Mechanisms controlling macropore flow during infiltration

Dye tracer experiments and simulations

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZÜRICH
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DOCTOR OF TECHNICAL SCIENCE

presented by
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**Greek Symbols**

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<tr>
<td>$\theta_s$</td>
<td>saturated volumetric water content [-]</td>
</tr>
<tr>
<td>$\psi_f$</td>
<td>wetting front suction [L]</td>
</tr>
</tbody>
</table>
List of Symbols
Macropore flow describes the fast movement of water in structural features like wormholes, root channels, or cracks in soils. The influence of macropore flow on infiltration, transport of solutes, and the generation of runoff is generally accepted; however, the mechanisms controlling macropore flow are not very well known. Several studies have shown that the initiation of macropore flow and the water flow from the macropores in the surrounding soil matrix (interaction) mainly determine the infiltration in macroporous soils. Yet an integrated approach to investigate the processes controlling macropore flow, to identify the major factors influencing these processes, and to determine their effects on runoff generation is lacking. Concentrating on soils containing macropores built by earthworms, this study observed and analysed in detail macropore flow processes during flood producing rainfall events.

Combined sprinkling and dye tracer experiments with different rainfall intensities and initial soil moisture conditions were carried out on four sites in Switzerland. The experimental set-up allowed the observation of macropore flow initiation and interaction at a high spatial and temporal resolution. The sites were selected to cover a wide variety of properties that can influence macropore flow. However, the land-use was restricted to grassland to ensure an undisturbed development of the macropore network and all sites were located on hillslopes to be able to measure overland flow. The experiments provided detailed soil water regime measurements in order to detect water content changes in different depths and to determine the time of saturation and the saturation deficit at the beginning of the experiment.

Several vertical and horizontal soil sections showing the patterns of the applied dye tracer Brilliant Blue FCF were prepared for each experiment. Despite dye patterns showing only one picture of the cumulative flow pattern at the end of the experiment, preferential flow pathways can be visualized and identified with a high spatial resolution. A series of image analysis procedures was first applied to the photographed soil sections to distinguish between stained and unstained areas and to classify the stained areas for different concentration classes. Using the classified vertical dye patterns, a new approach was developed to recognize five different flow processes within the soil profile: two processes in which only the soil matrix is involved and three processes in which macropores with a different degree of interaction dominate the infiltration. The resulting profiles showed a logical sequence of flow processes for each experiment, which were later used to validate the modelling results. The horizontal sections were
used to derive the macropore density. Furthermore, the interaction was quantified by a method describing the spatial relation between macropores and stained areas.

The detailed analysis of the macropore processes showed that the high macropore flow rate and the velocity in vertically oriented macropores formed by earthworms usually does not limit infiltration. However, initiation and interaction and especially their interdependence determine infiltration into macroporous soils. Initiation of macropore flow can either take place on the soil surface or in a saturated soil layer. Both initiation processes significantly change the flow rate distribution within the macropores, resulting in a high rate in some macropores and in a very low rate in the majority of macropores. This flow variability considerably alters the interaction and thus the generation of runoff.

These mechanisms were integrated in the new macropore infiltration model IN3M. This model is capable both of simulating the observed soil water regime and of reproducing the observed variability of dye patterns. The comparison of the simulated and observed dye patterns provided an innovation to validate the model results. Testing the sensitivity of some parameters, the major factors influencing the macropore flow processes were identified. Different impacts of macropores on infiltration were shown to depend mainly on the balance between initiation and interaction of macropore flow. The permeability near the soil surface and the surface characteristics control whether macropore flow is directly initiated at the soil surface or delayed after saturating a soil layer. Interaction is mainly influenced by the soil moisture content, since matric potential is the major driving force of water flowing from the macropore into the soil matrix. In a macroporous soil, the average saturated hydraulic conductivity mainly determines the interaction and thus the infiltration. In contrast, in a soil without macropores, the soil layer with the lowest conductivity controls infiltration. Finally, the geological bedrock material or the properties of the subsoil influence the drainage of the macropores and thus the flow pathways for runoff generation.

The findings of this study have important implications for hydrological applications. As the initiation process in combination with interaction can considerably accelerate the runoff response, the leaching of solutes will most likely be affected and should be studied in more detail in this respect. Related to this area is the question about movement of "old" and "new" water in the soil. Besides the modification of runoff generation by macropore flow processes, also the resulting heterogeneous distribution of the water content in the soil should be taken into consideration for rainfall-runoff modelling in catchment hydrology. The results should encourage hydrologists to consider macropore flow processes when assessing runoff generation mechanisms or whenever macropores are relevant for the problem.

licher Interaktion den Infiltrationsvorgang dominiert. Die klassifizierten Profile zeigen eine logische Sequenz von Fließprozessen für jeden Versuch, die später dazu benutzt wurden, die Modellergebnisse zu validieren. Mit den horizontalen Fließmustern wurde die Makroporendichte bestimmt und die Interaktion mit einer Methode quantifiziert, die den räumlichen Bezug zwischen Makroporen und gefärbten Flächen auswertet.

Es zeigte sich bei der Prozesseauswertung, dass die Fließraten und die Fließgeschwindigkeit in Regenwurmgängen normalerweise nicht limitierend für die Infiltration ist. Vielmehr bestimmen Initiierung und Interaktion das Infiltrationsverhalten in Böden mit Makroporen. Die Initiierung kann von der Bodenoberfläche oder von einem gesättigten Bereich im Boden ausgehen. Beide Mechanismen verändern die Verteilung der Fließraten in den Makroporen, was zu sehr hohen Fließraten in einigen wenigen Makroporen und zu sehr geringen Fließraten in der Mehrzahl der Makroporen führt. Diese Variabilität verändert die Interaktion und somit auch die Abflussbildung signifikant.


Macropore flow causes a rapid downward movement of water in structural pore spaces such as worm channels, shrinking cracks and root holes and subsequently a bypassing of parts of the soil profile. Thus macropore flow influences the infiltration of rainfall in natural soils, in which these structures are common (Larson, 1999). It is important to distinguish between macropore flow and macropore transport (Wilson et al., 1998). Macropore flow originates from non-equilibrium conditions in hydraulic pressure between pore regions, while macropore transport is caused by non-equilibrium in solute concentration between pore regions. The pore space is commonly divided into macropores and matrix pores. Macropore flow affects the generation of runoff and macropore transport the leaching of solutes (Figure 1.1). This study concentrates on the effects of macropore flow and does not directly consider macropore transport; however, statements related to macropore flow can also improve knowledge on macropore transport.

The generation of runoff at a site determines the runoff processes and the flow pathways in catchments and thus flood formation under extreme rainfall events. Only a correct simulation and prediction of flow pathways lead to a correct description of the internal hydrological behaviour in a catchment (Beven, 2001). Although the prediction of the flow hydrograph in rivers using rainfall-runoff models that do not account for the relevant runoff processes may be acceptable, we get "right results for the wrong reason" (Klemes, 1986). A correct description of the internal hydrological behaviour is especially important for simulating transport processes in the catchment (e.g. nitrate or phosphate leaching) and for predicting runoff for land-use or climate change scenarios. Yet, macropore flow is often not considered in rainfall-runoff models, despite abundant experimental evidence. Many rainfall simulation experiments on hillslopes and continuous measurements of runoff on hillslopes pointed out the influence of macropore flow on the runoff generation (e.g. Bronstert, 1999; Faeh et al., 1997; McDonnell, 1990; Navar et al., 1995; Smettem et al., 1991; Weiler et al., 1998). Indirect evidence of macropore flow at the catchment scale can be obtained by model interpretation. In some studies where rainfall-runoff models have been used which do not account for macropore flow, the mismatch between simulated and measured discharge has been attributed to macropore flow (Germann, 1981; Burch et al., 1989; Katzenmaier et al., 2000).

The impact of macropores is governed to a large extent by the water supply in macropores, water flow in macropores, and the water transfer from the macropores into the surrounding soil.
Introduction

In order to understand these mechanisms and to quantify their influence factors, the results of field experiments should be interpreted using models. If the relevant mechanisms were identified and
included into the model, the simulations can also be used to study the effects of macropore flow on runoff generation.

Because the main forming process of macropores by earthworms (anecic species, e.g. *Lumbricus terrestris*) generates a vertically oriented, continuous network of channels, the flow rate in macropores can be very high compared to the rate in the soil matrix. Even for unfavourable conditions, the flow rate in macropores is always higher than the rainfall intensity (BOUMA et al., 1982; WANG et al., 1994).

Macropore flow initiation is a function of initial water content, rainfall intensity, rainfall amount, hydraulic conductivity, and surface contributing area (TROJAN & LINDEN, 1992). FLÜHLER et al. (1996) pointed out that the reasons of initiation of preferential flow and in particular of macropore flow, which is a subset of preferential flow, should be especially investigated. Water can flow into macropores from the soil surface or from a saturated or partially saturated soil layer. Subsurface initiation is mainly influenced by the arrangements and properties of the soil layers (ELA et al., 1992; LI & GHUDRATI, 1997; WEILER et al., 1998). Some studies verified that macropore density, slope and roughness of the surface mainly influence surface initiation (TROJAN & LINDEN, 1992; LÉONARD et al., 1999).

Water transfer from macropores into the surrounding soil matrix has been referred to as lateral infiltration from the macropores (BEVEN & CLARKE, 1986). In this study, the term interaction is used for this process. Interaction is one of the critical processes describing water flow in macroporous soils (LOGSDON et al., 1996; FAEH et al., 1997). Despite some experiments to measure interaction in single artificial or natural macropores in the laboratory (SMETTEM, 1986; GHUDRATI et al., 1999) or with field experiments using dye tracers and soil water measurements (VAN STIPHOUT et al., 1987), a consistent description, parameterization and verification of the interaction process was not yet achieved.

Previous rainfall experiments on macroporous soils showed that rainfall intensity and initial soil moisture content can influence the infiltration into soils with macropores (VAN STIPHOUT et al., 1987; BOUMA, 1990; TROJAN & LINDEN, 1992). Therefore, macropore infiltration studies should be performed with different rainfall intensities and initial soil moisture conditions (BEVEN & GERMANN, 1982; BOUMA, 1990).

The overall objectives of this thesis is to understand the processes controlling macropore flow, to identify the major factors influencing these processes, and to determine their effects on runoff generation. These objectives have been achieved by:

- performing combined sprinkling and dye tracer experiments with different rainfall intensities and initial soil moisture conditions on four sites. The sites were selected in catchments where macropore flow plays an important role and where pedologically similar soils react hydrologically different (Ch. 2).
- analysing the dye patterns and soil water regimes with respect to initiation and interaction of macropore flow (Ch. 3, Ch. 4 and Ch. 5).
Introduction

- systematically analysing the major processes controlling macropore flow with the aid of results from field experiments, model simulations, and additional information from other studies (Ch. 6).
- developing the INfiltration-INitiation-INteraction Model (IN³M). This new dual-porosity model was necessary as none of the existing macropore flow models accounted for all the major processes controlling macropore flow. Additionally, the model uses analytical solutions of flow in porous media allowing stable and fast simulations which make the model applicable in a hydrological framework (Ch. 6 and Ch. 7).
- modelling the experiments with IN³M and validate the simulation results using the detailed field measurements. The validation results and a sensitivity analysis of the model allowed to identify the factors influencing macropore flow (Ch. 7).
- assessing the effect of macropore flow on runoff generation using the simulation results of the four experimental sites and six reference sites (Ch. 7).

Finally, it is discussed how these results can be implemented in rainfall-runoff models depending on different objectives.
2.1 INTRODUCTION

The experimental work and set-up are oriented towards understanding the initiation of macropore flow and the water exchange between macropores and the soil matrix for extreme rainfall events. In recent years, efforts have been made to understand the flow processes in natural soils and to quantify macropore flow. Dye tracers were successfully used in field experiments to visualize the continuity and hydrological effectiveness of preferential flow paths in soils (Bouma & Dekker, 1978; van Stiphout et al., 1987; Ghodrati & Jury, 1990; Flury et al., 1994; Natsch et al., 1996; Forrer et al., 1999; Perillo et al., 1999). For example, Flury et al. (1994) observed considerable differences in the dye patterns in 14 different agricultural soils which were exposed to rainfall at low intensities. In some soils, dye penetrated beyond 1 m depth, whereas in others it remained in the top 50 cm. Structured soils were more prone to produce bypass flow, deep dye penetration, and pulse-splitting than non-structured soils.

There is currently little information on what rainfall intensity is required to initiate macropore flow (Beven & Germann, 1982; Bouma, 1990). Flury et al. (1994) for instance concluded that there was no clear effect of the initial water content of the soil on the infiltration pattern. However, Feyen (1998) could explain the runoff reaction of forest soils by an increase of bypass flow in macropores depending on the initial soil water regime. As several other studies confirmed the influence of rainfall intensity and initial soil moisture content on the infiltration in macroporous soils (van Stiphout et al., 1987; Bouma, 1990; Trojan & Linden, 1992), macropore infiltration studies must be performed with different rainfall intensities and also with different initial soil moisture contents.

An interesting study has been performed by van Stiphout et al. (1987) who studied infiltration into structured soils by combining dye tracers and soil water measurements under dry and wet initial soil moisture conditions. They determined the water flow between macropores and the surrounding soil matrix at various depths. To study interaction on the plot scale, their method tends to be more promising than measurements in single macropores in the laboratory. The performed field experiments were designed to study factors influencing macropore flow at the plot scale by combining dye tracer and sprinkling experiments with different rainfall intensities and initial soil moisture conditions.
2.2 EXPERIMENTAL SITES

2.2.1 Field site selection

To study the variety of flow processes in macroporous soils at the field scale and to make sure the boundary conditions are comparable, experimental sites have to be selected that fulfil the following criteria:

• The sites have been covered by grassland, preferably meadow, for at least 20 years to ensure an undisturbed development of the macropore network in the soil (Syers & Springett, 1983).

• The sites are located on a gentle hillslope. Thus, overland flow produced during the experiments, can be collected and measured at the bottom end of the sites.

• The sites are similarly exposed to ensure comparable evapotranspiration rates.

• The sites should be located in catchments, where additional hydrologic measurements or information about extreme floods in the past 50 years are available.

• The soils at the sites have either a high or a low water exchange potential between the macropores and the soil matrix. Some sites with a low water exchange potential were already localized in previous experiments (Scherrer, 1997; Faeh et al., 1997). Sites with a high water exchange potential were selected based on soil types and bedrock.

Experiments in the first year concentrated on sites, where information about the potential infiltration processes was already available (Rietholzbach and Heitersberg). The selection for the second year was based on the experiences of the first year and an intensive field evaluation of potential sites. In Table 2.1 the four selected experimental sites are listed.

<table>
<thead>
<tr>
<th>No.</th>
<th>Site</th>
<th>Long (E)</th>
<th>Lat (N)</th>
<th>Altitude (m a.s.l.)</th>
<th>Exposition</th>
<th>Relief</th>
<th>Date of experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rietholzbach</td>
<td>8°58'29&quot;</td>
<td>47°22'32&quot;</td>
<td>860</td>
<td>N</td>
<td>concave slope</td>
<td>22.7.98–26.8.98</td>
</tr>
<tr>
<td>2</td>
<td>Heitersberg</td>
<td>8°20'52&quot;</td>
<td>47°24'47&quot;</td>
<td>660</td>
<td>NE</td>
<td>convex slope</td>
<td>1.9.98–5.10.98</td>
</tr>
<tr>
<td>3</td>
<td>Koblenz</td>
<td>8°15'19&quot;</td>
<td>47°35'30&quot;</td>
<td>450</td>
<td>NW</td>
<td>concave slope</td>
<td>5.5.99–15.6.99</td>
</tr>
<tr>
<td>4</td>
<td>Niederweningen</td>
<td>8°21'49&quot;</td>
<td>47°30'23&quot;</td>
<td>520</td>
<td>NW</td>
<td>convex slope</td>
<td>15.7.99–25.8.99</td>
</tr>
</tbody>
</table>

2.2.2 Site description

The experimental sites were described by the textural and structural soil properties, by soil classification and vegetation. The physical soil properties such as the particle size distribution,
the soil texture, the content of organic matter, the bulk density and the pH were determined for each site at depth intervals of 10 cm (exceptional 20 cm). The properties for each site are listed in Table 2.2 to Table 2.5.

