracks.

6.3 Grid of suction cells

A suction-cell plate (0.64 m^2, 25 suction cells) was installed horizontally at 1.1 m depth underneath a sandy-loam soil (crumb structure; no details) (Trapp et al., 1995). Total simulated rainfall on the soil was 153 mm in 25 days, while 48 mm of drainage water was collected by the suction cells (pressure minus 20 hPa) in 30 days. Spatial distribution of water outflow was heterogeneous; about 50% of the outflow was collected in 20% of the total suction area. The water outflow per cell ranged from < 2% to 500% of the mean cell outflow. Bromide ion eluted in an heterogeneous pattern to a total amount of 1.1% of the dosage. The herbicides isoproturon and terbuthylazine were detected in the outflow collected in some of the suction cells. This first appearance of the herbicides was not influenced by their adsorption to soil. In one of the suction cells, the herbicides even appeared in the first drainage water.

A horizontal grid of suction cups was installed at 1.3 m depth in a field plot of cultivated loamy-sand soil (Jene, 1998). The cups were installed via the vertical wall of a trench, in the ceiling of a frame placed via a window in the wall. Bromide (as water tracer) and benazolin-ethyl (herbicide; ^{14}C labeled) were sprayed in November, in a circular plot on the cultivated and leveled soil surface. Rainfall was supplemented by sprinkler irrigation, up to at least 800 mm precipitation per year. The grid of suctions cups allowed spatial sampling of water ouflow and substance elution from the soil. Water outflow showed a large spatial variability in the collection area: ratios between extreme fluxes were at least an order of magnitude (Figure 6.4). The elution of the substances occurred at certain locations (hot spots), which indicated that water flow and substance transport were funneled in the soil profile. In most cases, the substances were collected in the main collection area below the application area, but in one case there was much elution outside the application area. More than half of the ^{14}C-labeled organic substances eluted in less than 20% of the main collection area (underneath the application area) and more than 90% in half of the main collection area. Although there were dominant outflow and elution locations in the collection area, the elution pattern changed somewhat in time (with variation in water percolation rate).

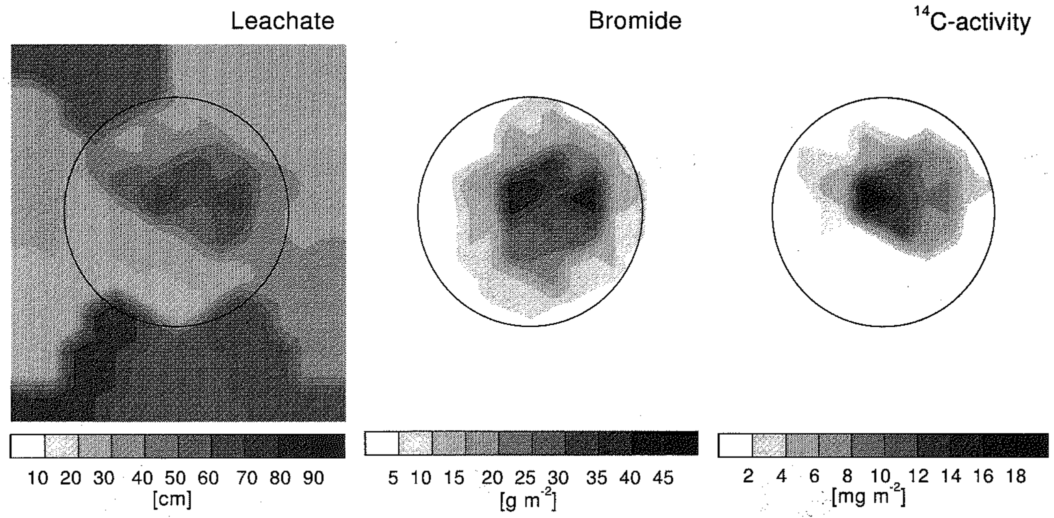


Figure 6.4
Spatial distribution in the suction-cup collection area at 1.3 m depth of: (left) the outflow water, (middle) the elution of bromide ion, and (right) the elution of ^{14}C-radioactivity originating from the ^{14}C benazolin applied (Jene, 1998). Circle encloses main collection area underneath the application area.

An intact soil monolith (1 m long, 0.8 m diam.) was taken from two sandy spodosols developed under wet (shallow water table) and dry (deeper water table) conditions, respectively (Seuntjens et al., 1999). The monolith was placed on a drainage base consisting of ten grid cells, each drained by a capillary sampler. A pulse of chloride ion was applied to the soil surface, after which water was applied at a rate of 10 mm/day. Highly different breakthrough curves were measured with the grid cells, especially for the 'wet' spodosol (Figure 6.5). Chloride measurements by TDR within the soil profiles indicated that heterogeneity in transport increased from the spodic B-horizon downwards. Averaging the breakthrough curves for four grids cells underneath the 'wet' spodosol even resulted in a double peak in the effluent (Figure 6.5). The transport patterns were determined to a large extent by the morphological properties of the two spodosols.

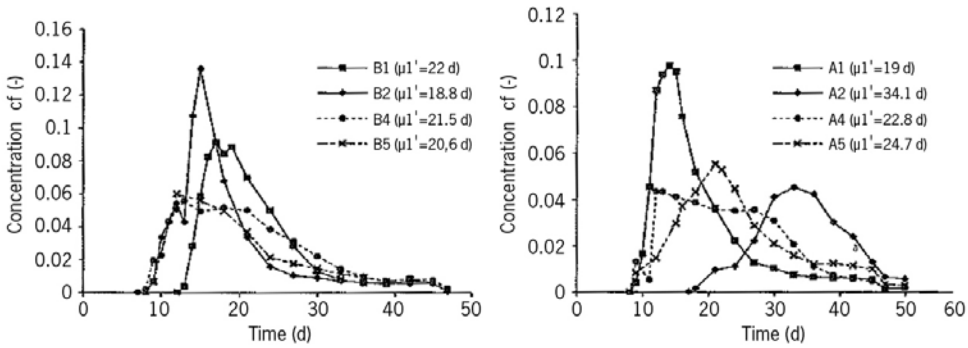


Figure 6.5
Breakthrough curves of chloride ion from undisturbed spodosol monoliths measured with different grid cells (Seuntjens et al., 1999; ©WAP, with permission). Left: for spodosol formed with deeper water table; right: for spodosol formed with shallower water table.

6.4 Field studies

Bromide-ion was applied (December) to a strip of bare arable land with loamy-sand soil (Hulselse Beek catchment, NL) exposed to natural rainfall (480 mm in 190 days) (Van Ommen and Dijksma, 1988; Van Ommen et al., 1989a). The field was tube-drained at a depth of around 1 m. The water flowing from the drains (370 mm in 190 days) was analysed for bromide. In the first half-year, 53% of the bromide dosage was measured to appear in the tile drain effluent (Figure 6.6). The shape of the effluent curve indicated that bromide transport was rather uniform in a top layer of the soil, while preferential transport occurred in the layers below.