Table 2.2  Soil properties of the Rietholzbach site

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Particle size distribution*</th>
<th>Soil texture†</th>
<th>Corg‡ (%</th>
<th>Density** (g cm⁻³)</th>
<th>pH††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand (%) Silt (%) Clay (%)</td>
<td>loam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10</td>
<td>46 31 23</td>
<td>loam</td>
<td>6.1</td>
<td>1.14</td>
<td>4.0</td>
</tr>
<tr>
<td>10-20</td>
<td>37 37 26</td>
<td>loam</td>
<td>3.6</td>
<td>–</td>
<td>4.0</td>
</tr>
<tr>
<td>20-30</td>
<td>40 34 26</td>
<td>loam</td>
<td>2.6</td>
<td>1.26</td>
<td>4.0</td>
</tr>
<tr>
<td>30-40</td>
<td>37 38 25</td>
<td>loam</td>
<td>2.1</td>
<td>–</td>
<td>4.5</td>
</tr>
<tr>
<td>40-50</td>
<td>40 35 25</td>
<td>loam</td>
<td>1.4</td>
<td>1.23</td>
<td>4.5</td>
</tr>
<tr>
<td>50-60</td>
<td>37 35 28</td>
<td>clay loam</td>
<td>1.3</td>
<td>–</td>
<td>4.5</td>
</tr>
<tr>
<td>60-70</td>
<td>44 28 28</td>
<td>clay loam</td>
<td>1.1</td>
<td>–</td>
<td>4.0</td>
</tr>
<tr>
<td>70-80</td>
<td>40 30 20</td>
<td>clay loam</td>
<td>0.9</td>
<td>1.34</td>
<td>4.0</td>
</tr>
<tr>
<td>80-90</td>
<td>35 33 32</td>
<td>clay loam</td>
<td>1.2</td>
<td>–</td>
<td>4.0</td>
</tr>
<tr>
<td>90-100</td>
<td>35 31 34</td>
<td>clay loam</td>
<td>1.2</td>
<td>–</td>
<td>4.0</td>
</tr>
</tbody>
</table>

* pipette method (sand 2 mm–50 μm, silt 2–50 μm, clay < 2 μm), (% by weight)
† after KLUTE (1986)
‡ organic matter content obtained by oxidation with H₂O₂ (% by weight)
** arithmetic average of at least 4 samples
†† in H₂O with pH indicator

Table 2.3  Soil properties of the Heitersberg site

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Particle size distribution*</th>
<th>Soil texture†</th>
<th>Corg‡ (%</th>
<th>Density** (g cm⁻³)</th>
<th>pH††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand (%) Silt (%) Clay (%)</td>
<td>loam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10</td>
<td>36 38 26</td>
<td>loam</td>
<td>3.8</td>
<td>1.34</td>
<td>7</td>
</tr>
<tr>
<td>10-20</td>
<td>37 37 26</td>
<td>loam</td>
<td>–</td>
<td>1.44</td>
<td>6.5</td>
</tr>
<tr>
<td>20-30</td>
<td>43 30 27</td>
<td>loam</td>
<td>1.1</td>
<td>1.57</td>
<td>6.5</td>
</tr>
<tr>
<td>30-40</td>
<td>43 31 26</td>
<td>loam</td>
<td>–</td>
<td>–</td>
<td>6.5</td>
</tr>
<tr>
<td>40-60</td>
<td>40 37 23</td>
<td>loam</td>
<td>0.8</td>
<td>1.66</td>
<td>6.5</td>
</tr>
<tr>
<td>60-80</td>
<td>46 32 22</td>
<td>loam</td>
<td>0.6</td>
<td>1.68</td>
<td>–</td>
</tr>
<tr>
<td>80-100</td>
<td>47 27 26</td>
<td>loam</td>
<td>–</td>
<td>–</td>
<td>5.5</td>
</tr>
</tbody>
</table>

* pipette method (sand 2 mm–50 μm, silt 2–50 μm, clay < 2 μm), (% by weight)
† after KLUTE (1986)
‡ organic matter content obtained by oxidation with H₂O₂ (% by weight)
** arithmetic average of at least 4 samples
†† in H₂O with pH indicator
### Table 2.4 Soil properties of the Koblenz site

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Particle size distribution</th>
<th>Soil texture†</th>
<th>C_{org}‡</th>
<th>Density**</th>
<th>pH††</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>26 51 23</td>
<td>silt loam</td>
<td>2.7</td>
<td>1.31</td>
<td>—</td>
</tr>
<tr>
<td>10-20</td>
<td>24 53 23</td>
<td>silt loam</td>
<td>2.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>20-30</td>
<td>26 53 21</td>
<td>silt loam</td>
<td>0.8</td>
<td>1.35</td>
<td>—</td>
</tr>
<tr>
<td>30-40</td>
<td>27 51 22</td>
<td>silt loam</td>
<td>0.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>40-50</td>
<td>26 51 23</td>
<td>silt loam</td>
<td>0.4</td>
<td>1.46</td>
<td>—</td>
</tr>
<tr>
<td>50-60</td>
<td>22 53 25</td>
<td>silt loam</td>
<td>0.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>60-70</td>
<td>24 49 27</td>
<td>loam</td>
<td>0.2</td>
<td>1.51</td>
<td>—</td>
</tr>
<tr>
<td>70-80</td>
<td>25 46 29</td>
<td>loam</td>
<td>0.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>80-100</td>
<td>20 50 30</td>
<td>clay loam</td>
<td>0.0</td>
<td>1.65</td>
<td>—</td>
</tr>
</tbody>
</table>

* Pipette method (sand 2 mm-50 μm, silt 2-50 μm, clay < 2 μm), (% by weight)
† After Klute (1986)
‡ Organic matter content obtained by oxidation with H₂O₂ (% by weight)
** Arithmetic average of at least 4 samples
†† In H₂O with pH indicator

### Table 2.5 Soil properties of the Niederweningen site

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Particle size distribution*</th>
<th>Soil texture†</th>
<th>C_{org}‡</th>
<th>Density**</th>
<th>pH††</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>55 23 22</td>
<td>sandy clay loam</td>
<td>2.1</td>
<td>1.41</td>
<td>5</td>
</tr>
<tr>
<td>10-20</td>
<td>60 20 20</td>
<td>sandy loam</td>
<td>1.4</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>20-30</td>
<td>60 20 20</td>
<td>sandy loam</td>
<td>0.7</td>
<td>1.50</td>
<td>5</td>
</tr>
<tr>
<td>30-40</td>
<td>58 21 21</td>
<td>sandy clay loam</td>
<td>0.3</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>40-50</td>
<td>59 21 20</td>
<td>sandy loam</td>
<td>0.0</td>
<td>1.44</td>
<td>5</td>
</tr>
<tr>
<td>50-60</td>
<td>62 21 17</td>
<td>sandy loam</td>
<td>0.0</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>60-70</td>
<td>61 22 17</td>
<td>sandy loam</td>
<td>0.0</td>
<td>1.37</td>
<td>5</td>
</tr>
<tr>
<td>70-80</td>
<td>63 22 15</td>
<td>sandy loam</td>
<td>0.0</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>80-90</td>
<td>71 18 11</td>
<td>sandy loam</td>
<td>0.0</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>90-100</td>
<td>74 18 8</td>
<td>sandy loam</td>
<td>0.0</td>
<td>1.46</td>
<td>5</td>
</tr>
</tbody>
</table>

* Pipette method (sand 2 mm-50 μm, silt 2-50 μm, clay < 2 μm), (% by weight)
† After Klute (1986)
‡ Organic matter content obtained by oxidation with H₂O₂ (% by weight)
** Arithmetic average of at least 4 samples
†† In H₂O with pH indicator

In Table 2.6 the soil classification and the geological parent material are given to summarise the soil characteristics. Besides the soil texture, structural properties are described for every diagnostic soil horizon. It is assumed that structural features in the soil like roots, aggregates or stones influence the hydraulic properties of the soil matrix. The most important structural
features for this study, the earthworm channels, are described in detail in Ch. 6.1. The soil structure is described according to the Soil Survey Staff (1951). The root density and the stone content were visually estimated and the humus type was determined.

Table 2.6  Description of the soils of the experimental site

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil Classification</th>
<th>Geological parent material</th>
<th>Structure‡</th>
<th>Root density (dm⁻²)</th>
<th>Humus†</th>
<th>Stones</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Type</td>
<td>Class (mm)</td>
<td></td>
<td>(%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rietholzbach</td>
<td>Umbric Cambisol</td>
<td>Conglomerates (molasse)</td>
<td>subangular blocky</td>
<td>5-10</td>
<td>21-50</td>
<td>1-2</td>
</tr>
<tr>
<td>0-15</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-30</td>
<td>A/B</td>
<td>angular blocky</td>
<td>10-20</td>
<td>6-10</td>
<td>2-5</td>
<td>gravelly</td>
</tr>
<tr>
<td>30-60</td>
<td>B</td>
<td>angular blocky</td>
<td>10-20</td>
<td>1-2</td>
<td>5-10</td>
<td>cobbly</td>
</tr>
<tr>
<td>60-100</td>
<td>C</td>
<td>subangular blocky</td>
<td>5-10</td>
<td>1-2</td>
<td>5-10</td>
<td>cobbly</td>
</tr>
<tr>
<td>Heitersberg</td>
<td>Mollic Cambisol</td>
<td>Moraine</td>
<td>subangular blocky</td>
<td>10-20</td>
<td>6-10</td>
<td>1</td>
</tr>
<tr>
<td>0-20</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-45</td>
<td>A/B</td>
<td>subangular blocky</td>
<td>10-20</td>
<td>3-5</td>
<td>9</td>
<td>stony</td>
</tr>
<tr>
<td>45-100</td>
<td>B/C</td>
<td>subangular blocky</td>
<td>10-20</td>
<td>0</td>
<td>20</td>
<td>stony</td>
</tr>
<tr>
<td>Koblenz</td>
<td>Eutric Cambisol</td>
<td>Moraine</td>
<td>subangular blocky</td>
<td>10-20</td>
<td>11-20</td>
<td>&lt;1</td>
</tr>
<tr>
<td>0-15</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-45</td>
<td>B</td>
<td>subangular blocky</td>
<td>10-20</td>
<td>3-5</td>
<td>&lt;1</td>
<td>gravelly</td>
</tr>
<tr>
<td>45-90</td>
<td>B/C</td>
<td>subangular blocky</td>
<td>10-20</td>
<td>0</td>
<td>&lt;1</td>
<td>gravelly</td>
</tr>
<tr>
<td>Niederweningen</td>
<td>Eutric Cambisol</td>
<td>Sandstone (molasse)</td>
<td>subangular blocky</td>
<td>5-10</td>
<td>3-5</td>
<td>0</td>
</tr>
<tr>
<td>0-15</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-30</td>
<td>A/B</td>
<td>subangular blocky</td>
<td>5-10</td>
<td>3-5</td>
<td>&lt;1</td>
<td>gravelly</td>
</tr>
<tr>
<td>30-55</td>
<td>B/G</td>
<td>subangular blocky</td>
<td>5-10</td>
<td>3-5</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>55-85</td>
<td>B/C</td>
<td>single grain</td>
<td>—</td>
<td>1-2</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>85-120</td>
<td>C</td>
<td>single grain</td>
<td>—</td>
<td>0</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

* Food and Agricultural Organization (1974)
† Blume (1996)
‡ Soil Survey Staff (1951)
** Soil Survey Staff (1951)

The soil classification and the soil structure of the sites are quite similar, with all sites being classified as Cambisols and a subangular blocky structure dominates. The stone content varies and depends primarily on the geological parent material. The soil texture respectively the particle size distributions of the sites are different, but the texture is still related to a loamy soil. The density and the organic matter are related to soil depth.
Experiments

The dominating plants at the experimental sites are also quite similar. The anthophytes and grasses are listed with their preferred location in Table 2.7. The vegetation indicates that the soils are usually rich in nitrogen, in bases and in nutrients, and frequently fresh to moist.

**Table 2.7 Dominating plants at the experimental sites**

<table>
<thead>
<tr>
<th>No.</th>
<th>Site</th>
<th>Anthophytes</th>
<th>Grasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rietholzbach</td>
<td>Taraxacum officinale (s), Plantago lanceolata (s,b,f,l), Trifolium medium (b), Ranunculus repens (m,l,s), Anthriscus sylvestris (s,f)</td>
<td>Pao annua (f,n), Pao pratensis (f,n,l)</td>
</tr>
<tr>
<td>2</td>
<td>Heitersberg</td>
<td>Taraxacum officinale (s), Plantago lanceolata (b,s,f,l), Trifolium medium (b), Ranunculus repens (m,l,s), Anthriscus sylvestris (s,f)</td>
<td>Lolium multiflorum (n,l,f), Poa trivialis (f,n,l)</td>
</tr>
<tr>
<td>3</td>
<td>Koblenz</td>
<td>Taraxacum officinale (s), Rumex sanguineus (b,s,m,l), Matricaria chamomilla (b,s,l)</td>
<td>Lolium multiflorum (n,l,f), Poa trivialis (f,n,l), Dactylis glomerata (f,n,s)</td>
</tr>
<tr>
<td>4</td>
<td>Niederweningen</td>
<td>Trifolium pratense (b,s), Plantago lanceolata (b,s,f,l), Ranunculus lanuginosus (b,s,f,l), Taraxacum officinale (s), Galium mollugo (b,f,l), Leontodon hispidus (s,l)</td>
<td>Lolium multiflorum (n,l,f), Trisetum flavescens (n,f), Holcus lanatus (fe)</td>
</tr>
</tbody>
</table>

Preferred location:
s = rich in nitrogen, b = rich in bases, n = rich in nutrients, l = loamy soils, f = fresh, m = moist

### 2.3 EXPERIMENTAL SETUP

#### 2.3.1 General idea

The experimental set-up was designed to allow the:
- application of a dye tracer on an area larger than 1 m²,
- measurement of overland flow at the bottom end of the plot,
- measurement of soil water content and matric potential without disturbing the soil surface of the experimental plot,
- application of different rainfall intensities,
- experiments to be carried out under different initial soil moisture conditions.

Thus, four combined tracer and sprinkling experiments with different rainfall intensities and different initial soil moisture conditions were carried out at each site. The two selected rainfall intensities correspond to an extreme convective and an advective event. Convective processes are short-time rainfall events of high intensity whereas advective events last several hours with a moderate intensity. Therefore, around 75 mm of water was applied at a constant rate within 70 min for the high rainfall intensity experiment and within 6 hours for the low rainfall intensity experiment.

The two different initial soil moisture conditions of the experiments were obtained by the following procedure. For dry conditions, the experimental plot was protected with a tarp against...
Experimental setup

rainfall for at least three weeks prior to the sprinkling experiment. For wet conditions, the plot was sprinkled with 75 mm of water one day prior to the experiment. This procedure did not create similar initial conditions for the dry and wet states at the four different sites, but absolute initial soil moisture conditions were determined with tensiometer and TDR measurements. The set-up of the four experimental plots with the different initial and boundary conditions at each site and the location of the instrumentation plot are shown in Figure 2.1. The four different initial and boundary conditions are related to high and low rainfall intensity and to dry and wet soil moisture conditions.

Fig. 2.1 Experimental set-up (LOW = low rainfall intensity, HIGH = high rainfall intensity, DRY = low initial water content, WET = high initial water content)
2.3.2 Sprinkling device

A sprinkling device was designed to fulfil the following requirements:
- spatial uniform application of water and liquid dye tracer on an area of 1.1 m by 2.7 m.
- simulation of rainfall intensities between 10 and 70 mm h\(^{-1}\).
- automatic rainfall simulation during several hours with a constant intensity.
- simple setup of the device on slopes.

The sprinkling device (Figure 2.2) was developed at the Institute of Hydromechanics and Water Resources Management of ETH Zürich. It consists of a spray bar with 15 flat-spray nozzles (JATO, F I-R \(\frac{1}{4}\"\), size 0.5) with a spray angle of 90° spaced at intervals of 180 mm. The bar was installed 100 cm above the ground and moved 180 mm between two mountings driven by an electric linear actuator. With the movement of the bar and the nozzles spraying orthogonal to the bar, uniform application is achieved. The mountings and the actuator are fixed on two poles that are drilled orthogonally to the soil surface into the ground at a 3 m distance. The device is protected with a tarp to minimize wind effects and to prevent tracer losses.

![Sprinkling device](image)

During the experiment, desalinated water, which reduce calcification in the nozzles, was pumped from a 200 l tank. The pressure at the nozzles inlet was 320 kPa resulting in a sprinkling intensity of 70 mm h\(^{-1}\). Thus, the high rainfall intensity was achieved by permanent pumping. To obtain the low intensity of 13 mm h\(^{-1}\), the spray bar and the pump were in operation for 15 s, then both were stopped for 100 s resulting in repeated intermittent irrigation.
The kinetic energy of natural rainfall and of rainfall from the sprinkling device are different. As the soil surface was covered with grass and thus protected against a direct impact of rain drops, the kinetic energy at the soil surface should not be quite similar to natural conditions. Prior to the field experiments, the spatial uniformity of the irrigation was measured using several square cups of 11.4 cm or 5.5 cm side length to gauge the artificial rainfall. For different intensities and rainfall amounts the standard deviation $s$ and average collected rainfall $\bar{x}$ were determined. The resulting uniformity coefficient $(1 - s / \bar{x})$ was above 0.85 in all cases. These coefficients agree with values found for other rainfall simulators (Lascelles et al., 2000; Flury et al., 1994).

Because no studies exist about spatial variation of natural rainfall at the plot scale (Lascelles et al., 2000), a comparison between the variation of rainfall for a simulator and under natural conditions is not possible.

During the sprinkling experiments, the cumulative amount of irrigation water and the water which fell outside the plot and which was collected in gutters were measured and the actual rainfall intensity was determined (Figure 2.3). The variations were usually small (Table 5.1 in Ch. 5.2), except for two experiments when a tube connected to a nozzle broke. The overland flow was measured accurately with tipping buckets.

The sprinkling device was built to apply water on the whole area of rainfall application or only on 2/3 of the area (Figure 2.1). Water without the dye tracer Brilliant Blue was applied to the wet and instrumental plot on the 1st day. The measured soil water regime showed the reaction of the dry plot. Wet initial conditions were produced on the wet plot (Figure 2.3 –1st day). The next day, water with Brilliant Blue was applied to the wet, dry and instrumental plots. Thus, the soil water measurements show the reaction of a wet plot. This procedure allowed the simultaneous staining of the dry and the wet plot and the monitoring of the soil water changes for the dry and wet initial conditions with only one instrumentation set-up (Figure 2.3 –2nd day).

### 2.3.3 Soil water regime

The water regime in the soil of the instrumentation plot was measured prior, during and after the sprinkling experiments. The water content changes were monitored with two or three TDR probes (Model MP-917, ESI Environmental Sensors Inc.). The probes are long rods with five 15 cm long segments measuring an average moisture content over each segment (Type PRB-H). The MP-917 instrument interrogates each segment of the probe, analyses the data and logs a five segment probe in 60 seconds. Thus, the soil moisture at 10 or 15 locations was measured in intervals of two minutes. The probes were installed slightly inclined from the instrumentation trench below the instrumentation plot to measure the water content in depth intervals of around 10 cm. Usually, the water content was monitored to a depth of 100 cm.

Four to six tensiometers were installed horizontally from the trench at different depths with a smaller spacing in the topsoil. The tensiometer tubes were 90 cm or 120 cm long (Type 2630AL, Soilmoisture Equipment Corp.). The cups were 60 mm long and had an outer diam-
Experiments

1st day: sprinkling wet and instrumental plot without Brilliant Blue

2nd day: sprinkling wet, dry and instrumental plot with Brilliant Blue

3rd day: preparing 4-5 vertical sections at each plot

4th day: preparing 4-5 horizontal sections at each plot

Fig. 2.3  Experimental procedure

eter of 22 mm (Type 2630-1, Soilmoisture Equipment Corp.). Matric potential was measured with temperature compensated pressure transducers (Type 5301, Soilmoisture Equipment
Experimental setup

The instruments were covered by tinfoil to avoid radiative heating. They were installed horizontally to prevent vertical flow along the tubes and to reduce temperature effects (Buchter et al., 1999).

The tensiometers and TDR-probes were carefully excavated after the experiments. Their exact locations were surveyed and it was checked whether the tensiometer cups or TDR probes had hit a visual macropore and whether the surrounding soil was stained. If a tensiometer hits a macropore, a fast reaction to saturation might be observed due to macropore flow (Flury, 1993). Additionally, it was checked, if flow along the tubes or rods influenced the measurements.

2.3.4 Tracer application

Different tracers added to the sprinkling water were used to visualize the cumulative flow pattern of the infiltrating water. Bouma et al. (1977), for instance, used the dye Methylene Blue, van Ommen et al. (1989) used a coloring technique with iodide and chloride, Ghodrati & Jury (1990) used the dye Acid Red 1, and Flury et al. (1994) introduced using the dye Brilliant Blue FCF. The food dye Brilliant Blue FCF (C.I. 42090) was chosen for the experiments because it is one of the best compromises available to date as dye tracer to visualize flow pathways in vadose zone hydrological studies (German-Heins & Flury, 2000). Brilliant Blue FCF provides low toxicity, high visibility and high mobility. The properties of Brilliant Blue FCF were studied in detail by Flury & Flühler (1995), Perillo et al. (1998), Ketelsen & Meyer-Winde (1999) and German-Heins & Flury (2000). A strong non-linearity of the sorption isotherm was observed. Therefore, Brilliant Blue FCF was applied at a concentration of 4 g l⁻¹ to ensure that the dye is still visible after dilution and adsorption. Despite the non-linear sorption isotherm, Brilliant Blue FCF fronts are likely to be very sharp and produce a strong colour contrast to the soil material, due to a self-sharpening effect (German-Heins & Flury, 2000).

Patches with a size of 5 cm by 5 cm and with concentrations of 0, 400, 800, 1600, 3200 and 4000 g l⁻¹ of Brilliant Blue FCF were prepared on horizontal soil sections in the topsoil and in the subsoil within the experimental site after the sprinkling experiments. The solutions with different tracer concentrations were uniformly dropped on the dry soil until saturation and then the patches were photographed. Thus, the visibility limit was detected and the patches were later on used to classify the stained areas into three categories (Ch. 3.2.5).

2.3.5 Sampling strategy of soil sections

On the 3rd day of the experimental procedure and one day after the sprinkling with Brilliant Blue FCF, four to five vertical soil sections were prepared within the dry and wet plot, starting 15 cm away from the plot border (Figure 2.3 –3rd day). At least 15 cm space from the border
was left to reduce boundary effects. The spacing of the sections was 5-7 cm. The vertical sections covered an area of 100 cm by 100 cm. They were carefully prepared with a spade and the surface was smoothed with a sharp spatula.

The following day, four to five horizontal sections were prepared parallel to the soil surface at different depths with a smaller spacing near the surface (Figure 2.3 –4th day). The horizontal sections were adjacent to the last vertical section and covered an area of 100 cm by 50 cm. They were carefully prepared with a spatula and loose particles were removed with a vacuum cleaner. As the macropore openings were uncovered and cleaned, the horizontal sections could be used to classify and count the macropores (see Ch. 3.2.6).

The photographic recording of the soil sections was done according to Forrer et al. (1999). The soil profiles were photographed under daylight conditions under a whitish opaque foil (light tent) to diffuse the light and to avoid direct radiation. White reflection panels were mounted on the sides of the soil sections to balance differences in the illumination of the upper and lower part of the profile or between the centre and the corners. A grey frame with a ruler and a Kodak gray and colour scale was attached framing the soil profile. A standard colour slide film (Kodak Ektachrome Elite 200) without any optical filters was used.

For each plot four to five vertical sections and four to five horizontal sections were prepared. This sampling strategy resulted in 32 to 40 soil profiles for each experimental site.
3.1 INTRODUCTION

Dye tracer covered soil sections can be directly viewed and the pattern can be subjectively interpreted. The human brain can recognise dye patterns and their relation to soil properties very well. However, it is necessary to objectively classify the dye patterns in order to analyse and compare the results.

Dye tracer covered soil sections were frequently classified into stained and unstained areas by manually sketching the stained area of the photographs (Ghodrati & Jury, 1990; Flury et al., 1994; Peterson et al., 1997). This so-called dye coverage is then a binary image that delineates the actual flow paths of the tracer, but underestimates large and overestimates small tracer concentration. However, the manual approach is time consuming and subjective. Therefore, a semi-quantitative approach was developed to classify stained and unstained areas and to process the images of the soil sections for further analysis (Ch. 4).

In laboratory (Aebly, 1998) and field studies (Forrer, 1997) digital image analyses was used to estimate the spatial distribution of tracer concentration. However, there are still difficulties with this approach reported for field experiments (Forrer et al., 1999; Forrer et al., 2000):

1. Shadows caused by the roughness of the structured surface, macropores or stones may interfere with the spectral reflectance characteristic of the tracer. The darker regions in these shaded areas mimic a larger concentration.
2. The background signal of a soil is unknown, because the same profile cannot be photographed with and without tracer.
3. A soil profile consists of different horizons with different reflectance characteristic and texture.

Image analyses of heterogeneous soil profiles is especially affected by these difficulties. Therefore, a methodology was developed that can clearly distinguish between stained and unstained areas and additional disturbing features for the quantitative analyses of the tracer distribution.

In the following section, the methodology to classify all stained horizontal and vertical soil section with a comparable quality and accuracy will be described in detail. Figure 3.1 gives an overview of the image analysis procedure written in the programming language IDL.
Image analysis

Original image of a vertical section

Corrected image

Geometric correction
Background subtraction
Colour adjustment

Classification of stained areas

Contours of classification
(visual check)

Definition of other objects

Combination

Improved classified dye pattern

Fig. 3.1  Flow chart of the image analysis procedure
3.2 IMAGE ANALYSIS PROCEDURE

3.2.1 Scanning

For each soil section, three to five pictures were taken with different duration of exposure (see also Ch. 2.3.5). The pictures with the best overall illumination and sharpness were selected. Usually, the over-exposed pictures were selected due to their better brightness and contrast. The colour slides were scanned with a SlideScanner in 24 bit colour depth with a resolution of 3072 x 2048 pixels.

3.2.2 Correction of geometric distortion

Panoramic effects are the main reason of geometric distortion of the images of the vertical and horizontal sections. The panoramic effects are mainly caused by the optical error (aberration) in the lens of the camera, the view angle to the soil section plane and to the roughness of the soil section. Because the various types of distortion could not be exactly quantified to correct the images of the soil section, another common approach was chosen in which a mathematical relationship between the addresses of pixels in an image and the corresponding coordinates of those pixels on the soil profile was established (RICHARDS, 1993). An algorithm defining the spatial transformation and an algorithm for grey-level interpolation are required.

Usually, a polynomial equation describes the spatial transformation. The equation is fitted with a least square estimation to "tie points" (TPs) that are a subset of pixels whose location are known in the distorted and corrected image. The TPs were selected from the ruler at the grey frame. Because TPs were only selected near the border of the image, applying high order polynomials would introduce large errors in the centre of the image further away from TPs (RICHARDS, 1993). Therefore, a first order polynomial was chosen, which resulted in a maximum geometric error of two pixels (equal to two millimeter in nature).

The nearest neighbour interpolation was used to assign grey levels to the geometrically corrected image. This method simply choose the grey levels from the closest pixel of the input coordinate that exactly match the coordinate of the pixel of the corrected image. The nearest neighbour resampling is a common method because the new image still consists of the original brightness values, simply rearranged in position to give a correct image geometry (RICHARDS, 1993).

Geometric correction reduces the resolution of the image. One pixel of the geometrically corrected image corresponds to a square of 1 mm x 1 mm in the soil for the vertical section and 0.5 mm x 0.5 mm for the horizontal section. These resolutions provide enough detailed information and prevent interpolations of the original image.
3.2.3 Background subtraction

The soil profiles were only illuminated with daylight, thus the lower part of the vertical sections and the corners of the horizontal sections were darker than the other portions. Background subtraction was used to compensate the images for the unevenness in the illumination. For this purpose, the RGB (red-green-blue) image was converted into the HSV (hue-saturation-value) colour space. The variation of illumination in the V space was extracted from the values of the grey frame. In a homogeneous illuminated image, the V values on the grey frame would be constant. To generate the background image, 15 to 20 actual V(x,y) values on the grey frame were sampled and the median within five neighbouring points was calculated. The background image was interpolated from the V(x,y) values to a smooth quintic surface and divided by the mean of the V colour space. The corrected V plane, as a product of the background image with the original V colour space, was finally combined with the unchanged H and S plane. The planes were then converted into the RGB colour system.

3.2.4 Colour adjustment

The spectral composition of the daylight changes during the day. As the photographs were taken at different times under daylight, the brightness value of every channel differs between the images. A colour adjustment is therefore necessary to guarantee comparable images. The Kodak grey scale, which consists of 20 patches from white to black, was used for the adjustment. The mean brightness value of every channel for the patch no. 6 of the grey scale was set to 255, because very bright regions were not of interest for the analysis. The darkest patch was set to 0 and the remaining values were linearly stretched between 0 and 255 to calculate norm values for every channel. This procedure is also known as saturating linear contrast enhancement (Richards, 1993).

Because the grey frame and grey scale were not longer necessary for the further analysis, the images were cut along the grey frame resulting in a size of approximately 1000 by 1000 pixels for the vertical sections and 2000 by 1000 pixels for the horizontal sections. All preprocessed images were stored in the tagged image file format (TIFF).

3.2.5 Classification of stained areas

Because estimating the spatial distribution of tracer concentration on heterogeneous soil profiles still raises difficulties (Forrer et al., 2000), a robust semi-supervised classification technique was applied to distinguish between stained and unstained areas and to classify the tracer concentration into three categories, based on the study of Aeby et al. (1997).

After having tested different classification methods (e.g. maximum likelihood classification), image segmentation, where each pixel is assigned to a particular object or region, was chosen
To classify objects by segmentation, a thresholding of the grey level histogram is possible, if all objects have approximately equal contrast above the background. The optimum threshold can be selected, if the objects and the background are characterized with a bimodal histogram. One peak corresponds to the background and the other to the objects. In cases like this, the sensitivity of placing the threshold at the minimum separating the two maxima of the histogram is minimised and the histogram can be used for the segmentation process (Castleman, 1996).

However, this segmentation technique can only be applied, if visual properties of the object (stained areas) and the background (unstained soil) can be found. To identify the visual properties of the stained areas in relation to the unstained soil, test patches with different dye concentration were prepared at each experimental plot in the topsoil and in the subsoil. The selected concentrations were 0, 400, 800, 1600, 3200 and 4000 mg l⁻¹. The images of each patch (size 5 by 5 cm) were pre-processed in a similar way as the soil profiles. The colour values of the RGB colour planes were not suitable for the segmentation, because the colour values of the different dye concentrations were correlated. In the HSV colour space, a high relation between the H and V values and the concentration was detected (see also Ewing & Horton, 1999). However, the values were not linearly correlated to the dye concentration and heterogeneity of the soil disturbs the correlation. Therefore, a linear regression model was not adapted to classify the images, as done by Forrer (1997). A new algorithm was developed, which separates the different concentrations and the unstained areas independently from the underlaying soil structure and soil colour.

\[
T = \left( \frac{H}{360\pi} \times (1 - V) \right) \times 100
\]  

(3.1)

The value \( T \) of Equation 3.1 was then used in combination with the concentration patches to classify the images into four categories:

- Unstained areas (\( c < 400 \text{ mg l}^{-1} \) = detection limit with this method
- Stained areas with low concentration (\( 400 \text{ mg l}^{-1} < c < 1000 \text{ mg l}^{-1} \))
- Stained areas with medium concentration (\( 1000 \text{ mg l}^{-1} < c < 3000 \text{ mg l}^{-1} \))
- Stained areas with high concentration (\( c > 3000 \text{ mg l}^{-1} \))

The results of the classification were improved by a conditional dilation algorithm (Serra, 1988). This algorithm uses two thresholds to partition the image into three classes. The upper and lower class certainly belong to the object or the background. The middle class is the uncertainty range. If a pixel value belongs to the uncertainty range, the neighbouring pixels are used to decide whether the uncertain pixel belongs to the upper or lower class (contextual classification). The search area around the uncertain pixel can be defined according to the proposed spatial arrangement. The algorithm works iteratively until no more uncertain pixels can be found in the neighbourhood of already classified pixels. The conditional dilation algorithm results in images with a higher spatial coherence and a lower interference of noise.
The overall classification firstly separated unstained and stained areas. The stained areas are then classified into the three concentration categories. The thresholds were chosen according to the concentration patches of the experimental site. The classified pictures were visually checked for agreement. For 15% of the images, the thresholds were shifted and the classification had to be repeated. Finally, a median filter with a rectangular area of interest of 3 pixels was applied to remove misclassified single stained pixels.