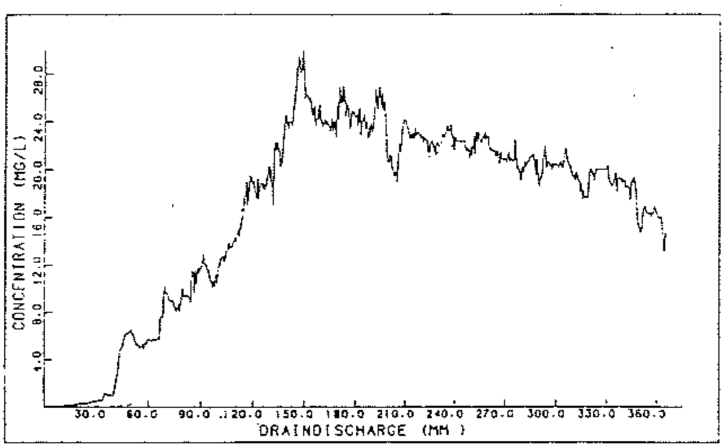


Figure 6.6
Concentration of bromide ion in tube-drain water from a loamy-sand soil as a function of drain discharge (Van Ommen and Dijksma, 1988).

In the autumn, isoproturon and pendimethalin were sprayed on fields (Germany) with humic-sandy soil and silt-loam soil (Traub-Eberhard et al., 1995). Cumulative rainfall on the sandy soil was about 171 mm in the study period (November to April). The plots were tube-drained at a depth of around 0.9 m. Drainflow was measured and the water was sampled for chemical analysis of the herbicides. Isoproturon appeared in the drainflow from the humic-sandy soil (fallow) at 2 months after application, at low concentrations. Cumulative drainflow in the winter period was only 3.3 mm and cumulative isoproturon leaching was 0.0001% of the dosage. Pendimethalin was not detected in the drainwater of the humic-sandy soil. In the case of the silt-loam field (winter cereals; higher rainfall and drainage), the herbicides appeared in the first drainwater shortly after application in the autumn. Soil analyses confirmed that there was transport of isoproturon to the deeper layers of the silt-loam soil. In both cases, the concentrations of isoproturon in the drainwater were substantially higher than those of pendimethalin (slowly transformed), which reflects the lower sorption of the former to soils.

Bromide ion was sprayed on an arable field with humic-sandy soil, tube-drained at a depth of 1.0 m (Wichtmann et al., 1998). Following the application at the end of November (Germany), water drainage was 343 mm in the next half-year. Bromide ion appeared in the drainwater after about 40 mm of drainage and the concentration gradually increased to a first peak around 100 mm of drainage. Leaching from a loamy soil with cracks started already with the first drainflow and the highest concentrations of bromide ion were measured at the beginning. So bromide transport in the humic-sandy soil was much less heterogeneous than that in the loam soil.

A solution of bromide ion was sprayed (October) on an arable field with loamy-sand soil (South Sweden), tube-drained at a depth of 0.9 m (Larsson et al., 1999). Flow-proportional water samples were taken from the drainwater for chemical analysis. Under the rainfall conditions in winter (363 mm; October to March), about 46% of the bromide dosage was discharged via the drain water. The front part of the breakthrough curve of bromide ion appeared somewhat earlier than computed with the convection-dispersion concept applied to a one-flow-domain model (Figure 6.7). In the second simulation, the mobile-flow-domain fraction was assumed to increase from 0.7 in the top layer to 1.0 in the subsoil. This resulted in the computed front part of the bromide ion breakthrough curve to be somewhat closer to the measured breakthrough. Overall, the differences between the computed and measured breakthrough were rather small.

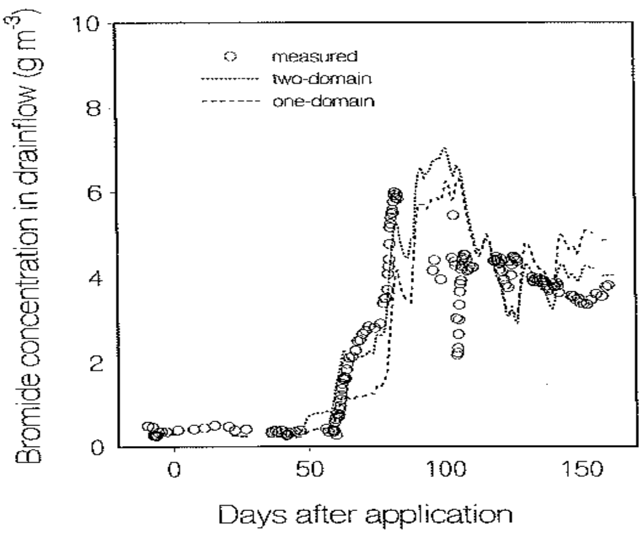


Figure 6.7
Measured and computed concentrations of bromide ion in the drainflow from a field with loamy sand soil in winter (Larsson et al., 1999; ©Elsevier, with permission).

6.5 Discussion and conclusions

Comparatively little research has been carried out on the leaching of substances from sandy soils to tube drains, as compared to the research for loamy/clayey soils. Tube drainage in sandy soils can be expected in fields under specific conditions, e.g. with layers of low water-permeability in the soil profile and/or with risk of a high water table. The latter can be the result of upward seepage or lateral flow, e.g. to land-surface depressions. In the present study, the main interest is in the information provided by the tube-drain leaching patterns on the nature of the transport of substances in sandy soils: chromatographic or preferential.

In comparative studies for different soils, preferential leaching of substances from sandy soils to tube drains was usually found to be lower than that from loamy/clayey soils. In the latter soils, the large voids (cracks, biopores) were often visible at the soil surface.

Sometimes the authors seem to conclude prematurely that preferred transport from sandy soils to the tube-drains occurred. A more definite conclusion can only be drawn if the measured leaching pattern is compared with the pattern computed with the convection-dispersion equation, using a moderate value of the dispersion length. In such computations, water flow in the soils and the water balance should be simulated adequately.

The amount of pesticide leached from sandy soils to the tube drains was often found to be low: much less than 1% (often less than 0.1%) of the dosage. Although the fast leaching was measured, the study period may have been too short to measure the total leaching of the pesticide.

The soil of an arable field can be roughly divided into a cultivated top layer and a little-disturbed subsoil underneath. It seems difficult to locate the layer(s) in which (most) preferential transport occurs on the basis of the tube-drain measurements alone.

In a comparatively new type of research, a horizontal grid of suction cups is installed in the subsoil for detailed soil solution sampling. In a study for a loamy-sand soil, water outflow and leaching of substances was highly variable (with hot-spots) in the horizontal plane. Localised lateral water flow and transport out of the application area also occurred.