### 3.2.6 Classification of macropores in horizontal sections

Macropores (holes or cracks with an area larger than 2 mm²) that were visible on the images of the horizontal sections were classified. Macropores appeared as darker areas surrounded by stained or unstained areas. Therefore, the macropores had to be detected independently from the surrounding reflectivity. A part of each horizontal image was used as a training set where the visible macropores were digitized. Different algorithms were tested to classify the macropores and the results were compared with the training sets. The algorithm should fulfil four criteria:

- only macropores should be detected without classifying other areas.
- the shape of macropores should be classified correctly.
- the area of macropores should be classified correctly.
- the algorithm should work independently from image properties like illumination, surface roughness, and percentage of stained areas.

Finally, the following expression was derived to calculate the values $r$ for each pixel $(i,j)$ for the grey colour image, which was then used to perform an image segmentation with the conditional dilation algorithm:

\[
 r(i, j) = \frac{w^2}{\sum_{m=0}^{w-1} \sum_{n=0}^{w-1} V(i + m - w/2, j + n - w/2)} V(i, j)
\]  

(3.2)

where $w$ is the window width of the mean filter that is set to 40 and $V$ is the value of the V colour space.

On average, the correctly classified macropore area for all training sets was 67% of the digitized macropore area. The percentage of correctly classified macropores was around 90%. Because of slight variations in the optimal threshold for the segmentation, an initial guess was used to classify the image. If the result was not satisfying after a visual check, the image was reclassified with a variation of the threshold. After the segmentation procedure, a median filter with a dimension of 4 pixels was applied to remove classified areas with an area smaller than or equal to 1 mm² (4 pixels).
3.2.7 Classification of other objects

Three other objects in the images were identified to provide additional information for the dye pattern analysis:
• Grass and soil surface
• Large stones
• Shadows near the border of the image.

The vertical images include the grass cover on top of the image. The border between grass and soil is the soil surface. This border was manually digitized and the area above was classified as grass. For all vertical images, the average soil surface is defined as the lowest row of the image, where the classified grass coverage exceeds 50% of the total image width. This row is the reference to calculate soil depth within the vertical image.

Larger stones (diameter > 20 mm) were manually digitized, because stones have different reflectances and could not be classified automatically. The digitized stones mark areas, where flow through a stone is not possible, but where flow around a stone is quite frequent. The horizontal sections show also shadows near the edge of the image, where the soil was accidentally removed. Such areas were manually digitized and were not considered in the further analysis of the images.

3.2.8 Storage of the classified images

The images of the different classification steps were combined to one final classified image and stored in the graphics interchange format (gif). Table 3.1 gives the identification codes and colours of the classified objects.

Table 3.1 Identification codes and colours of the classified objects

<table>
<thead>
<tr>
<th>Code</th>
<th>Object</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Unstained areas</td>
<td>light gray</td>
</tr>
<tr>
<td>1</td>
<td>Stained areas with low concentration</td>
<td>light blue</td>
</tr>
<tr>
<td>2</td>
<td>Stained areas with medium concentration</td>
<td>blue</td>
</tr>
<tr>
<td>3</td>
<td>Stained areas with high concentration</td>
<td>dark blue</td>
</tr>
<tr>
<td>4</td>
<td>Dark areas in vertical images</td>
<td>black</td>
</tr>
<tr>
<td>5</td>
<td>Grass above the soil surface</td>
<td>green</td>
</tr>
<tr>
<td>6</td>
<td>Stones</td>
<td>gray</td>
</tr>
<tr>
<td>9</td>
<td>Shadows near the border of the image</td>
<td>white</td>
</tr>
<tr>
<td>10</td>
<td>Macropores in horizontal images</td>
<td>red</td>
</tr>
</tbody>
</table>
3.2.9 Improvement of classified dye pattern

The classified dye patterns still had some flaws. Small areas in the organic rich topsoil were classified as dark areas, which were in reality dyed. Small connected stained areas were classified to be unconnected. To correct these defects, mathematical morphology was applied to the image analysis (details in Soille, 1999).

Mathematical morphology uses concepts from set theory, geometry and topology to analyse geometrical structures in an image. It examines the geometrical structure of an image by probing it with a structuring element ($B$) characterized by shape, size, and location of its centre. This procedure results in operators that are well-suited to explore geometrical and topological structures. If such operators are applied to an image, meaningful information can be distinguished from irrelevant distortions.

There are two fundamental types of mathematical morphology operations, namely dilation and erosion. Dilation, in general, causes objects to dilate or grow in size; erosion causes objects to shrink. The amount and way of growing or shrinking depends on the structuring element. Erosion of a binary image $X$ ($X_{st}$ = stained pixels, $X_{unst}$ = unstained pixels) is defined in Equation 3.3, dilation in Equation 3.4.

$$X_c = X \ominus B = (x, B \subset X)$$

$$X_c = X \oplus B = \{x, (B \cap X) \neq 0\}$$

With the help of these operators, the classified dye patterns were improved. The selection of the structuring element depends on the orientation of the image. The two selected structuring elements for the vertical and horizontal sections are shown in Figure 3.2.

![Structuring elements](image)

**Fig. 3.2** Structuring elements ($B$ = dark area, $o$ = center)

The first algorithm was developed to find small black holes in stained areas. The binary image of the classified dark areas $X_{dark}$ was combined with the binary image of stained areas $X_{si}$ for each concentration categories:

$$X_1 = [(X_{si} \oplus B) \oplus B] \cap X_{dark}$$  

(3.5)

The second algorithm eliminated small unstained areas ($X_{unst}$) within larger stained areas:

$$X_2 = [(X_{si} \oplus B) \oplus B] + [(X_{unst} \oplus B) \oplus B] - X_{unst}$$

(3.6)
Finally, an improved classified dye pattern $X_{new}$ was calculated by combining the results of Equation 3.5 and Equation 3.6 with the binary image of the stained areas:

$$X_{new} = X_{st} \cap X_1 \cap X_2$$ (3.7)

Visually, an improvement of the classified images for all sites could be seen. The algorithm mainly reduces small areas, which were not correctly classified. For the horizontal dye pattern, Equation 3.5 is not used to calculate the improvement, because these defects were not obvious.

### 3.3 CONCLUSION

The applied image analysis procedure is a fast and objective tool to quantify the dye tracer covered soil sections. The methodology allows to clearly distinguish between stained and unstained areas. Additionally, the stained areas were classified into three concentration categories. An estimation of the continuous dye concentration distribution was not considered, because there are still some difficulties with this estimation in heterogeneous soil profiles and these continuous information is not required for the further analysis. Macropores were correctly classified with a low error. Other objects like grass and larger stones could only be manually delineated. The applied procedure proved successful for the 138 analysed images. However, the procedure may not be applicable for images of a dye covered soil section when the sampling strategy is different (see Ch. 2.3.5).
Image analysis
Dye pattern analysis

4.1 INTRODUCTION

Dye tracer experiments to stain flow pathways have become more and more common to visualize and describe the effects of macropore flow in soils. However, there is no generally accepted approach to quantify the resulting dye patterns (Droogers et al., 1998). Digital image analysis allows the quantitative description of dye patterns. Quantitative parameters can be subdivided into basic and morphometric parameters like the total stained area or a geometric description of stained objects, and into more complex expressions like the fractal dimension and spatial statistics. They can be directly used to describe a dye pattern or they can be combined to classify a dye pattern. Another possibility to subdivide quantitative parameters is to describe stained objects or to describe the dye pattern as a whole (Droogers et al., 1998). An example for describing the pattern as a whole is the depth function of the dye coverage of a soil profile (e.g. Flury et al., 1994; Ghodrati & Jury, 1990). The total number of separate objects per depth was calculated to describe the preferential behaviour of the flow process (Perillo et al., 1999). The shape of separate objects as a ratio between area and perimeter was used to distinguish individual pores in terms of rounded voids or cracks (Bouma et al., 1977). Besides the analysis of dye patterns, the quantitative description of the soil structure of resin impregnated soils has initiated new methods in image analysis, which can also be transferred to dye pattern analysis (e.g. Rigrose-Voase, 1990a; McBratney et al., 1992). A more complex expression to quantify patterns is the mass fractal dimension. The mass fractal dimension describes the fractal properties of space-filling objects. Hatano et al. (1992) pioneered this approach for soils and showed that the mass fractal dimension varies considerably both among soils and with depth for a given soil. More recently, Hatano & Booltink (1998) derived the fractal dimension from horizontal dye patterns and used the fractal dimension to explain the amount of outflow due to preferential flow. Baveye et al. (1998) have shown that the mass fractal dimension depends more on the image resolution and the thresholding algorithm used to classify the dye pattern than on the characteristics of the dye pattern. They believe that a dye pattern is not a mass fractal and that the value for describing dye patterns with a fractal dimension is therefore limited.
Spatial statistical parameters can be used to evaluate the distribution of pores in dye patterns. For example, the point to nearest neighbour distances distribution (Droogers et al., 1998) or the minimal area of 50% of the dye mass (Vanderborght et al., 1999) was used to characterise the movement of water between macropores and the surrounding soil matrix (interaction) for horizontal dye patterns. The applicability of geostatistical tools like the variogram was also tested. However, the spatial statistical parameters could not better describe the dye patterns than basic parameters like number of stained objects, average area per object and shape of the objects (Droogers et al., 1998).

With regard to the objectives of this thesis, the dye pattern analysis should be able to identify flow processes in the soils only on the basis of the tracer covered soil sections with emphasis on initiation and interaction. The analysis was separately carried out for the vertical and horizontal dye patterns. The vertical dye patterns were used to derive basic parameters for the pattern as a whole using the methods of stereology. Object describing parameters in a statistical framework were additionally used to classify the vertical dye patterns in regions with different dominant flow processes (percolation in the matrix, macropores, interaction, combination, structure). The horizontal dye patterns were used to statistically describe the water exchange between macropores and the soil matrix.

4.2 VERTICAL DYE PATTERN ANALYSIS

4.2.1 Introduction

Vertical dye patterns give a comprehensive and coherent picture of the flow processes at different depths (depth function). Methods of stereology were applied to the vertical dye patterns to derive depth functions of basic parameters like volume density and surface density. These parameters cannot be directly used to identify flow processes in soils, but they are easy to derive and the dye patterns can be compared to the results of other studies. Therefore, it was tried to assign the dye patterns at different depths to different flow processes in the second part of the analysis. This classification of vertical dye patterns was based on object describing parameters, which were applied in a statistical framework. The resulting stained path width (SPW) was then used to objectively derive the depth function of flow processes in the soil for each experiment.
4.2.2 Stereology

Theory

Stereology are mathematical methods relating three-dimensional parameters defining a structure to two-dimensional measurements obtainable on sections of the structure (Weibel, 1979). In this study, the two-dimensional measurements are the dye patterns that are related to different three-dimensional parameters. Structural parameters can be correctly estimated, if the structure is isotropic or a random sampling method is used for an anisotropic structure. From a variety of parameters, which can be derived with stereological methods, two particular parameters describing the density of the structure in space were selected. The volume density, which is similar to the dye coverage, and the surface area density.

The volume density can be derived from one or two-dimensional information, because the volume density $V_V$ is equal to the areal density $A_A$ and to the length density $L_L$. Thus, the volume density can easily determined by the fraction of points laying in the structure:

$$V_V = A_A = L_L$$  \hspace{1cm} (4.1)

The surface area density $S_V$ in three dimensions is the surface area of a structure divided by the volume of the reference space. It can be estimated from the perimeter density $B_A$ in two dimensions or the intercept density $I_L$ in one dimension. The intercept density can be determined from the number of intercepts of a profile boundary with the structure divided by the total length of the profile. The relation is given by:

$$S_V = \frac{4B_A}{\pi} = 2I_L$$  \hspace{1cm} (4.2)

The depth functions of the volume and surface density with a vertical resolution of 1 mm were calculated for all 4-5 vertical dye patterns of each experiment. After the soil surface ($z = 0$) was determined for each dye pattern (Ch. 3.2.7), the depth function $f(z)$ of the volume and surface density was related to the real soil depth. Thus, an averaged depth function of each parameter for all vertical dye patterns of one experiment was calculated. The standard deviation was also calculated, but not used for further analysis, because the variation was usually low.

Volume density

The resulting depth function of the volume density, which is similar to the dye coverage, gives a first overview of the dye patterns of the experiments. The volume density was calculated separately for the three concentration classes and was then superimposed in order to indicate the total volume density. Figure 4.1 shows the depth function of the volume density for the four experimental sites and the different initial and boundary conditions of the experiments (Ch. 2.3.1).
Dye pattern analysis

The volume densities give a first impression of the differences and similarities of dye patterns from the experiments under the particular initial and boundary conditions. At the Rietholzbach site, the volume density shows, that the dye tracer stained mainly the depth range of 20-70 cm for the high rainfall intensity and the low intensity under dry soil moisture conditions. However, the tracer stained only the upper part at the experiment with low rainfall intensity and wet soil moisture conditions. At the Rietholzbach site, the sprinkling water percolated rapidly to a deeper soil layer for high rainfall intensities or dry soils.

The Heitersberg site shows a pronounced staining of the upper soil layer for all experiments. The soil moisture conditions determined the thickness of the stained upper soil layer, espe-
cially for the experiments with the high rainfall intensity. The soil below 30 cm is only slightly, but continuously stained. The volume density of this layer is higher for the dry soil moisture conditions, but the differences between the high and low rainfall intensity are only minor.

The results of the experiments with the high rainfall intensity at the Koblenz site were affected by a heavy rainstorm in the night after the experiment, resulting in an extreme flood in northern Switzerland. Although the surface of the plot was protected by a tent, the groundwater table reached the soil surface. The groundwater leached the dye tracer from the soil under the experimental plot and delayed the preparation of the soil section by one week. The results are labelled with a question mark as the dye patterns were heavily disturbed and cannot be used for further analysis. The experiment with the low rainfall intensity produced a similar pattern as observed at the Heitersberg site. The upper soil layer is extensively stained and the lower part is only slightly stained. In contrast to the sharp drop of the volume density at the Heitersberg site, the Koblenz site shows a more gradual decrease of the volume density with depth.

The depth functions of the volume density at Niederweningen differ distinctly from the results of the other sites. The staining of the upper soil layer is more expanded for the dye patterns of the low rainfall intensity. At a depth of 30 to 40 cm, the volume density shows a local minimum. Below 40 cm, the volume density increases again. The depth and height of the peak depends on the boundary and initial conditions. The staining never reaches the bottom of the vertical soil section (100 cm).

The depth functions of the volume density show distinct differences between the experimental sites, but also similarities depending on rainfall intensity and initial soil moisture conditions. Particularly the volume density of the experiments with the low rainfall intensity and the dry soil show more similarities for the sites than the other boundary and initial conditions.

Surface area density

The depth function of the surface area density was calculated for the stained areas without differentiating between the concentration classes, because the surface area density is quite sensitive to errors of the image analysis procedure. The depth function of the surface density should be interpreted together with the depth function of the volume density, because the volume density can be different for the same surface density. For example, the surface density and the volume density can be low because small stained areas have also a small surface. However, the volume density can be high and the surface density can be low, because a stained object covering the whole soil volume has a small surface. Figure 4.2 illustrates the depth function of the surface area density.

For the high rainfall intensity experiments at the Rietholzbach site, the surface area density change little with depth as the geometry of the stained areas is similar between the two experiments and within the soil. The pattern of the experiments with the low rainfall intensity shows a distinct peak in 60 cm depth (dry) and in 25 cm depth (wet). The peaks coincide with a sharp
Dye pattern analysis

The four depth functions of the surface area density of the Heitersberg site are quite similar. The surface area density shows also a peak at the same soil depth where the volume density decreases. Below this peak, the surface density declines. However, the surface density is relatively high compared to the volume density. Only small stained objects with a large surface can explain this behaviour. Especially patterns from the experiments with the low rainfall intensity show a high surface area density in the middle part of the profile due to many distinct stained features, which reach this depth.
The significance of the results of the Koblenz site are limited due to the above mentioned interferences during the experiments with high rainfall intensity. The surface area density of the patterns for the experiments with low rainfall intensity show low values compared to all other experiments. This means that mainly larger stained areas characterise these experiments. The patterns of all experiments of the Niederweningen site are comparable in terms of their distinct peak of the surface density in the depth range of 30 to 40 cm. This range correlates to the local minima of the volume density. The pattern splits in a lot of small features with a low volume density, but high surface density in the depth range. The surface density declines below 40 cm despite an increase of the volume density. Thus, the pattern changes to larger features with a relatively low surface density.