Incidental measurements of (high) concentrations of pesticides in shallow groundwater, sampled via groundwater tubes, have been reported. Such measurements should be evaluated with caution for their validity, on the basis of details in the procedures. Examples of shortcomings in measurements of pesticide residues in shallow groundwater are:

– - lack of sealing around the groundwater tubes (risk of short-circuit flow);
– - spraying over the top of the groundwater tubes;
– - contamination of the samples in the procedure from sampling to analysis;
– - the use of only one method of chemical analysis;
– - poor irrigation practices on the field;
– - damage to the groundwater tubes by farm machinery.

7 Fields with ridges and furrows

7.1 Introduction

Almost all (field) experiments are carried out for soils with a rather level soil surface. In model computations, the soil surface is usually assumed to be level. Crops like potato are grown in rows on ridges build up with soil material from between the ridges, thus forming furrows. This results in a very uneven soil surface, which can have effects on water flow and pesticide transport in soil. In general, localised water flow and pesticide transport (i.c. below the furrows) increase the risk of leaching of residues to groundwater and tile-drain water (discharged to water courses). Then, much of the soil matrix is by-passed, resulting in limited time for transformation in the most bioactive soil zones.

Ridges are prepared to improve the plant root environment. The higher soil temperatures of the ridges in spring, as compared to those for a level field, promote crop emergence. In wet periods, potatoes in ridges are less vulnerable to decay due to water logging. Using furrows as driving path, the loose structure in the ridges is maintained and damage to the tubers is minimised. Ridges provide room for tuber growth and mechanical harvesting potatoes from ridges (lifting by the shares) is comparatively easy.

7.2 Water flow

The impact of the drops from rainfall and sprinkler irrigation on the soil surface can drastically reduce the rate of water infiltration into potato ridges (Agassi et al., 1989, 1993). Before crop development, much of the water flowed along the surface of the loamy-sand soil from the ridges to the furrows because of surface sealing. The ridges can be even severely eroded, with a sediment layer deposited in the furrows. Much of the water and fertiliser move comparatively fast beyond the reach of the most intensively rooted soil zone, thus causing low uptake by the crop and high leaching losses to the subsoil. Runoff from the ridges decreases in the course of the growing season, when more and more of the precipitation water is intercepted by the crop canopy.

Stieber and Shock (1995) sprinkler-irrigated a ridged potato field (silt loam soil) in the presence of a fully-developed canopy. Soil moisture distribution was measured with a grid of sensors (Granular Matrix Sensors based on electrical resistance). At the low irrigation rate used (2.8 mm/h), the soil in the top of the ridges was wetted well. However, at high rainfall/irrigation rates, a fraction of the water surface-flowed from the ridges and infiltrated into the furrows.

Patterns of soil moisture in the ridge-furrow system of a corn field (sandy-loam soil) were studied by Waddell and Weil (1996) using a grid of tensiometers. Rainfall was supplemented by sprinkler irrigation. In the presence of the corn crop, stemflow through the canopy contributed to the wetting of the top of the ridges around the stems. After corn harvest, surface flow of water from the ridges (with maize stumps) to the furrows was an important process.

Potatoes grown on ridges in a field with sandy soil were sprinkler-irrigated regularly at a very high rate (21 mm in 1.5 min), in addition to the rainfall (Robinson, 1999). Soil moisture condition at various places in soil was measured by capacitance probes and tensiometers. The irrigations hardly increased soil moisture content at 0.15 and 0.25 m depth in the ridges. During a rain storm, much of the soil in the ridges remained dry. The soil in the furrows was much wetter than that in the ridges. The difference was clearly visible: wet soil (dark colours) in the furrows and dry soil (light colours) in the ridges. Much of the water surface-flowed from the ridges to the furrows (Figure 7.1), which was promoted by the water-repellent character of the sandy soil when dry.

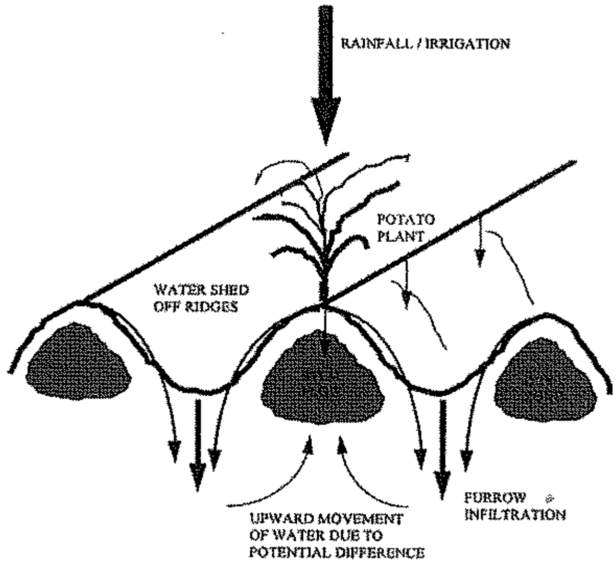


Figure 7.1
Conceptual diagram of water infiltration pathways for a field with a potato crop planted in ridges (Robinson, 1999; ©Elsevier, with permission).

A potato crop grown on ridges in a field with loamy sand soil was sprinkler-irrigated frequently in low amounts (2.5 to 13 mm) (Starr et al., 2005). Volume fractions of water at various positions in the ridge-furrow system were measured via a grid of TDR probes (Time Domain Reflectometry). The sprinkler irrigation was not able to wet the centre of the ridges: here the soil remained dry. Much of the sprinkled water flowed from the ridges and infiltrated into the furrow soil.

Moisture content and water repellency in a sandy soil were measured monthly during a rotation cycle of potatoes, maize and fallow (Keizer et al., 2007). The level of water repellency in the top layer of the ridges was distinctly higher than that in the furrows. The volume fractions of water (measured by ThetaProbe based on the dielectric constant) in the furrow soil were higher than those in the ridge soil, because a fraction of the rainwater flowed from the ridges. Water repellency of the ridge topsoil showed a large variation in time during the crop rotation cycle. As expected, water repellency was greater as soil moisture content was lower, but other factors also played a part.

Potato plants grown on ridges in a field with loamy sand soil received water by rainfall and sprinkler irrigation (27 mm/h) (Cooley et al., 2007). The volume fractions of water in the soil profile across the ridges and furrows were measured by a grid of TDR probes. The soil in the ridges was on average substantially drier than that in the furrows. There was little stem flow to the centre of the ridges, because of subsidence of the canopy later in the growing season (stems no longer erect). A fraction of the irrigation water surface-flowed from the ridges to the furrows, which was possibly enhanced by water repellency of the top layer. Further, water uptake by the denser root system in the ridge was comparatively high.