4.2.3 Flow process oriented classification of vertical dye patterns

Introduction

The derived depth functions of volume density and surface density provide some general information on flow processes in soils. However, it turned out that the information content of these basic parameters is too small in order to characterise a dye pattern for flow processes. It was assumed that parameters describing single stained objects could be used to derive the depth function of flow processes in the soil for each experiment. First, different flow processes were defined and characteristic dye patterns were analysed to find an appropriate parameter describing the dye patterns. Different approaches were tested to distinguish between these dye patterns. Finally, the most promising approach was selected and rules were derived to classify the vertical dye patterns into depth function of flow processes. This approach only recognizes dye patterns and relates them to pre-defined flow processes. However, it provides a quantitative way to describe and easily compare dye patterns.

Flow Processes in Soils

The observed flow processes of the experiments in this study were divided into processes, in which macropores and the soil matrix are involved and processes, in which only the soil matrix is involved. A detailed description and theoretical considerations of the flow processes in soils with macropores are given in Ch. 6 and can be found in many studies (e.g. Ehlers, 1975; Bouma & Wösten, 1979; Bouma et al., 1982; Flury et al., 1994; Buttle & House, 1997; McIntosh et al., 1999; among many others). Flow in the soil matrix can be homogeneous or heterogeneous. When the matrix is spatially heterogeneous, two types of preferential flow were identified: fingering in water repellent soils, when water percolates from a fine-textured into a coarse-textured layer, or when the air pressure increases ahead of the infiltration front.
Dye pattern analysis

and *funnel flow* (Ritsema & Dekker, 1993; Bauters et al., 1998; DiCarlo et al., 1999; Doerr et al., 2000).

For the following analysis, five different flow processes in soils with macropores were distinguished (Table 4.1). In three processes macropores are involved, and in two processes only the soil matrix is involved. Table 4.1 illustrates the flow processes, names the type of flow, and lists soil characteristics that are related to each flow process and shows one characteristic dye pattern. The dye pattern is a result of the flow processes in the soil, the amount of dyed water infiltrating into the soil, and the tracer used for staining the water. Since the last two factors are similar for all experiments, the flow processes in the soil mainly control the dye patterns.

The characteristic dye patterns were selected based on soil properties that strongly influence the flow processes (Ch. 2.2.2) and the measured water regime in the soil during the sprinkling experiments (Ch. 5).

**Table 4.1  Flow processes in soils**

<table>
<thead>
<tr>
<th>Type of flow</th>
<th>Flow processes</th>
<th>Soil features</th>
<th>Example of a characteristic dye pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macropore flow with low interaction</td>
<td>Macropore in a low permeable or saturated soil matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macropore flow with mixed interaction (high and low)</td>
<td>Macropore in a heterogeneous soil matrix or macropores with variable macropore flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macropore flow with high interaction</td>
<td>Macropores in a permeable soil matrix (texture or aggregation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heterogeneous matrix flow and fingering</td>
<td>Spatially heterogeneous soil (texture or aggregation), water repellency or flow instability in coarse texture soils or texture changes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous matrix flow</td>
<td>Permeable soils (texture or aggregation)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An obvious possibility to distinguish the characteristic dye patterns is the extent and distribution of the stained objects. For example, the characteristic dye pattern of macropore flow with low interaction shows many long but narrow features, whereas the macropore flow with mixed...
interaction shows a distribution of stained objects with different width. Therefore, a distribution describing the width of the stained objects for each depth is a promising way to distinguish the characteristic dye patterns and thus, to recognize and classify all dye patterns of the experiments.

**Stained path width (SPW)**

A possibility to derive the width of the stained objects for each soil depth is to measure their extension on the dye patterns. Referring to the theories of stereology, this one dimensional extension is called intercept length and estimates the area of the object in two dimensions, if the object is isotropic (Weibel, 1979). Therefore, the object width for a given depth of the vertical dye pattern is used as a proxy for the size of the object at this soil depth (Figure 4.3).

![Figure 4.3](image)

*Fig. 4.3 Vertical sections and the definition of stained path width*

Because the object width describes the extension of a stained flow pathway, it is referred to as stained path width (SPW). The depth function of the stained path width for each object is evaluated for each vertical dye pattern. This procedure results in a frequency distribution of SPWs for each soil depth (Figure 4.4). The SPW was then classified into eight classes and the volume density of all objects within each class was calculated. The volume density is the total SPW divided by the width of the section (1000 mm). The SPW classes were sorted according to their size and the volume densities with their related SPW class were superimposed. The depth function of stained path width for each experiment can be derived by combining all vertical dye patterns of each experiment.

Figure 4.5 illustrates the resulting depth functions of stained path width for each experiment. The SPW was calculated without differentiating between the concentration classes of the stained areas. Because the SPW classes are shown per volume density, the maximum value is equal to the value for the volume density of all concentration classes in Figure 4.1.

**Flow process classification**

The stained path width (SPW) was also derived for the characteristic dye patterns in Table 4.1.
**Dye pattern analysis**

**Fig. 4.4** Procedure to derive the depth function of stained path width (SPW)
An evaluation of the SPW showed that three categories of SPWs are necessary to distinguish between the five flow processes. The chosen limits of 20 mm and 200 mm of SPW are only valid for the experimental set-up in this study. For example, the lower category represents flow pathways, where the dyed water flows in macropores and stains only a small area surrounding the macropore. The evaluation also revealed that the volume density is not needed to distinguish between the five flow processes. Thus, the proportion of the three remaining SPW classes relative to the volume density were used to develop a classification rule. This rule was...
Dye pattern analysis

Fig. 4.6 Classification rule of flow processes using three SPW categories

tested on several characteristic dye patterns in order to recognize and classify the dye pattern consistent. The classification rule is illustrated as a ternary diagram in Figure 4.6.

The objective classification of the vertical dye patterns of each experiment into a depth function of flow processes was performed according to the following steps. The three SPW categories at every soil depth were derived from the depth functions of SPW (Figure 4.5) and the respective proportions were determined. Then, the classification rule (Figure 4.6) was used to assign a depth function of flow processes to each experiment. Afterwards, a median filter with a window width of 2 cm was applied to the depth function of classified flow processes to remove small scale artifacts. Figure 4.7 shows the resulting depth functions of the classified flow processes for each experiment, except for the experiments with high rainfall intensity at the Koblenz site (see Ch.).

A first glance at the depth functions of the classified flow processes shows the continuity of each flow process and a frequently occurring transition from a specific flow process to another one. A more detailed look at the profiles for each experiment shows comparable differences and similarities for the experiments as already stated in the previous sections. For the Rietholzbach site, the classified flow patterns for high and low rainfall intensity differ considerably. The experiments with high rainfall intensity caused mainly macropore flow with high interaction in the upper 60 cm, without a transition zone at the soil surface. The other two classified flow patterns show transitions from homogeneous matrix flow near the soil surface via heterogeneous matrix flow to macropore flow with high, mixed and low interaction. The vertical extent of each process depends on the initial soil moisture conditions. Macropore flow with low interaction dominated the flow below 60 cm for all experiments.

The results of the Heitersberg site are quite similar for all experiments. In the upper soil layer, mainly flow in the soil matrix determines the flow processes. The vertical extent of the matrix
flow depends on the initial soil moisture conditions. Below a soil depth of 30 cm, a sharp transition towards macropore flow with a low interaction can be observed for all experiments. Thus, the boundary and initial conditions do not influence the processes below 30 cm.

As already mentioned, the results for the Koblenz site can only be evaluated for low rainfall intensity. The results are similar to the Heitersberg site, but the transition zone from matrix flow to macropore flow with low interaction is larger. The experiment under dry initial conditions also shows a deeper zone that is dominated by matrix flow processes near the soil surface.
The experiments at the Niederweningen site are governed by a zone of macropore flow with high interaction at a soil depth below 50 cm. The extent of this zone determines boundary and initial conditions. In the depth range of 30-50 cm, macropore flow with mixed or low interaction was detected for all experiments. In the top soil layer under dry initial conditions matrix flow processes are more pronounced. The classification at this site shows that the upper soil layer channels the water into macropores, the water bypasses the next layer by macropore flow with low interaction and the water entered the soil matrix in the deepest layer.

**Conclusion**

The classification of vertical dye patterns into five different flow processes in the soil provides a concise and clear picture of the dominant flow processes occurring during the sprinkling experiments. Although the classification only determines the flow processes for each depth without considering the dye pattern above, the results showed a logical sequence of flow processes in the soil profile. These classification results will later be used to compare the modelling results (Ch. 7.1) with the observed dye patterns.

### 4.3 HORIZONTAL DYE PATTERN ANALYSIS

#### 4.3.1 Introduction

The key objective for the analysis of horizontal dye patterns is the quantification of the interaction between macropores and the surrounding soil matrix. The horizontal dye patterns provide detailed information about the location of macropores and the surrounding dye pattern. The horizontal dye patterns can also be analysed using stereology, however, the values can only be used to verify the data of the vertical dye patterns. A method was developed to describe the spatial relation between macropores and stained areas and finally to quantify the interaction. This method is based on statistical parameters to evaluate the distribution of pores in dye patterns by a point to nearest neighbour distances distribution (DROOGERS ET AL., 1998).

#### 4.3.2 Method

In a first step the Euclidean distance of each pixel to the nearest macropore was computed from the classified horizontal dye pattern. Figure 4.8a shows an example of the resulting Euclidean distance map. Then, the Euclidean distance map was overlaid with the dye pattern of the same horizontal section (Figure 4.8b). In the next step the frequency distribution of the Euclidean distance map under the condition that the pixel was stained was computed. The three concen-
tration classes of stained areas were not considered. The so-called stained distance distribution (SDD) characterises the spatial distribution of tracer between the macropores. The stained distance probability is defined as the number of occurrences divided by the total number of pixels in the section.

![Example of (a) Euclidean distance map derived from macropores and (b) overlaid with stained area for a horizontal section](image)

The cumulative distribution was derived from the stained distance distribution and from the frequency distribution of the Euclidean distance map without considering the dye pattern. Finally, the difference between the cumulative distribution of Euclidean distances and the cumulative distribution of stained distances was calculated for each horizontal dye pattern. The resulting function is referred to as cumulative stained distance (CSD). The CSD specifies the following characteristics of each horizontal dye pattern:

- the value at a distance of 0 mm describes the proportion of stained macropores.
- the value at the maximum distance of each section is equal to the volume density.
- how fast the curve drops is a measure of the average staining distance.
- the shape of the distribution describes the pattern of the stained area in relation to the macropores.

Figure 4.9 shows the variety of horizontal dye patterns from selected experiments. The method should allow to characterise the patterns and extract information related to interaction.

4.3.3 Results

A detailed description and evaluation of the results for each horizontal dye pattern would not be reasonable. Therefore, the results of the stained distance distribution (SDD) and cumulative stained distance distribution (CSD) will be compared with some selected dye patterns in order to easier imagine the characteristics of the pattern. First, the results of the horizontal dye pat-
Dye pattern analysis

**Fig. 4.9** Example of horizontal dye patterns
tern of the high-dry experiment at the Rietholzbach site (Figure 4.9a) are compared with the
corresponding distributions. The section shows small contiguous stained areas, mainly
grouped around macropores. There are also large unstained areas. The related distributions are
shown for the same dye pattern in Figure 4.10a and Figure 4.11a. The peak of the SDD is broad
and the probability for larger distances is still high. Thus, the expansion of the stained areas
around the macropores is quite large, which can also be seen in the slow drop-off of the CSD.
The CSD starts at a value of around 0.8, because the immediate surrounding of all macropores
is not completely stained.

![Fig. 4.10 Selected stained distance distribution of horizontal dye patterns](image)

The patterns of the two selected sections of the low rainfall intensity experiments at the
Rietholzbach site (Figure 4.9b and Figure 4.9c) look quite similar. Only the concentration is
different, but as already mentioned the concentration classes were not considered in the ana-
lysis. Both sections show a quite contiguous pattern with few macropores. However, there are
also some unstained areas. The SDDs of both sections look also quite similar with a broad dis-
tinct peak and a slow decrease (Figure 4.10b and c). Only the CSDs show small differences, as
the curve drops slower for the section of the low-wet experiment. This difference can be seen
in the dye patterns, as the staining around the macropores is more expanded for the section of
the low-wet experiment.

At the Heitersberg site, the dye pattern in the subsoil of the high-dry experiment shows small
stained areas around the macropores (Figure 4.9d). The corresponding CSD is characterised
by a very fast drop at small distances (Figure 4.11d). The small value at large distances points
to a volume density of 0.04. However, the high value at zero distance means that the surround-
ing of many macropores is stained, which can also be seen in the horizontal dye pattern. The
resulting SDD is difficult to characterise, due to the low values of stained probability. However, the values at a small distance show a significant decrease towards larger distances. The other example of the Heitersberg site is the dye pattern near the soil surface of the low-wet experiment (Figure 4.9e). The stained area is very large and only some small spots are unstained. Because the macropore density is quite high, the SDD results in a narrow peak at a distance of 20 mm. The corresponding CSD shows a nearly constant value at a probability of 1.0.

For the Koblenz site only one dye pattern of the low-wet experiment was selected (Figure 4.9f). The pattern shows some stained spots, mainly clustered around some macropores. But there are also some macropores where the surrounding areas are not stained. The corresponding SDD in Figure 4.10f shows a low stained probability and a distinct peak at a distance of 8 mm. The shape of the curve looks like a reduction of the SDD of the upper soil layers. The CSD decreases relatively slowly compared to the CSD of the Heitersberg site. The low value of 0.55 at zero distance can be explained by many macropores showing no staining of the surrounding soil matrix.

The pattern of the high-wet experiment at the Niederweningen site is quite different compared to the patterns already discussed (Figure 4.9g). The pattern illustrates a kind of a stained network. The shape of the corresponding SDD shows a long tailing. The shape of the CSD is more distinct with a fast drop at low distance and then a lower decrease after an inflexion point at a distance of 12 mm. The shape of the CSD is a result of the networked dye pattern. The staining around the macropores stops only in some directions, but in other directions the staining
Horizontal dye pattern analysis

explores. This networked pattern may be a result of a heterogeneous soil matrix due to cracking and aggregation.

The last example provides the dye pattern in the subsoil for the low-wet experiment at the Niederweningen site (Figure 4.9h). This pattern is characterised by some larger spots around one or more macropores. Compared to the other examples, the stained areas are well-defined. The corresponding SDD shows relatively low probabilities, but a long tailing. The shape of the CSD is characterised by a slow decrease and a final value at 0.3. The slow decrease is a result of the large, well-defined stained area around the macropores. The value of 0.8 at zero distance again indicates that the surrounding of some macropores is unstained. This behaviour means that water did not flow in some macropores, hence, no coloured water could stain the surrounding soil matrix.

4.3.4 Conclusion

The developed method to analyse the horizontal dye patterns describes the spatial relationship between visible macropores and stained soil matrix. The resulting stained distance distribution (SDD) and cumulative stained distance distribution (CSD) provide a comprehensive characterisation of this relation. The distributions characterise not only the dye pattern but also the direct staining of the soil matrix around macropores and the extension of the staining. Thus, the shape of the CSD quantifies the interaction. The cumulative staining probability at a distance of 0 mm describes the water flow distribution in the macropores. If the surrounding soil matrix of some macropores was not stained and a homogeneous interaction is assumed, dyed water did not flow in these macropores. A possible reason for this unequally distributed water flux in macropores is the initiation of macropore flow (Ch. 6.2). The results, especially the water flow distribution in the macropores, can be used to verify the modelling results (Ch. 7.1).
Dye pattern analysis
5.1 INTRODUCTION

The water regime in the soil of the experimental plots was measured before, during, and after the sprinkling experiments with TDR probes and tensiometers. Details of the instruments and the survey can be found in Ch. 2.3.3. The temporal soil water regime measurements were used to determine water content changes and the time of saturation at different depths and, additionally, the saturation deficit at the beginning of the experiment for each soil layer.

5.2 WATER BALANCE OF THE PLOT

The water balance of the experimental plot during the sprinkling experiment is expressed by the following equation:

\[ P = OF + SSF + \Delta SM \]  

where the total rainfall \( P \) is equal to the sum of overland flow \( OF \), the lateral or vertical subsurface flow \( SSF \) and the change of soil moisture \( \Delta SM \) within the soil profile. The total rainfall and the overland flow was measured accurately during the sprinkling experiments (Ch. 2.3.2). In this context, subsurface flow is the water flowing vertically into the bedrock or subjacent soil layers below 100 cm depth or horizontally within a saturated zone above a low permeable bedrock. The soil moisture change was determined with TDR probe measurements (Ch. 2.3.3). It was intended from the experimental set-up to measure the depth range from the soil surface to a depth of 100 cm. However, only 50-90% of the soil profile was surveyed at the sites due to a slight change of the inclination of the rods. The error of the TDR probes measurement (0.015 to 0.02 m\(^3\)m\(^{-3}\), Frueh & Hopmans, 1997) and the limited region of influence around the TDR probe (90% of the field of influence is within 3 cm distance from the probe axis) limit the accuracy of the results. Because of these limitations, the total soil moisture change within the upper 100 cm of the soil was calculated with three different approaches. The first approach uses only the measured depth range of the TDR probes to calculate the soil moisture change.
between the start and the end of the sprinkling. For the second and third approach the TDR measurements were extrapolated to cover the whole depth range of 100 cm. For the second approach the soil moisture changes were estimated with the soil moisture profile at the end of the sprinkling; for the third approach the soil moisture profile 2 hours after the experiment was used. The subsurface flow could not be directly measured. Only some qualitative conclusions could be drawn from observed staining of the bedrock or from observing tracer in the neighbouring creek.

In Table 5.1 the directly measured components of the water balance are summarised. The difference between total rainfall and overland flow is the infiltrated water \( I \). In Table 5.2, the infiltrated water is compared with the estimated soil moisture changes and the occurrence of subsurface flow.

<table>
<thead>
<tr>
<th>Site</th>
<th>Intensity</th>
<th>Soil moisture</th>
<th>Sprinkling ( \Delta t ) (min)</th>
<th>( P ) (mm h(^{-1}))</th>
<th>( P ) (mm)</th>
<th>( OF ) (mm)</th>
<th>( I ) (mm)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rheinholzbach</td>
<td>high</td>
<td>dry</td>
<td>75</td>
<td>69.2 (±9.3)</td>
<td>86.5</td>
<td>19.1</td>
<td>67.4</td>
<td>fast response of OF</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>71</td>
<td>62.2 (±8.8)</td>
<td>73.6</td>
<td>2.7</td>
<td>70.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>360</td>
<td>15.2 (±1.5)</td>
<td>91.7</td>
<td>0</td>
<td>91.7</td>
<td>for 10 min 50 mm h(^{-1}) (hose break)</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>351</td>
<td>11.2 (±2.4)</td>
<td>65.2</td>
<td>0</td>
<td>65.2</td>
<td></td>
</tr>
<tr>
<td>Heitersberg</td>
<td>high</td>
<td>dry</td>
<td>74</td>
<td>64.3 (±6.0)</td>
<td>79.3</td>
<td>1.0</td>
<td>78.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>72</td>
<td>65.6 (±7.8)</td>
<td>78.7</td>
<td>7.0</td>
<td>71.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>360</td>
<td>12.2 (±1.6)</td>
<td>73.1</td>
<td>0</td>
<td>73.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>350</td>
<td>13.2 (±1.1)</td>
<td>77.2</td>
<td>0</td>
<td>77.2</td>
<td></td>
</tr>
<tr>
<td>Koblenz</td>
<td>high</td>
<td>dry</td>
<td>73</td>
<td>61.2 (±3.8)</td>
<td>74.4</td>
<td>1.7</td>
<td>72.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>75</td>
<td>62.1 (±5.8)</td>
<td>77.6</td>
<td>4.9</td>
<td>72.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>345</td>
<td>13.0 (±2.5)</td>
<td>75.0</td>
<td>0</td>
<td>75.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>315</td>
<td>13.1 (±1.7)</td>
<td>68.7</td>
<td>0</td>
<td>68.7</td>
<td>(hose break)</td>
</tr>
<tr>
<td>Niederwangen</td>
<td>high</td>
<td>dry</td>
<td>70</td>
<td>64.9 (±6.4)</td>
<td>75.7</td>
<td>0</td>
<td>75.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>68</td>
<td>68.0 (±9.2)</td>
<td>77.1</td>
<td>0.8</td>
<td>76.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>380</td>
<td>11.8 (±1.7)</td>
<td>70.7</td>
<td>0</td>
<td>70.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>359</td>
<td>13.0 (±2.3)</td>
<td>77.7</td>
<td>0</td>
<td>77.7</td>
<td></td>
</tr>
</tbody>
</table>

Values of total overland flow smaller than 2 mm were probably produced by small saturated or low permeable areas near the overland flow collector. The low amounts of observed overland flow at the Heitersberg site were not consistent with results of sprinkling experiments covering an area of 60 m\(^2\) in which high amounts of overland flow were observed (Scherrer, 1997). Because the dominating runoff process of this site for wet initial conditions was saturation overland flow, boundary effects of the small experimental scale influenced the measurements.
### Water balance of the plot

<table>
<thead>
<tr>
<th>Site</th>
<th>Intensity</th>
<th>Soil moisture</th>
<th>I (mm)</th>
<th>ΔSM (mm)</th>
<th>Remark to SSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rietholzbach</td>
<td>high</td>
<td>dry</td>
<td>67.4</td>
<td>65</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>70.9</td>
<td>67</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>91.7</td>
<td>111</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>65.2</td>
<td>71</td>
<td>85</td>
</tr>
<tr>
<td>Heitersberg</td>
<td>high</td>
<td>dry</td>
<td>78.3</td>
<td>45</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>71.7</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>73.1</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>77.2</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td>Koblenz</td>
<td>high</td>
<td>dry</td>
<td>72.7</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>72.7</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>75.0</td>
<td>44</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>68.7</td>
<td>16</td>
<td>23</td>
</tr>
<tr>
<td>Niederweningen</td>
<td>high</td>
<td>dry</td>
<td>75.7</td>
<td>51</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>wet</td>
<td>76.3</td>
<td>66</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>dry</td>
<td>70.7</td>
<td>80</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>wet</td>
<td>77.7</td>
<td>47</td>
<td>53</td>
</tr>
</tbody>
</table>

* measured depth range of TDR probes  
† integrated between surface and 100 cm depth using the soil moisture profile after the end of the experiment  
‡ integrated between surface and 100 cm depth using the soil moisture profile 2 hours after the end of the experiment

The results in Table 5.2 show that the experiments with the high rainfall intensity at the Rietholzbach site produced a small amount of subsurface flow. At the Heitersberg site, the subsurface flow was more pronounced for the wet soil moisture conditions. For the dry soil moisture conditions, SSF was negligible. At the Koblenz site, the subsurface flow could be directly observed in the creek some hours after the beginning of the experiment. Dye-coloured water, which percolated from the macropores into the saturated bedrock, reached a creek at 110 m distance. The values of the soil moisture changes support the hypothesis that a large amount of the infiltrating water left the soil profile. With a tracer experiment using NaCl, the flow velocity of the fast subsurface flow pathways was measured (Weiler & Naef, 2001). The high
observed velocity of 0.08 m s\(^{-1}\) indicates that the water flowed preferentially in the saturated bedrock. In contrast to the results from the Koblenz site, no soil was stained below 100 cm at the Niederweningen site. The high values of the soil moisture changes support the observations that stained water did not leave the soil profile.

5.3 SOIL WATER CONTENT

The temporal measurements of the TDR probes in different depths were used to obtain the space-time distribution of soil water content changes. Because the TDR probes were not calibrated for every soil at each site, relative measurements of the TDR probes are more accurate and can be better compared than absolute values. The data of the TDR measurements were prepared as follows:

1. Data of segments of TDR probes which were exposed to vertical flow along the rods were removed.
2. The surveyed upper and lower depths of the segments (Ch. 2.3.3) were assigned to the respective depth range of the segments.
3. The water content value at the beginning of the sprinkling was subtracted from the other values for each probe segment to obtain the water content changes.
4. The values between two consecutive measurements were linearly interpolated to a time step of one minute because the water content was measured in irregular time intervals.
5. For each experiment, the water content changes were summed up to determine the temporal changes of the total soil water content within the measured depth range of the TDR probes.

The resulting soil water content changes for each experiment are illustrated in a depth-time graph (Figure 5.1 to Figure 5.4). The time from the beginning of the sprinkling is depicted on the abscissa; the depth from the soil surface on the ordinate. The water content changes are colour-coded and illustrated for the depth range of each segment. A point corresponds to the average segment depth and the time of measurement. Grey shaded areas reflect depths at which the water content was not monitored. The total soil moisture change is shown as a gray area graph above the depth-time-graph of water content changes.

The results for the four experiments at the Rietholzbach site differ considerably (Figure 5.1). In the experiment with high intensity and dry initial soil moisture conditions, the water content increased only between 20 and 50 cm depth. The infiltrated water reached this soil layer without significantly wetting the top layer. A similar behaviour was observed for the low-dry experiment, but the layer at which the water content increased is deeper and the increase of the top layer started later. The experiments with the wet soil show a general increase of the water content from the top to the bottom.

The water content changes of the four experiments at the Heitersberg site are quite similar (Figure 5.2). The changes below 30 cm depth are very small. The water content of the top layer
Fig. 5.1  Depth-time plot of water content changes at the Rietholzbach site
Fig. 5.2  Depth-time plot of water content changes at the Heitersberg site
Fig. 5.3 Depth-time plot of water content changes at the Koblenz site
Fig. 5.4  Depth-time plot of water content changes at the Niederweningen site
increased by 15 to 25% for the dry initial conditions and much less for the wet initial conditions. The Koblenz site behaved similarly to the Heitersberg site (Figure 5.3). The soil water content mainly increased in the top layer, especially for the dry initial conditions. The change of the water content below 30 cm was very low. Figure 5.4 shows the results of the experiments at the Niederweningen site. The water content primarily changed in the top layer (0-30 cm) and in the bottom layer (50-90 cm). The change of the top layer is pronounced for dry initial conditions because of the high saturation deficit. The change of the bottom layer is pronounced for wet initial conditions. Because the saturation deficit of the top layer is nearly exhausted, the water could percolate into the bottom layer. The water content changes between 30 and 50 cm are low, thus the water bypassed the soil matrix of this layer and percolated to the bottom layer.

5.4 SOIL MATRIC POTENTIAL

The tensiometer measurements can be used to obtain the time of saturation of the soil or individual soil layers. Furthermore, the reaction of tensiometer readings can be interpreted for the location of the tensiometer cup in the soil matrix or in a macropore (see also Ch. 2.3.3). The matric potential is illustrated for each experiment (Figure 5.5 to Figure 5.8). Figure 5.5 shows the results of the matric potential measurements for the Rietholzbach site. The measurements at the beginning of the high dry experiment were lost due to a problem with the data storage module. For the experiments with high intensity, the matric potential increased (“increase of matric potential” means an increase of the values from negative to positive) at first in the lower soil layer until saturation. The measurement in the upper layer showed a delayed or no reaction during the sprinkling. The upper soil layer did not saturate. The experiment with the low intensity and dry initial condition shows a slow, continuous, and parallel increase of the matric potential at all depths. This behaviour indicates a more or less simultaneous wetting of the whole soil profile from water in macropores than percolation in the soil matrix. The reaction of the matric potential under wet conditions started at the top and propagated to deeper layers. The soil was nearly completely saturated at the end of the experiment; however, no water table built up because of the drainage of the soil profile. The results from the Heitersberg site are illustrated in Figure 5.6. The reactions of the matric potential for all experiments show a similar pattern. A sharp rise of the matric potential in the top layer was detected after the application of 10 to 15 mm of water. The matric potential increased until the top layer was saturated. Then the matric potential of the bottom layer (below 40 cm depth) increased slowly, starting at the lowest tensiometer. This behaviour can only be explained with a wetting front saturating the top layer followed by macropore flow that continuously saturated the bottom layer. Depending on the rainfall intensity, a water table built up in the soil profile. When the water table reached the surface during the high intensity experi-
Soil water regime

*Fig. 5.5  Matric potential at the Rietholzbach site (z = depths of the tensiometer cups from the soil surface, white background limits the duration of the sprinkling)*

ments, overland flow started. The overland flow rate was determined by the drainage of the soil profile. During the experiments with the low intensity, the water table levelled off at 40 to 50 cm below the surface. The drainage of the soil was sufficient to regulate the water table within this depth.

Figure 5.7 illustrates the results of the matric potential measurements of the Koblenz site. At the beginning the saturated zone was approximately at a depth of 100 to 120 cm. The high intense sprinkling resulted in a slow increase of the matric potential in the top layer, except for the tensiometer at 48 cm depth, which showed a sharp rise. This tensiometer cup was connected to a macropore as the excavation of the tensiometer showed. Thus, the tensiometer measured the water flow in this macropore. Although the top layer was never saturated during the experiment, the matric potential in the bottom layer continuously increased until saturation. However, a water table did not build up, because of the drainage of the soil. The results of the experiments with the low rainfall intensity show a similar picture to the experiments with the high intensity, except for a faster and sharp rise of the matric potential in the top layer. The low rainfall intensity was lower than the permeability of the top layer, resulting in a wetting front and a saturation of the top layer before the matric potential in the bottom layer reacted.
Figure 5.6  Matric potential at the Heitersberg site (z = depths of the tensiometer cups from the soil surface, white background limits the duration of the sprinkling)

Figure 5.8 shows the results for the Niederweningen site. The reactions of the four experiments are quite different. The tensiometer at a depth of 17 cm is striking. The reason for the sharp rise is the connection of the tensiometer cup to an earthworm channel. The reaction immediately after the beginning of the sprinkling can only be explained by an initiation of the macropore at the soil surface (see also Ch. 6.2.2). The results of the matric potential can be generalised by a reaction from top to bottom, except for the tensiometers at a depth of 21 cm respectively 23 cm. The matric potential at this depth slowly increased. The reaction below this depth depends on the initial and boundary conditions of the experiment. The experiments under dry initial conditions showed a reaction of the matric potential only for the upper tensiometer. The results for the wet experiments showed a reaction to a depth of 100 cm. For the experiments with low intensity, the soil did not saturate; however, the high intensity experiments showed a saturation at a depth of 50 cm that is probably related to a change in the hydraulic conductivity at this depth.

The matric potential measurements give a clear picture as to how saturation takes place within the soil profile and the drainage processes. If tensiometer cups are connected to macropores, the initiation of macropore flow can also be determined. From the temporal progression of the
Fig. 5.7 Matric potential at the Koblenz site (z = depths of the tensiometer cups from the soil surface, white background limits the duration of the sprinkling)

Matric potential at different depths, the influence of macropore flow or bypassing was interpreted.

5.5 SOIL HYDRAULIC PROPERTIES

Knowledge of soil hydraulic properties (water retention and hydraulic conductivity) are required to simulate water flow in the vadose zone. Measurements are the most accurate way to obtain these properties. However, the spatial variability of the hydraulic properties in soils makes it difficult to derive parameters from limited soil hydraulic measurements that are representative for the hydrological scale (Mallants et al., 1997; Schaap et al., 1998). An alternative is the use of pedotransfer functions (PTFs) that are based on soil data like texture, bulk density, etc. Although predictions by PTFs are not as accurate as measurements, they often provide the only feasible way in hydrological studies to obtain soil hydraulic properties under the given temporal and spatial constraints.
Different approaches to derive pedotransfer functions were developed and evaluated by Tietje & Tapkenhinrichs (1993). A more recent study based on a large calibration data set follows a hierarchical approach to estimate hydraulic properties with neural networks (Schaap et al., 1998). Its PTFs estimate parameters of a hydraulic model describing the water retention. The parametric approach is preferred in vadose zone modelling as it yields a continuous and closed-form equation of the water retention curve. The water retention is given by the following equations (van Genuchten, 1980):

\[
\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \left[ 1 + \left( \frac{\alpha |h|}{n} \right)^n \right]^{-m}
\]

(5.2)

where \(\theta(h)\) is the volumetric water content as a function of water pressure head, \(\theta_s\) is the saturated water content, \(\theta_r\) is the residual water content, \(\alpha\) is a scaling parameter that is inversely proportional to the mean pore diameter, \(n\) is the pore size distribution index, and \(m = 1 - 1/n\) with \(n>1\). The left part of the equation can also be expressed as:
where $S_e$ is the relative saturation, $SD_{\text{max}} = \theta_s - \theta_r$ is the maximum saturation deficit and $\Delta \theta$ is the saturation deficit. These equations in conjunction with the pore-size distribution model by Mualem (1976) lead to the van Genuchten-Mualem model describing the unsaturated hydraulic conductivity (van Genuchten, 1980):

$$K(\theta) = K_s (S_e)^2 \left\{ \frac{1}{1 - \left[ 1 - (S_e)^{1/m} \right]^2} \right\}$$

where $K(\theta)$ is the hydraulic conductivity as a function of volumetric water content and $K_s$ is the saturated hydraulic conductivity.