7.3 Nitrate and bromide transport

Nitrate was applied as a line source at a depth of 5 cm in ridges on a field with loamy soil (Hamlett et al., 1990). Parts of the field (not cropped) were sprinkler-irrigated at 25 mm/hour for 1, 2 and 3 hours, respectively. A fraction of the irrigation water was observed to flow along the ridge surfaces to the furrows, which made the furrow soil wetter than the ridge soil. When applied to the ridges, nitrate movement in soil was much less than movement after application to a more level field. Loss of nitrate from the top 1.2 m of the soil was estimated to be about 10% (ridges) and 50% (flat field) of the dosage. This was explained from the substantial fraction of the irrigation water flowing from the ridges to the furrows, thus by-passing the nitrate applied in the ridge. Nevertheless, nitrate moved as a plume in the ridge soil to a depth increasing with the amount of irrigation water (Figure 7.2). In spite of the high amounts of irrigation water, the highest concentrations of nitrate (not adsorbed) were still present in the top of the ridges.

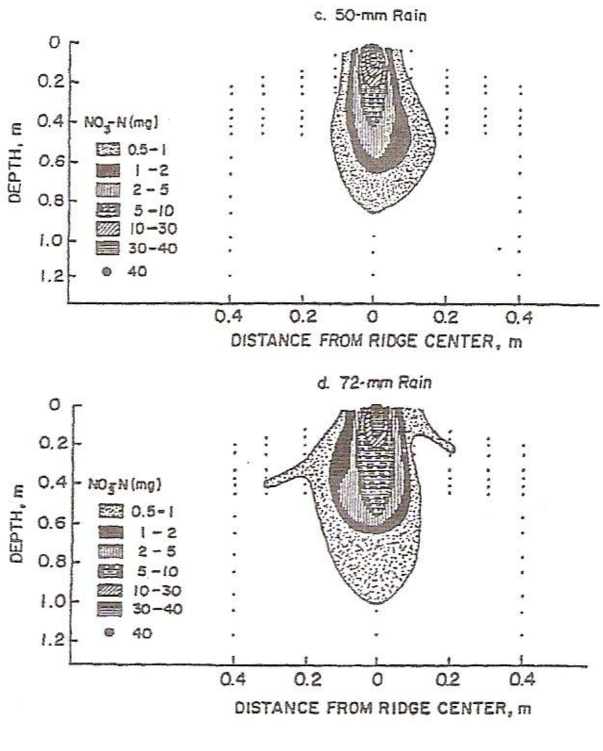


Figure 7.2

Movement of nitrate-ions applied as a line source to ridges, induced by 50 and 72 mm of sprinkler irrigation (Hamlett et al., 1990; ©ASABE, with permission).

Kung (1990a) reported about a field experiment of J.S. Brasino (unpublished PhD thesis, 1986) in which bromide-ion was applied to two sandy-soil plots grown with potatoes. On the first plot, bromide was applied to the bottom of the furrows, while on the second plot it was applied as a band over the centre of the ridges. Soil solution was collected via suction samplers at 0.9 and 1.8 m depth for bromide analysis. Bromide applied to the furrow bottom leached as a wave with peaks in the subsoil at 40 to 50 days after application. Breakthrough of the ridge-applied bromide mostly took more time (flatter waves in the subsoil). The difference was explained by a) the higher water infiltration in the furrows, b) the higher uptake of bromide by the plant roots in the ridges and c) the release of bromide from senescent plants later in the growing season.

7.4 Dye-tracer transport

Two fields with loamy-sand soil grown with potatoes on ridges were sprinkler-irrigated and the resulting water flow was studied (Saffigna et al., 1976). Stemflow of water from the potato plants was measured by collecting water via funnel-shaped collars around the stems. A substantial percentage of the irrigation water (e.g. 14 to 46%) was collected as stemflow. Water infiltration into the soil was visualised by spraying a water-soluble dye on the soil surface. There was a maximum in water infiltration into the soil around the base of the potato stems due to stem flow (Figure 7.3). Local wetting of the ridges was confirmed by tensiometer measurements of moisture pressure (less negative). Another maximum in infiltration was observed to occur in the furrows. Water surface-flowed from the ridges to the furrows, especially between the potato plants on the ridges.

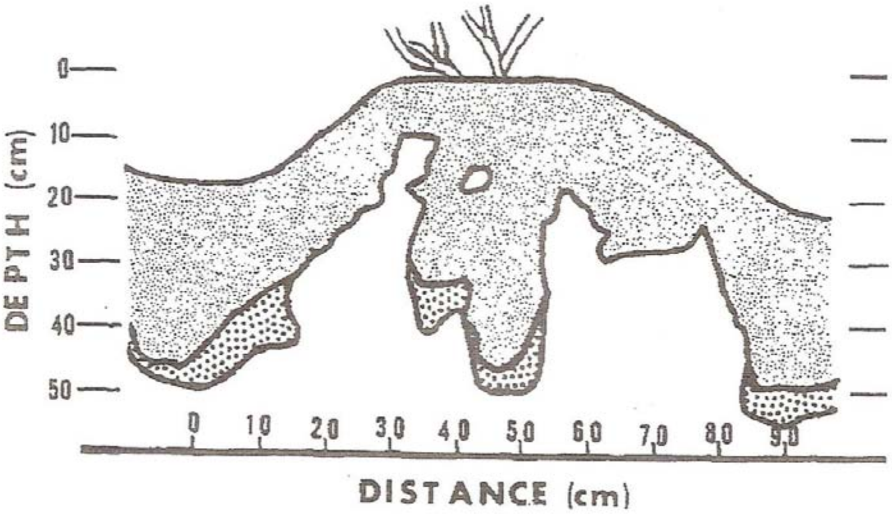


Figure 7.3
Distribution and redistribution of a dye in the ridges (loamy-sand soil) under 49-day old potato plants and in the furrows. Times: 1 day (shaded) and 4 days (stippled) after 33 mm of sprinkler irrigation (Saffigna et al., 1976; ©ASA, with permission).

Dyes were applied to the sandy soil of a potato field on the Central Sand Plain of Wisconsin (Kung, 1988). A green dye was applied to the centre of the ridges, while a red dye was applied as a band to the bottom of the furrows. Rainfall was supplemented by sprinkler irrigation. At potato harvest (2.7 months after the start of the applications), the green dye in the ridge soil had moved to a depth of 0.7 to 0.9 m. The red dye in the furrow soil had moved to 1.1 to 1.4 m depth. Unfortunately, no observations on the flow of water at the soil surface were reported.

Bromide ion and three anionic dyes were injected at different positions (10 cm deep): 1) in the top of the ridges, 2) in the shoulder of the ridges or 3) in the furrows (Jaynes and Swan, 1999). The ridges (silt-loam and loam soils) were not cropped and they were exposed to natural rainfall. The tracers in the top and shoulder of the ridges moved much less downward than the tracer injected in the furrows. This was caused by the flow of a fraction of the rainfall down the ridge slopes to the furrows.