The saturated hydraulic conductivity should be treated carefully in soil hydrological modelling applications, as it is usually a highly sensitive parameter. For PTFs using bulk density and textural parameters, the uncertainty in the prediction of the saturated hydraulic conductivity is nearly one order of magnitude (Schaap & Leij, 2000). However, the spatial variation of the saturated hydraulic conductivity is also very high. For example, Mohanty et al. (1994) found a coefficient of variation of about 100% for 140 hydraulic conductivity measurements for different tensions in a regular grid of 100 cm.

The uncertain prediction of the hydraulic conductivity with most of the existing PTFs is partly due to the lack of incorporating critical soil structural information (Lin et al., 1999b). This is partly because there are no proper means to quantify soil structure. Therefore, a system to quantify soil structure based on morphological properties was developed by Lin et al. (1999a). Class PTFs using the resulting morphometric indices or continuous PTFs using physical properties to estimate the hydraulic conductivity for flow in micropores (pores with radius < 0.063 mm), mesopores (pores with radius of 0.063-0.5 mm), and macropores. The continuous PTFs were selected to estimate the hydraulic conductivity of the soil matrix, which is the sum of the micro- and mesopore hydraulic conductivity. The necessary physical properties are mass fraction of the clay separates and organic carbon, bulk density, initial water content and macroporosity. The analysis of Lin et al. (1999a) showed that structure related properties are required to estimate the hydraulic conductivity in the meso- and macropores.

For all sites in this study, the soil hydraulic properties were estimated for soil layers with enough information. The van Genuchten parameter were derived from soil texture, bulk density and the water content at 330 kPa. This water content was estimated using the measurements of water content and matric potential in the field. The saturated hydraulic conductivity was, on the one hand, estimated from soil texture and bulk density (Schaap & Leij, 2000) and, on the other hand, from soil texture and structure related properties (Lin et al., 1999b). Table 5.3 gives the overview of the derived parameters using PTFs.
### Table 5.3 Soil retention and conductivity parameters of the experimental sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>$\theta_r$ (cm$^3$ cm$^{-3}$)</th>
<th>$\theta_s$ (cm$^3$ cm$^{-3}$)</th>
<th>$\phi$ (cm$^3$ cm$^{-3}$)</th>
<th>$\alpha$ (m$^{-1}$)</th>
<th>$n$</th>
<th>$K_s$ (mm h$^{-1}$)</th>
<th>$K_{s^*}$ (mm h$^{-1}$)</th>
</tr>
</thead>
<tbody>
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<td>Riedholzbach</td>
<td>0-10</td>
<td>0.061</td>
<td>0.464</td>
<td>0.453</td>
<td>2.683</td>
<td>1.442</td>
<td>22.9</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.068</td>
<td>0.460</td>
<td>0.476</td>
<td>1.424</td>
<td>1.379</td>
<td>12.0</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>0.067</td>
<td>0.450</td>
<td>0.487</td>
<td>1.035</td>
<td>1.410</td>
<td>9.6</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>70-80</td>
<td>0.079</td>
<td>0.457</td>
<td>0.509</td>
<td>0.652</td>
<td>1.433</td>
<td>4.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Heitersberg</td>
<td>0-10</td>
<td>0.063</td>
<td>0.431</td>
<td>0.507</td>
<td>2.195</td>
<td>1.456</td>
<td>11.3</td>
<td>12.9</td>
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<td>0-20</td>
<td>0.061</td>
<td>0.389</td>
<td>0.437</td>
<td>2.062</td>
<td>1.381</td>
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<td>7.4</td>
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<tr>
<td></td>
<td>20-40</td>
<td>0.063</td>
<td>0.368</td>
<td>0.386</td>
<td>1.668</td>
<td>1.329</td>
<td>1.9</td>
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<td></td>
<td>40-60</td>
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<td>0.338</td>
<td>0.351</td>
<td>1.711</td>
<td>1.306</td>
<td>1.4</td>
<td>1.0</td>
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<tr>
<td></td>
<td>60-80</td>
<td>0.052</td>
<td>0.338</td>
<td>0.351</td>
<td>2.089</td>
<td>1.280</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Koblenz</td>
<td>0-10</td>
<td>0.054</td>
<td>0.410</td>
<td>0.505</td>
<td>2.070</td>
<td>1.470</td>
<td>10.7</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.056</td>
<td>0.410</td>
<td>0.491</td>
<td>1.059</td>
<td>1.456</td>
<td>10.2</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>0.068</td>
<td>0.399</td>
<td>0.451</td>
<td>0.699</td>
<td>1.574</td>
<td>3.8</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>60-70</td>
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<td>1.521</td>
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<td>5.4</td>
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<td></td>
<td>60-100</td>
<td>0.071</td>
<td>0.372</td>
<td>0.378</td>
<td>0.935</td>
<td>1.433</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Niederweingern</td>
<td>0-10</td>
<td>0.060</td>
<td>0.421</td>
<td>0.469</td>
<td>2.177</td>
<td>1.381</td>
<td>14.5</td>
<td>8.4</td>
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<tr>
<td></td>
<td>20-30</td>
<td>0.057</td>
<td>0.393</td>
<td>0.436</td>
<td>3.002</td>
<td>1.418</td>
<td>17.4</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>0.060</td>
<td>0.408</td>
<td>0.458</td>
<td>3.412</td>
<td>1.516</td>
<td>29.3</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>60-70</td>
<td>0.060</td>
<td>0.419</td>
<td>0.482</td>
<td>4.088</td>
<td>1.841</td>
<td>54.8</td>
<td>15.8</td>
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<td></td>
<td>90-100</td>
<td>0.047</td>
<td>0.387</td>
<td>0.448</td>
<td>4.334</td>
<td>1.810</td>
<td>60.7</td>
<td>14.2</td>
</tr>
</tbody>
</table>

* $\theta_r, \theta_s, \alpha$, and $n$ were determined from soil texture, bulk density, and $\theta$ at 330 kPa (Schaap et al., 1998).

† Porosity $\phi$ is calculated from soil samples (at least 4) and with a real soil density of 2.65 g cm$^{-3}$.

‡ Determined from soil texture and bulk density (Schaap & Leu, 2000).

*** Sum of micro- and mesopore hydraulic conductivity (Lin et al., 1999b).

The results for the saturated hydraulic conductivity give a comprehensive picture. The differences between the texture and the structure related approaches are usually small. However, larger differences were mainly observed in the upper soil layers, where the soil structure seems to be more important. A detailed comparison was not performed due to problems in measuring the saturated hydraulic conductivity in a macroporous and heterogeneous soil.
Soil water regime
6.1 MACROPORE FLOW

6.1.1 Introduction

Macropores are defined either by their size, their forming process (soil fauna, decay of plant roots, wetting and drying processes, freeze-thaw cycle, the erosive action of subsurface flow) or the dominant type of flow (laminar and turbulent) in the macropores (Beven & Germann, 1982). In this study, macropores are defined by their forming process. The majority of macropores at the experimental sites were formed by the anecic earthworm species *Lumbricus terrestris*. These macropores are usually vertically oriented, continuous channels (Baker & Lee, 1993).

The characteristics of earthworm channels determine the flow in the macropores. Kretzschmar (1988) has determined five main characteristics of an earthworm channel: density, mean length, angular orientation, centre coordinates and diameter. However, such a characterization of a macropore may not be sufficient. Munyankusi et al. (1994) characterized macropores by their continuity from surface to depth or between different depths, their porosity, and their size distribution. Studies to quantify a macropore network in three dimensions have shown that tortuosity and topology is as important as the length of macropores, the hydraulic radius and the macropore density (Perret et al., 1999).

Little is known about the hydraulics of flow in either single macropores or macropore networks (Beven & Germann, 1982). Flow in a single macropore was measured directly in the field (Ehlers, 1975; Wang et al., 1994; Edwards et al., 1990) and in the laboratory with artificial macropores (Smettem, 1986; Logsdon, 1995; Ghodrati et al., 1999). However, no general theory on the hydraulics of macropore flow could be developed. Theories from open channel flow and pipe flow were adopted to macropore flow (e.g. Smettem, 1986; Chen & Wagenet, 1992; Gerke & van Genuchten, 1996; Faeh et al., 1997) or regression equations between parameters characterizing macropores and the flow in macropores were derived (Germann & Beven, 1981; Hatano & Booltink, 1998). Germann & DiPietro (1996)
adopted the kinematic wave theory to macropore flow. A detailed investigation of earthworm burrows formed by *Lumbricus terrestris* resulted in the perception that burrow geometrical properties are unlikely to accurately predict water flow in macropores (Shipitalo & Butt, 1999). The assumptions of those theories are usually not valid to apply to natural earthworm channels and the input parameters of those models are difficult to determine (Trojan & Linden, 1992).

The following section about macropore flow is divided into two parts: flow in a single macropore and description of the macropore system. The first subsection introduces theories describing macropore flow, followed by measurements and results from other studies that measured flow in filled and partially filled macropores. The second subsection links the information on flow in single macropores with the description of the macropore system.

### 6.1.2 Flow in a single macropore

#### General Overview

Flow in a single macropore is often described as laminar or turbulent flow in a long tube (e.g. Workman & Skaggs, 1990; Faeh et al., 1997). Turbulent and irregular flow in macropores formed by earthworms was directly observed with laboratory experiments (described in detail in the next section) or in other studies (Bouma et al., 1979; Logsdon, 1995).

The Manning equation is often applied to calculate the average flow velocity $v$ in macropores (Chen & Wagenet, 1992a):

$$ v = \frac{1}{n} R^{2/3} I^{1/2} \tag{6.1} $$

where $n$ is the Manning roughness coefficient, $R$ the hydraulic radius with $R = A / P$ ($A =$ flow cross-sectional area, $P =$ wetted perimeter) and $I$ is the friction slope. This equation is valid for large pipes and channels with $I < 0.03$. The slope of earthworm channels, however, ranges from 0.5 to 1.0 (Perret et al., 1999 and own measurements). Additionally, air inclusions influence the more or less vertical flow. Therefore, the Manning equation and other similar equations for open channel flow and pipe flow are not valid for macropores. Measurements of the flow rate and the flow velocity in natural macropores can bridge the problem that no adequate theory to describe flow in macropores exists.

Inflow into macropores is mostly much lower than the maximum flow rate within macropores (as was determined in Ch. 6.2.4). Although the flow rate and the flow velocity in filled macropores is known, the influence of flow rate in partially filled macropores on the flow velocity remains unknown. However, this relationship is required to estimate flow velocity in partially filled macropores. Two assumptions are reasonable, how flow velocity is related to flow rate in partially filled macropores. Firstly, the hydraulic radius will decrease linear, if the wetted
Macropore flow

perimeter of the macropore remains constant despite a decreasing flow rate. This behaviour occurs in macropores where the water flows completely on the macropore wall. Secondly, the hydraulic radius will decrease non-linear, if the wetted perimeter of the macropore decreases like the water level decreases in a horizontal circular pipe. This behaviour occurs in macropores with a low slope or with a high tortuosity. These two theoretical relations between flow velocity and flow rate in partially filled macropores can be calculated with Equation 6.1.

Measurement of flow in a filled macropore

The flow rate of undisturbed macropores was measured at the experimental sites. The rate of water flowing into single earthworm burrows was measured with a macropore infiltrometer (Wang et al., 1994). The macropore infiltrometer supplies water directly into the opening of a macropore at rates greater than the macropore can accept. With a hydraulic head of 0.0 m at the macropore opening, the initial flow rate $Q_1$ depends solely on the hydraulic properties of the macropore. After the macropore is completely filled, the flow rate usually suddenly decreases to a stable flow rate $Q_2$. This flow rate depends on flow from the macropore into the surrounding soil matrix (details in Ch. 6.3). Table 6.1 summarises the results of the measurements with the macropore infiltrometer.

**Table 6.1** Average flow rate measured with the macropore infiltrometer. $Q_1$ is the initial flow rate depending on the hydraulic properties and $Q_2$ the stable flow rate depending on the interaction

<table>
<thead>
<tr>
<th>Site</th>
<th>$Q_1$ (cm³ s⁻¹)</th>
<th>$Q_2$ (cm³ s⁻¹)</th>
<th>No. of experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rietholzbach</td>
<td>6.2 ± 4.4</td>
<td>3.9 ± 3.6</td>
<td>4</td>
</tr>
<tr>
<td>Heitersberg</td>
<td>2.9 ± 1.1</td>
<td>0.9 ± 0.4</td>
<td>2</td>
</tr>
<tr>
<td>Koblenz</td>
<td>3.5 ± 2.0</td>
<td>1.6 ± 1.4</td>
<td>4</td>
</tr>
<tr>
<td>Niederweningen</td>
<td>5.7 ± 1.8</td>
<td>3.0 ± 0.8</td>
<td>6</td>
</tr>
</tbody>
</table>

The measured flow rates in macropores were similar for the different sites. The relatively low standard deviation also indicates similar flow rates in different macropores. These results are confirmed in other studies. Wang et al. (1994) measured average values of $6.5 ± 0.9$ cm³ s⁻¹ for $Q_1$ and $2.3 ± 0.5$ cm³ s⁻¹ for $Q_2$ in 33 earthworm channels built by *Lumbricus terrestris*. With a similar approach, Bouma et al. (1982) determined maximum flow rates of $6.5 ± 1.6$ cm³ s⁻¹ and steady state flow rates of $2.3 ± 0.5$ cm³ s⁻¹ in 20 earthworm channels. Shipitalo & Gibbs (2000) also measured the flow rate in 20 earthworm channels built by *Lumbricus terrestris* and determined average maximum flow rates of $2.6$ cm³ s⁻¹ for the first two minutes and steady state flow rates of $1.8$ cm³ s⁻¹. Shipitalo & Butt (1999) also used a macropore infiltrometer to measure 56 earthworm burrows and determined an average maximum flow rate of $4.3$ cm³ s⁻¹ and a steady state flow rate of $3.5$ cm³ s⁻¹. They found no significant differences between flow rates for worm-removed or worm-in burrows. Similar hydraulic and
geometric properties of earthworm channels built by anecic species (e.g. *Lumbricus terrestris*) are the main reason for the comparable results of the maximum flow rate. Thus, the maximum flow rate for these macropores can be assumed to lie within a narrow range of values.

**Measurement of flow in a partially filled macropore**

The influence of the flow rate on the flow velocity in partially filled macropores was studied with laboratory experiments. This relation was determined by measuring the steady flow rate into a macropore and the resulting flow velocity. The geometry, orientation, and wall properties of the macropore should be similar to a natural earthworm channel. However, the surrounding soil matrix should be impermeable to avoid losses to the soil matrix. This assumption was achieved by the following steps. Earthworm burrows at the Niederweningen site were cast with hot paraffin and then excavated. The position of every excavated piece was surveyed to be able to reconstruct the cast channel. In the laboratory, the channel was reconstructed, muffled with sand, put inside a form, and resinated. After the resin had hardened, the paraffin was melted at 80°C to create the original shape and similar wall properties of the macropore.

Two macropores with a length of 40 cm were reconstructed. Firstly, the maximum flow rate of each macropore was determined and then the flow rate was decreased stepwise. For each flow rate, the flow velocity was measured by tracing the water. The travel time of the tracer (Brilliant Blue FCF) was measured several times and the average flow velocity was calculated. The maximum flow velocity measured for the two macropores was 68 cm s\(^{-1}\) and 60 cm s\(^{-1}\). These results are in agreement with Dixon & Peterson (1971), who measured a flow velocity of 50 cm s\(^{-1}\) in a macropore with a cross-sectional area of 0.28 cm\(^2\).