7.5 Pesticide transport

The nematicide aldicarb was incorporated by rototillage into the top layer (0.17 m) of a field with humic-sandy soil. After this, the upper part of this layer was used for making the ridges in which potatoes were planted (Smelt et al., 1981). At some times in the growing season they measured the distribution of aldicarb and its oxidation products with depth in soil, resulting from natural rainfall. Movement of the substances below the furrows was distinctly deeper than that below the ridges (Figure 7.4). This was explained from surface-flow of rainwater from the ridges to the furrows. This process may have been enhanced by the water-repellent nature of the humic-sandy topsoil in dry condition.

Aldicarb was applied at two times in different ways to potato crops on sandy soils with low organic matter content: a) at planting in the rows and b) at emergence to the top of the ridges and covered with some soil (Wyman et al., 1985). At some times in the growing season, soil samples were taken through the treated ridges to 3 m depth. As the result of rainfall supplemented by sprinkler irrigation (total of 466 and 722 mm, resp.), the residues were distributed throughout the whole ridge-soil profile. A fraction of the residue (aldicarb sulphoxide and sulphone) moved to depths of 1 m and more in soil. At the end of the growing season, distinct residues were still present in the top of one of the two soil profiles. This indicates that the high amounts of water flowed in an irregular way through the ridge soil.

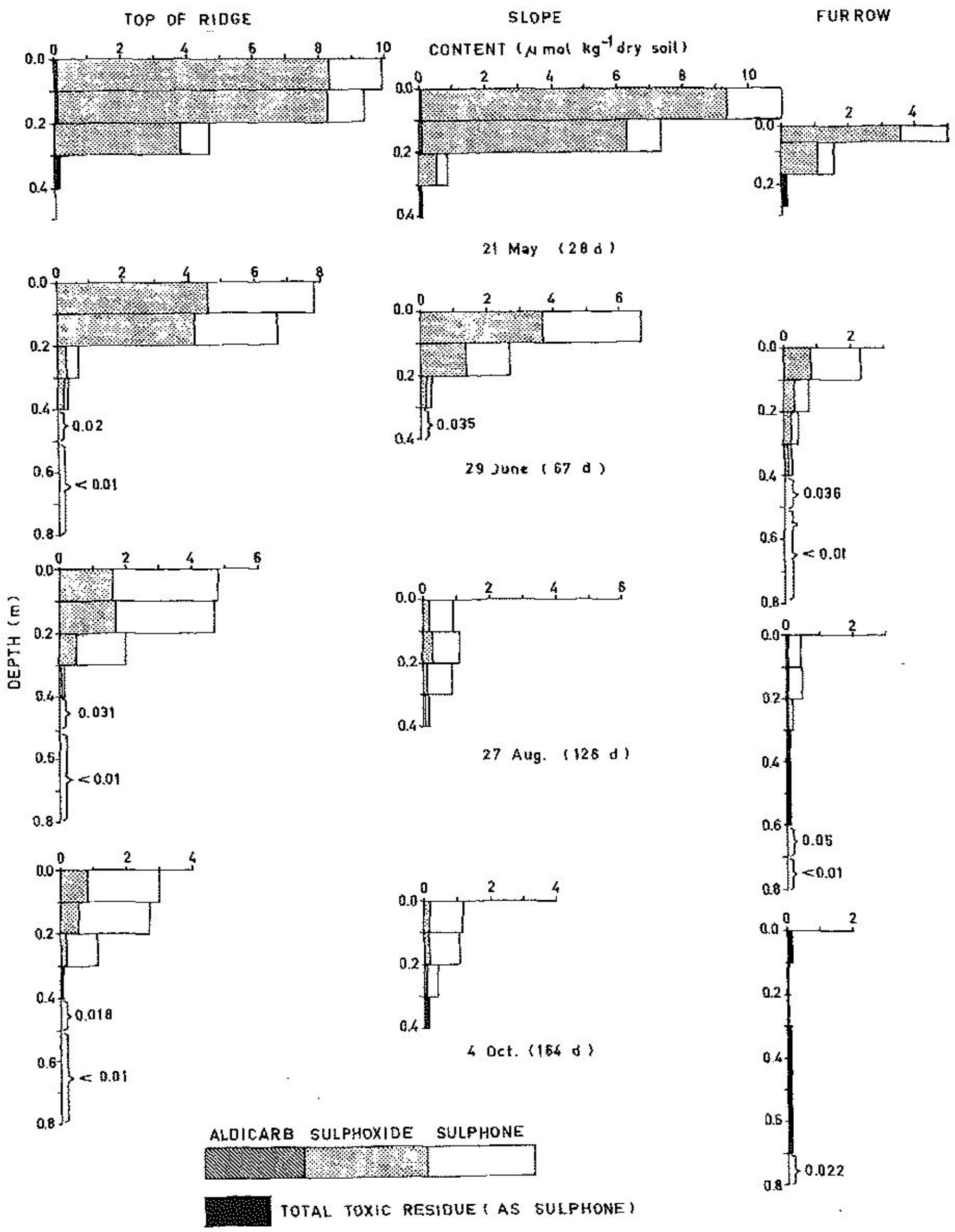


Figure 7.4

Contents of aldicarb and its oxidation products in the humic-sandy soil profile of a ridged potato field. Measured in the soil below the ridges, slopes and furrows at four times in the growing season of the potato crop (Smelt et al., 1981; ©Springer, with permission).

After planting potatoes in rows on ridges in a field with loamy-sand soil, the herbicide metolachlor was sprayed broadcast on the soil surface (Burgard et al., 1993). The field was sprinkler-irrigated in a scheme of moderate over-irrigation. Only the soil in the furrows was sampled over time, to a depth of 0.9 m. The amount of metolachlor in the furrow soil was measured to increase in the first period of about three weeks after application (Figure 7.5). This showed up in all four cases: two years, two dosages. It is likely that a fraction of the herbicide deposit on the ridges was surface-transported by the water to the furrows. It is remarkable that the authors did not realise that surface transport of a sprayed herbicide can be expected to occur in ridged fields.

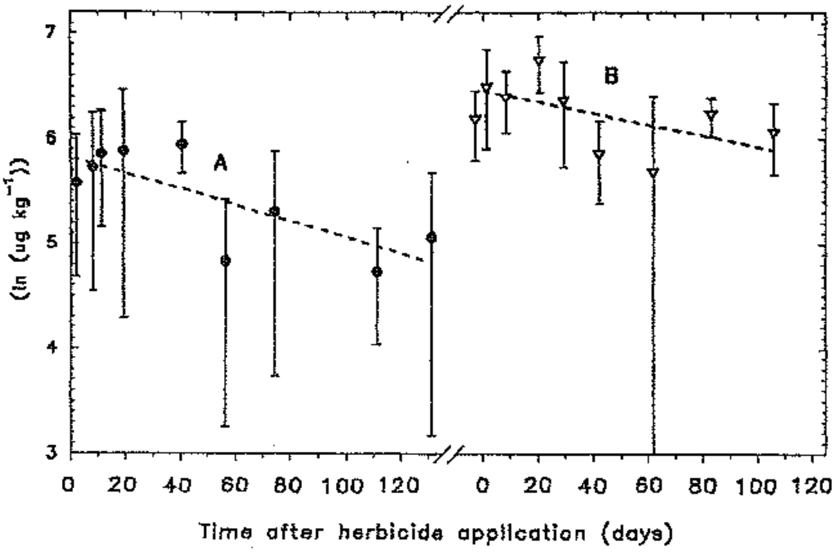


Figure 7.5
Contents of metolachlor in the 30 cm top layer of the furrows as a function of time in two cropping seasons (Burgard et al., 1993).

Prior to crop emergence, the tracer bromide ion and the insecticide carbofuran were sprayed on the humic-sandy soil of a potato field with ridges and furrows (Leistra and Boesten, 2010a). Rainfall was supplemented by sprinkler irrigation. The distribution of the substances in the soil profile of the ridges and furrows was measured on three dates in the potato growing season. The substances travelled deeper in the furrow soil than in the ridge soil, because of runoff from the ridges to the furrows. After 65 days, the peak of the carbofuran distribution in the ridge soil was still in the 0.1 m top layer, while the pesticide was rather evenly distributed in the top 0.6 m of the furrow soil. The runoff of water and pesticide from the ridges to the furrows, and the thinner root zone in the furrows, increased the risk of leaching to groundwater in ridged fields in comparison with more level fields (Leistra and Boesten, 2010b).

7.6 Discussion and conclusions

A fraction of the rainfall and sprinkler-irrigation water falling on a crop flows along certain flow paths through the canopy to the ridge soil. Some water flows along the stems (stemflow) and infiltrates around the stem base into the ridge soil. Another fraction of the water flows at certain drip places from the leaves and other plant parts (leafdrip).

Soil moisture distribution in the ridge soil can be very heterogeneous. Local infiltration occurs around the stem bases and at leafdrip places. Besides there are observations and measurements on places in the ridge soil remaining dry upon (intensive) rainfall and irrigation. Substantial movement of pesticides can occur in ridge soil, be it often to a lower extent than in furrow soil and in more level soil in the field.

Surface-flow of water from the ridges to the furrows is a common process, especially at the higher rainfall/irrigation intensities and when the soil is still bare. Surface-flowoff can be enhanced by previous drying of the top layer (e.g. of sandy soils), resulting in water repellency. A fraction of the sprayed pesticide (crop, soil) can be transported with the surface flow of water from the ridges to the furrows. The combination of

higher pesticide load and higher water infiltration in the furrows can be expected to increase the risk of pesticide leaching.
The occurrence of ridges and furrows in a field is a complication in addition to other complications that also occur at the soil surface of more level fields. Examples are 1) the local supply of precipitation water through the canopy (e.g. stemflow; Chapter 2), local water infiltration due to water-repellency of the top layer (Section 3.3) and surface flow to micro-depressions at the soil surface (Section 3.4).

The conditions in the ridge-furrow cropping system change in time. Rainfall intensity and duration, and wind speed and direction change in time. As the crop develops, the water flow through the canopy reaches the soil surface in a different way. Topography of the soil surface, soil-surface structure and soil moisture condition also change in time. Therefore it can be expected that water and pesticide are redistributed in a different way to local transport paths in the course of the growing season. This would result in some moderation of the complications in water flow and pesticide transport as compared to a permanent situation.

Actual transport of pesticides in field soils can be more complex than described by the concept of convective-dispersive transport, commonly adopted in computation models. The feasibility of modelling the movement of pesticides in ridged field soils in a realistic way should be studied. Both the process descriptions in such models and the availability of input data are important. Detailed experimental data sets are needed to develop and test such models, but up to now little research has been done in this area.

8 General discussion and conclusions

In the framework of the registration procedures, the risk of leaching of pesticides from agricultural fields to groundwater and water courses (e.g. via tube drains) has to be assessed. Often it is assumed that precipitation water flows through the whole soil body (matrix flow). The pesticide is then assumed to move as a wave through the whole soil body, with the spreading of the distribution described by the dispersion coefficient (chromatographic transport). A lot of research dealt with complications in water flow and pesticide transport in loamy/clayey soils with large voids (cracks, biopores), often visible at the soil surface. Large (visible) voids can also occur in non-cultivated soils of other textural classes. The present study deals with water flow and pesticide transport in cultivated humic-sandy and loamy-sandy soils, without large voids. On the one side the idea is that water flow and pesticide transport in these soils proceed rather uncomplicated. On the other hand, certain research results indicate that there may be large complications in such soils. In the present study, the emphasis is on the nature and extent of the complications in water flow and pesticide transport in cultivated humic-sandy and loamy-sand soils (not showing large voids).

The crop canopy has much effect on the distribution of rainfall and sprinkler irrigation over the soil surface underneath. A large fraction of the precipitation water is intercepted, after which stemflow and leafdrip lead to a high load of water on some places at the soil surface. It can be expected that water infiltration in soil is comparatively high at these places. A fraction of the pesticides sprayed on the plant surfaces can be washed-off with the precipitation water. Then places underneath the canopy with high loads of water and pesticide coincide. Flow paths through the canopy leading to locally high load of the soil surface are not directly dependent on soil type. Presumably, the pattern of water flow through the canopy is variable in time, dependent on crop development and weather conditions.

There are various potential causes of spatial variation in water infiltration at the soil surface. Heterogeneous wetting patterns resulting from the flow paths of precipitation water through the canopy have been measured in the soil. Infiltration capacity at the soil surface can be locally different because of differences in soil structure, in volume fraction of water, in water repellency, etc. The infiltration capacity tends to decrease in time due to the impact of precipitation on the soil and by soil settling. Microdepressions collect water when precipitation intensity exceeds infiltration capacity, which is followed by predominant infiltration from their bottom into the soil.

The volume fraction of water at a certain depth in sandy soils is often highly variable. This indicates that there is a pattern of wetter flow paths along which most of the water flows downward. The soil between the flow paths is comparatively dry and is wetted only slowly by lateral water flow from the flow paths. Water flow patterns were visualised by infiltrating solutions of weakly-adsorbed dyes. This type of experiment confirms that water can flow in an intricate pattern of flow paths through the soil. Water flow pattern will be affected by the textural layers formed by sedimentation in the past and by the obstacles formed later on by soil-forming processes. Detailed soil profile descriptions (often missing) are very helpful in the interpretation of the results of field and lysimeter studies. The rate of water flow out of the bottom of a soil profile (e.g. at 1 m depth) can show high local variation.

The concentration of substances measured at a certain depth in sandy soils often shows a wide variation. At the initial stages of infiltration, high concentrations can be expected to occur in the water flow paths. In between the flow paths, the concentration can be very low or even zero. The increased substance heterogeneity in the soil profile (as compared to the rather uniform application) also shows that there is lateral transport of substance to local (preferential) flow and transport paths. Because of the heterogeneous transport pattern in sandy soil, preferential transport patterns can be easily missed by soil and soil-solution sampling. Local pesticide transport can be expected to lead to comparatively high leaching concentrations: much of the soil matrix is by-passed and time available for transformation in the bio-active top layers is shortened.

Measurements of the concentrations in the outflow from sandy soil profiles show different patterns. In some cases, the substance appeared roughly as a wave, as expected for chromatographic transport. In comparative studies for different soils, preferential leaching of solutes from sandy soils (e.g. to tube drains) was found to be distinctly lower than that for loamy/clayey soils. In other cases, distinct preferential (local) transport out of the sandy soil profile was measured. The comparatively new technique of water and solute sampling via a horizontal grid of suction cells in the subsoil showed a high variation in substance outflow. Major factors in the differences in outflow concentration measured may be the build-up of the soil profile and the water regime.

The expression 'preferential transport of a substance in soil' is often used in a qualitative sense: there is no quantitative criterion. In the computation models based on the chromatographic transport theory, the spreading of the concentration distribution in the soil profile or in the breakthrough curve is described by using a dispersion coefficient. In most studies, however, no attempt has been made to describe the distribution/breakthrough using a reasonable value of the dispersion coefficient. Preferential transport would involve the fraction of the substance distribution and breakthrough moving ahead of the chromatographic wave.

Water flow and substance transport in soils can be expected to be variable in time, dependent on variable factors like:
– intensity and duration of rainfall and sprinkler irrigation;
– development and structure of the crop canopy;
– soil (surface) structure (cultivation, water impact, settling);
– moisture distribution in soil at the start of the precipitation;
– possible pattern of water-repellency in soil (dry places below threshold moisture condition).

As a result of preferential flow, substances can be transported quickly in only a fraction of the soil profile. This means that only a fraction of the soil matrix participates in adsorption of the substances. The residence time of the pesticide in the soil profile is reduced, so there is less time for transformation. The extent of substance leaching to groundwater and tile-drain water can be distinctly increased as compared to that for chromatographic transport. Computation models based on the convection-dispersion concept can then be expected to give under-estimations of the risk of leaching.

A particular situation is presented by fields with ridges and furrows, as used e.g. in growing potatoes. Precipitation water can flow along the soil surface from the ridges to the furrows, especially when falling at higher intensities. Pesticides sprayed on plants and soil can be carried along with this water. Thus the increased water load of the furrows can be accompanied by an increased pesticide load. Uptake of water and pesticide from the furrow systems is lower than that from the ridge systems. Experimental work confirmed the surface-flow of water from the ridges to the furrows, the increased pesticide load of the furrows and the deeper movement of pesticide in the furrow soil. The comparatively low residence time of a pesticide in the furrow systems results in less time for transformation and thus to an increased risk of leaching. More experimental and modelling work is needed to develop and use a representative scenario that can be used in the procedure for evaluating the risk of leaching of pesticides from ridged fields.

Prospects for modelling
Water flow and substance transport in sandy soils show a two/three-dimensional pattern. Two-dimensional models are particularly suitable for fields with crops grown in rows on ridges. Often a three-dimensional model

will be needed to simulate the processes in a realistic way. Another complication is that the soil-plant system is highly variable in time. At the start of each precipitation event the situation can be different. Much of the input data for detailed two/three-dimensional modelling may be missing. Sufficiently-detailed field measurements needed for testing two/three-dimensional models may be scarce. Simplified two/three-dimensional extensions of one-dimensional models may provide interim tools. Information on the range of practical conditions is needed to develop realistic scenarios to be used for risk evaluation in the registration procedures.

Prospects for the registration procedure
In the registration procedures, the risk of increased pesticide leaching to groundwater by preferential transport is not accounted for in an explicit way. The processes are highly complex, with large variations in space and great changes in time. The extent to which preferential transport occurs cannot be predicted yet. First of all, a computation model would be needed that describes the processes in a realistic way. Secondly, scenarios are needed that are representative of many practical situations.

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Appendix 1

Summary of research for grass-grown fields

The main line in the present study deals with the complications in water flow and substance transport in cultivated sandy soils, used for arable farming and horticulture. Much research has been carried out for experimental fields with permanent grass, e.g. a field with strongly water-repellent dune-sand soil near Ouddorp (NL). Although research for those fields is beyond the main line of the present study, it provides interesting background information. Further, pesticides are also used on fields with permanent grass, including orchards with grass strips. For those reasons, research for grass-grown fields is summarised in this Appendix.

The transport of bromide ions in a loamy-sand soil in the Hupselse Beek catchment area (NL) was studied in strips with a) permanent-grass vegetation and b) arable land (Van Ommen and Dijksma, 1988; Van Ommen et al., 1989a). Bromide-ions were sprayed on the soil surface in December and they were transported by natural rainfall. At various times, the soil was sampled by taking ten cores per strip to 0.7 m depth. The ranges of the concentration of bromide ion at a certain depth in the grass-grown soil were much wider than those in the arable soil. Further, the moisture contents and the dye-colouring patterns (Van Ommen et al., 1989b) in the grass-grown soil were much more heterogeneous than those in the arable soil. It was concluded that the transport of water and bromide ions in the grass-grown soil was much more heterogeneous (more preferential transport) than that in the arable soil.

Water contents and transport of bromide-ion in the water-repellent sand soil near Ouddorp (NL) were studied after spraying bromide on the soil in November (Hendrickx et al., 1988, 1993; Van Dam et al., 1990). The volume fraction of water in the grass-grown top layer was highly variable, with patches remaining dry even when substantial amounts of rain fell in the autumn. Bromide-ion moved deeper in the water-repellent soil than in the adjacent wettable (clay-amended) soil. After five weeks with a total of 120 mm rainfall, bromide-ion concentration in the upper groundwater was much higher beneath the water-repellent soil than beneath the wettable soil. This indicates that more preferential flow occurred in the water-repellent soil than in the wettable soil. In the latter, bromide-ion was transported more in a wave-type distribution.

After a rain shower of 20 mm, the distribution of water in a water-repellent sand soil (grown with grass; presumably at Ouddorp NL) was measured (Hendrickx and Dekker, 1991). Dye-colouring showed that the water flowed downwards through narrow channels, whereas the adjacent soil remained dry. The water ponded in shallow depressions and infiltrated into the soil from there. Further rainfall infiltrated and flowed through the earlier preferential flow paths. The volume fraction of water at 0.075 m depth in a transect 5.5 m long ranged from 0.04 (driest places) to 0.24 (in wet preferential flow paths).

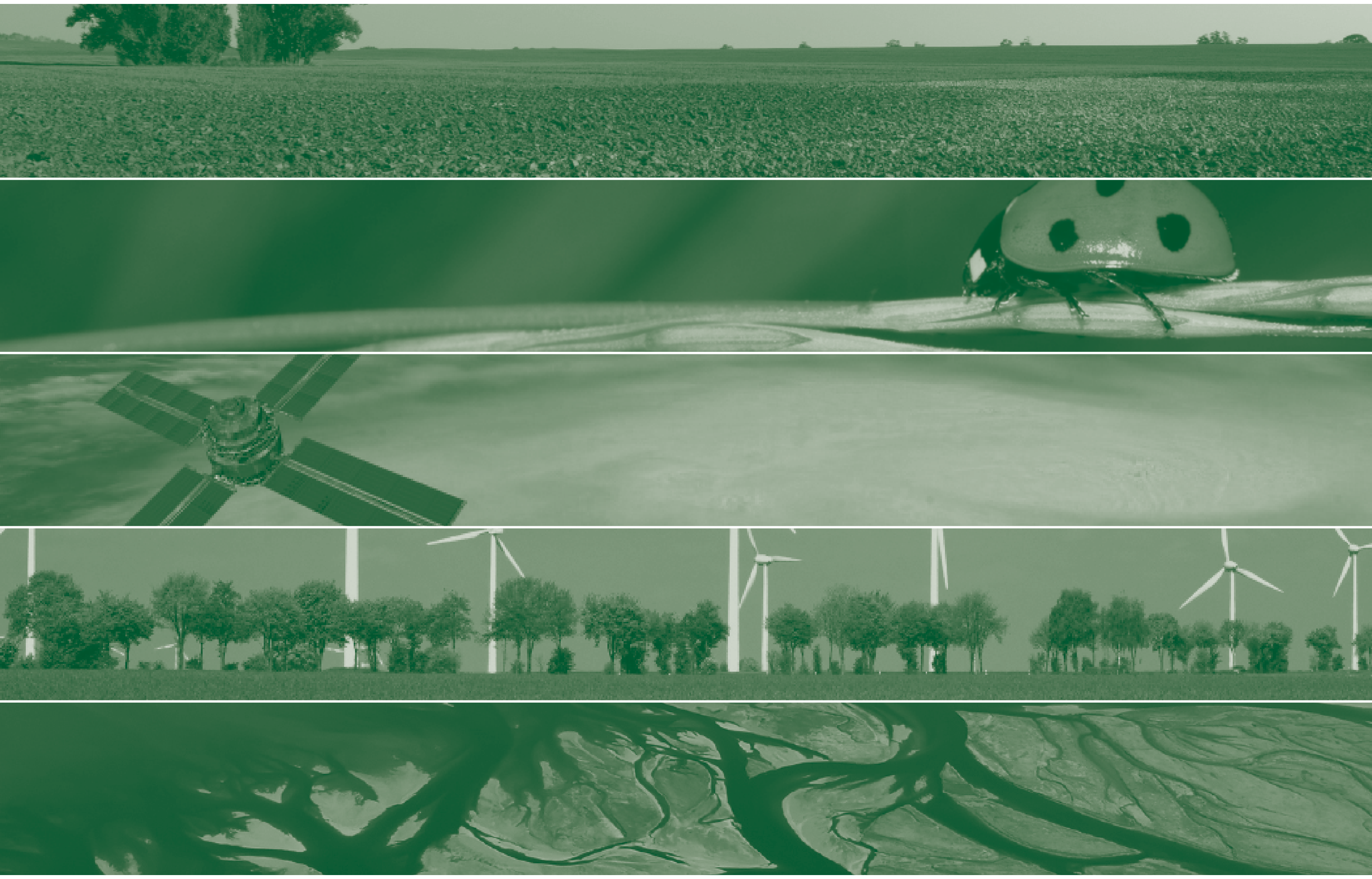
The wettable and water-repellent sandy soils grown with grass (Ouddorp, NL) were sprinkler-irrigated (non-ponding) with 100 mm of iodide-ion solution in water in 2 days in May (Hendrickx et al., 1988, 1993). The flow pattern was visualised by spraying chloride-ion and starch onto horizontal soil surfaces to produce the blue iodine-starch colour. The wettable soil was rather uniformly coloured/wetted. However, the water-repellent soil was only locally coloured/wetted: e.g. 35% of the horizontal cross-section at 0.05 m depth.

The field with potentially water-repellent sand soil (Ouddorp, NL) was exposed to natural rainfall. Soil moisture distributions were measured and observations were made on the flow patterns (Ritsema et al., 1993; Ritsema and Dekker, 1994; Ritsema and Dekker, 1995). The water flowed from the wetted top layer (grass sod; distribution layer) via preferential flow paths in the intermediate layer to the wettable subsoil with fluctuating water table. Variation in volume fraction of water in the intermediate layer with flow paths was very high. Dark (wetted) vertical flow paths were visible at some times. In successive rainy periods, the water flowed along the same flow paths through soil with comparatively low water-repellency (recurring fingered flow) (Ritsema et al., 1997).

Bromide-ion was sprayed in November on the potentially water-repellent sandy soil near Ouddorp (NL), grown with permanent grass (Ritsema et al., 1993; Ritsema and Dekker, 1995). The volume fraction of water in the water-repellent layer below the top layer showed a wide variation at the measuring times, with comparatively low average values. Similarly, the concentration of bromide-ion at each depth in the soil (20 cores) showed a wide variation. The spreading in the amount of bromide measured per core was distinctly greater than the spreading in the application. This was ascribed to lateral water flow and bromide transport in the upper part of the soil profile to preferential flow paths. Bromide-ion seemed to be transported laterally (in distributed flow) in the humous and wet top layer to preferential flow paths in the water-repellent intermediate zone. After eleven days, soil with a higher volume fraction of water also contained a higher concentration of bromide-ion. Below the water-repellent zone, bromide-ion showed substantial lateral transport (by diverged flow). At the permanent grass plots, the preferential flow paths recurred at the same places (least water-repellent) in subsequent rainy periods (Ritsema et al., 1997).

Water distribution patterns in the dune sand grown with permanent grass near Ouddorp (NL) were measured by Ritsema and Dekker (1996). Horizontal distribution of water occurred in the humous 0.09 m top layer. Below that, vertical preferential flow started at some places with comparatively low water repellency. The soil between the wetted fingers was wetted only very slowly. In successive rainy periods, the wetted fingers appeared at the same places as before. Bromide ion was locally transported to 0.9 m depth. Transport of bromide ion was partly faster and partly slower than calculated from piston flow.

Plexiglass slab chambers (1.8 and 2.8 cm thick) were filled with oven-dried water-repellent sand from the Ouddorp field (Wang et al., 1998, 2000). A layer of water was ponded on the soil surface, the rate of water infiltration was measured and the wetting pattern was observed on the slab walls. It took a long time (e.g. 40 min) before the wetting of the repellent sand started. Then water infiltration slowly proceeded in time. Water flow within the sand was unstable; it showed a fingered pattern. When the sand was ponded with a high water layer, water flow started earlier (e.g. after 6 min) and the wetting front in the sand was stable. However, after the ponding was stopped (ponding head fell below the water-entry head), the flow in the sand became unstable.



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