The relative values were calculated by dividing the measured values in partially filled macropores by the measured maximum value. The relative flow velocity and relative flow rate for the two macropores is shown in Figure 6.1, together with the theoretical relations derived in the previous section. The measured values lie within the theoretical relations. If the relative flow rate is high, the measurements are closer to the assumption that water is completely wetting the macropore wall. If the relative flow is low the values are closer to the upper line because the water does not completely wet the macropore wall. Macropore no. 2 shows lower values probably due to its smaller average cross-sectional area (0.13 cm\(^2\) compared to 0.5 cm\(^2\) for no. 1). For a smaller cross-sectional area, the influence of the macropore wall remains higher.

The measured maximum flow rates (34.1 cm\(^3\)s\(^{-1}\) and 20.8 cm\(^3\)s\(^{-1}\)) are significantly larger than the values reported in Table 6.1. The higher values for the laboratory experiments are probably because of the prevention of any flow from the macropores into the surrounding soil matrix and the unhindered steady outflow at the bottom end of the macropores.
6.1.3 Description of the macropore system

Introduction

Apart from properties of flow in a single macropore, the macropore density and macropore continuity determine the total flow rate. In this section, the classified images of horizontal sections of every site are used to determine the density of macropores and the pattern of macropores. The continuity of macropores is more difficult to determine. Therefore, estimates are only possible with casting of macropores in the field and other studies found in the literature.

Density of macropores

Macropores were successfully classified from the images of the horizontal sections (see details in Ch. 3.2.6). These classified images were then used to count the number of macropores within one image. A single macropore in the image is defined as a set of pixels, which are classified as macropore, within an eight-neighbour region around the pixel under examination. After the macropores were labelled according to this definition, the cross-sectional area and the perimeter of every macropore were determined.

At the experimental sites, the majority of studied macropores are vertically oriented earthworm channels. Because this study focuses on these channels, they had to be depicted from the clas-
Macropore flow, initiation and interaction

Macropore sections. Vertically oriented channels more frequently intersect orthogonal with horizontal sections. Their projection on the horizontal sections is then more or less round. This behaviour can now be used to select labelled macropores within a specific cross-sectional area and with a certain shape (Rigrose-Voase, 1996). The shape factor $S$ is defined as:

$$S = \frac{P}{\sqrt{4\pi A}}$$

(6.2)

where the cross-sectional area $A$ and the perimeter $P$ were already determined for every macropore. A subset of vertically oriented macropores built by anecic earthworm species with a cross-sectional area of 10–100 mm$^2$ and a shape factor of 1–1.6 was then selected (Stein et al., 1998). The average macropore density of this subset (with $n = 4$ horizontal sections) is illustrated in Figure 6.2a and for all detected macropores in Figure 6.2b.

---

**Fig. 6.2** Measured macropore density for (a) macropores with 10<area<100 mm$^2$ and round shape and for (b) all macropores

Figure 6.2 shows that the macropore density of the macropore subset is quite similar for the four sites. The values range between 100 and 200 m$^{-1}$. A maximum can be detected in 40 to 50 cm, except for the Heitersberg site. The macropore density for all macropores is 2 to 5 times higher, depending on the macropore distribution of the cross-sectional area.

Other studies showed similar values. Kretzschmar (1988) determined a macropore density of 100 m$^{-2}$. Warner & Nieber (1991) measured values with computed tomography (CT) for a macropore cross-section area larger than 10 mm$^2$ of 300 to 700 m$^{-2}$ under pasture and 250 to 600 m$^{-2}$ under tillage. Otto (1990) measured an abundance of *Lumbricus terrestris* of 140 to 240 m$^{-2}$ during 2 years in a meadow in Switzerland. Ehlers (1975) counted earthworm channels in a silty soil in Germany and detected 20–170 m$^{-2}$ in a tilled soil and 45–180 m$^{-2}$ in an untilled soil with an increase of soil depth. Trojan & Linden (1998) studied the macropore density of five soils with different tillage-residue management treatments. For macropores with a cross-sectional area larger than 12 mm$^2$, they measured a macropore density of 100–200 m$^{-2}$. 
For all macropores, they measured a macropore density of 300–700 m⁻². Munyankusi et al. (1994) counted between 50 and 500 macropores per m² for a cross-sectional area larger than 12 mm². Zehe & Flühler (2001) surveyed the macropore density at two sites (valley and ridge) and showed that the density of macropores larger than 12 mm² is 100–400 m⁻² at the site in the valley and 40 m⁻² at the site on the ridge. He also measured a decrease of the macropore density with soil depth. All these studies show that the macropore density in soils, which are ecologically suitable for earthworms, is comparable to the macropore density of this study.

Pattern of macropores

The pattern of macropores and the related distribution of distances from a point to the nearest macropore are important properties related to initiation and interaction (Droogers et al., 1998). If the process generating the pattern of macropores is known, fundamental assumptions can be drawn to describe the process of interaction and initiation (see also Ch. 6.2 and Ch. 6.3). The nature of the processes generating a point pattern can be evaluated with quadrat analysis (Smettem & Collis-George, 1985; Brimicombe & Tsui, 2000). The Index of Cluster Size (ICS), which can be calculated from the point counts in each quadrat, is a straightforward method to account for the generation process:

\[
ICS = \frac{s^2}{\bar{x}} - 1
\]

where \(\bar{x}\) is the mean and \(s^2\) is the variance of the counts in each quadrat. An ICS > 0 shows the existence of clustered pattern, ICS < 0 implies a uniform pattern and ICS = 0 indicates a random pattern. The ICS depends on the quadrat size, if the data set is not synthetic, because the generation process of non-synthetic data is usually scale dependent.

In this study, macropores, which were classified from the horizontal sections, were used to calculate the ICS. To account for scale effects, the size of the quadrates was varied. The centre of each macropore was determined and the resulting point pattern was used to derive the ICS. The average ICS and for each site of all horizontal sections is given in Table 6.2.

<table>
<thead>
<tr>
<th>Site</th>
<th>Index of Cluster Size (ICS) with quadrat size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 cm</td>
</tr>
<tr>
<td>Rieholzlbach</td>
<td>0.003 ± 0.013</td>
</tr>
<tr>
<td>Heitersberg</td>
<td>-0.004 ± 0.007</td>
</tr>
<tr>
<td>Koblenz</td>
<td>-0.006 ± 0.014</td>
</tr>
<tr>
<td>Niederweningen</td>
<td>0.000 ± 0.011</td>
</tr>
</tbody>
</table>

The values show that the underlying process of the macropore pattern is random except for large quadrates where the point pattern tends to be more clustered. The higher values at the
sites of Koblenz and Niederweningen result from high ICS values of horizontal sections near the soil surface. Those sections, however, are influenced by ant activity and mouse holes. The pattern of the macropores formed by earthworm activity is still a random point pattern. SMETEM & COLLIS-GEORGE (1985) also showed that patterns of earthworm channels are random and can therefore be statistically characterized by the Poisson model.

Continuity of macropores

The continuity of macropores is an important measure of the macropore system, which determines the potential depth of water flow in macropores (BOOLTINK & BOUMA, 1991). Assuming water flow is initiated in a macropore and interaction is limited, the water would flow continuously to the end of the macropore. In order to quantify the effects of the continuity of macropores, the burrow length of individual macropores can be determined and their effects considered.

The geometry of macropores can be determined either by casting macropores in the field or by using computed tomography of soil samples. In this study, the burrow geometry was determined using nine casted earthworm burrows at the Niederweningen site (Ch.). A measured average burrow length of 54.5 cm (± 28.2 cm) supported the results of other studies, that burrows of *Lumbricus terrestris* are mainly vertical oriented, have a great length and a high continuity (LANGMAACK ET AL., 1999). JOSCHKO ET AL. (1989) filled the burrows of *Lumbricus terrestris* in a 40 cm high soil column with gypsum and found an average length of 30.3 cm (± 10.5 cm). SHIPTALO & GIBBS (2000) filled 38 earthworm burrows in the field with resin, excavated the burrows and determined an average burrow length of 99 cm and an average burrow depth of 81 cm. If the length was not determined in particular for burrows built by *Lumbricus terrestris*, the results showed a lower average length. For example LIGHTHART & PEEK (1997) found an average length of 10 cm in the absence of *Lumbricus terrestris*. PERRET ET AL. (1999) measured a modal length of 4 cm for macropores determined with X-ray CAT scanning. They also showed that some macropores, although representing only a small percentage, reached a length of 75 cm and had a high continuity.

The results of this study’s observations and other studies demonstrated the high continuity of earthworm burrows built by *Lumbricus terrestris*. If the burrows were not formed by anecic species like *Lumbricus terrestris*, their length and their continuity can be relatively low. Therefore, it is reasonable to account only for macropores that are vertically oriented earthworm channels and due to their size are probably built by *Lumbricus terrestris*. These macropores were already classified and their macropore density was determined in the previous section.
6.1.4 Conclusion

It could be shown with the experiments that the maximum flow rate in macropores that are built by anecic earthworms species lies within a narrow range (1–7 cm$^3$ s$^{-1}$). If a low macropore density of 100 m$^{-2}$ is assumed, the total flow rate of the macropore system with a low average flow rate of 1 cm$^3$ s$^{-1}$ is 360 mm h$^{-1}$. This value, which is the lower limit, is a multiple of naturally occurring rainfall intensities. Thus, the flow rate of the macropore system is usually not the limiting factor during the infiltration process.

Because the rainfall intensity is always lower than the flow rate of the macropore system, the macropores are only partially filled. The flow velocity in a partially filled macropore can be calculated with the assumption of a linear decrease of the hydraulic radius. For example, if the rainfall intensity is 2% of the maximum flow rate, the flow velocity will be reduced in average by 80%. The flow velocity is then still 12 cm s$^{-1}$. Therefore, the high flow velocity in macropores is always sufficient to transport the water fast enough into deeper soil layers.

The density of selected macropores with a given cross-sectional area and a given shape is quite similar for the experimental sites. The macropore density of this study is comparable to the macropore density in soils, ecologically suitable for earthworms, in other studies. The macropore density can be determined quite rapidly in the field because an area of 200-2000 cm$^2$ is sufficient to determine the macropore density with an accuracy of 20% (Smettem & Collis-George, 1985). Soil classification, land use, and position in the landscape also regulate the macropore density. Unfortunately, studies on such regulation mechanisms are rare. For example, Zehe & Flühler (2001) and Buttle & McDonald (2000) measured the spatial distribution of macropore density in a catchment. The use of soil-landscape models to predict different soil attributes can also be used as a tool to predict the spatial distribution of macropore density (Gessler et al., 1996).

The continuity of macropores, in particular earthworm burrows formed by anecic species such as *Lumbricus terrestris* is generally high, since their burrow systems are mainly vertically oriented and the length of their burrows is high. Therefore, it is favourable to consider only macropores formed by anecic species because their burrows are hydrologically active. Simulation models should only account for these macropores. The high continuity, the high depth of penetration, and their relatively large diameter are the main reasons for the relatively large impact on hydrology of macropores formed by *Lumbricus terrestris*. 
6.2 MACROPORE FLOW INITIATION

6.2.1 Introduction

Macropore flow initiation is the process of water supply to macropores. It is a function of initial water content, rainfall intensity and amount, hydraulic conductivity, and surface contributing area (Trojan & Linden, 1992). There is still a large demand in experiments to explore the causes and extent of macropore flow initiation (Flühler et al., 1996). Water can flow into macropores from the soil surface or from a saturated or partially saturated soil layer. Léonard et al. (1999) investigated surface initiation with laboratory experiments and used the results to verify a flow model. Ruan & Illangasekare (1998) studied surface initiation with a model that coupled overland flow and infiltration into macropores. Subsurface initiation was studied in the laboratory (Phillips et al., 1989; Ela et al., 1992; Li & Ghodrati, 1997) and could also be detected in the field (Weiler et al., 1998).

Some studies could verify that the macropore density, the slope and the roughness of the surface mainly influence the surface initiation (Trojan & Linden, 1992; Léonard et al., 2000). Subsurface initiation, however, is driven by the hydraulic conductivity of the soil matrix and the water content. Macropore flow is initiated from a saturated horizon or even from the unsaturated soil matrix (Phillips et al., 1989).

Macropore flow initiation is difficult to study. Experiments in the laboratory cannot reproduce the complex natural relations between the surface and the macropores. Artificial macropores are only useful to study a selected detail of the initiation process (e.g. Phillips et al., 1989). Field measurements to directly observe surface initiation are very difficult or even impossible because vegetation covers the surface. However, removing the vegetation will change the surface characteristics. Indirect measurements of the soil water content and the matric potential or dye experiments (Ch. 4.2 and Ch. 5) can only verify the type of initiation.

An alternative way is to model the initiation process. The surface and the macropores can be reproduced using field data or the surface initiation process can be simulated with a hypothetical surface. Similar ideas can be applied to study the subsurface initiation process. With the help of a model, which can reproduce the initiation process, we can study how much water can enter the macropores, how the flow rate is distributed in the macropores, and what should be known to predict macropore flow initiation. This chapter will first focus on new ideas and methods to study surface initiation and will then logically improve the understanding of subsurface flow initiation.
6.2.2 Surface initiation

Analysis of surface topography

The surface topography of all experimental plots was manually surveyed. The area measured was 290 cm by 100 cm with a spacing of 10 cm. Thereby, the real soil surface was determined ignoring the vegetation cover. Using the measured surface topography, the average slope and the deviation of the surface from a fitted plane was calculated. Table 6.3 shows the characteristics of the surface topography for the four experimental sites.

Table 6.3 Characterization of the topography

| Site           | Slope (%) | Absolute deviation of the surface from a fitted plane (mm) | | |
|---------------|-----------|----------------------------------------------------------|---|---|---|---|
|               |           | Average | Median | 25% quantile | 75% quantile |
| Rietholzbach  | 22.1      | 7.8     | 6.0    | 3.0           | 10.9          |
| Heitersberg   | 22.9      | 6.6     | 5.5    | 2.5           | 9.1           |
| Koblenz       | 16.4      | 14.6    | 10.1   | 4.4           | 18.1          |
| Niederweningen| 16.2      | 14.0    | 8.0    | 3.6           | 14.4          |

The spatial resolution of the topography has to be increased to use the measured surface topography data for a more detailed analysis in the next section. Kriging was chosen as a gridding method to conserve the spatial correlation of the topography and to incorporate possible anisotropy and underlying trends (Huang, 1998). Because the surface topography was accurately measured, an exact interpolator like Kriging (without nugget effect) is a good choice.

To apply Kriging to the measured topography of the sites, the following steps were undertaken. After a plane was fitted to the measured values and subtracted from the values to incorporate the drift of the data, the experimental variogram was calculated (Stein, 1999). No relevant anisotropy could be detected. All experimental variograms showed an exponential behaviour and no nugget effect. Therefore, an exponential model with an anisotropy ratio of one was fitted to the experimental semi-variogram:

\[
\gamma(h) = C \left[ 1 - \exp\left( -\frac{h^2}{a} \right) \right]
\]

(6.4)

where \(\gamma(h)\) is the semi-varioagram, \(C\) is the scale for the structured component of the variogram, \(a\) is the range, and \(h\) is the separation distance. The scale or sill \(C\) is the vertical scale of the variogram where the function \(\gamma(h)\) converges. The range \(a\) is the horizontal range of the variogram and defines how rapidly the variogram components change with increasing separation distance. The derived parameters of the exponential model for the sites are listed in Table 6.4. The values show, that the surface topography of Heitersberg has the highest spatial correlation followed by Rietholzbach and Koblenz. At Niederweningen the spatial correlation is limited.
to a distance of 27 cm. The surface topography was then reproduced with a grid spacing of 1 cm and also visually checked for consistence.

Simulation of surface initiation

With knowledge of the site surface topography, the macropore density, and the pattern of the macropores near the soil surface, a way to describe and simulate the initiation of macropore flow at the soil surface can be sought. Assuming that the rainfall distribution and the infiltration into the soil surface beside the area of macropores is uniform, the excess between rainfall and infiltration will then flow on the soil surface driven by gravitation. If the water flows in a macropore opened to the surface, it will completely disappear into the macropore. Consequently, only the area that drains to a macropore determines the initiation of flow in the macropore. This macropore drainage area (MDA) is proportional to the macropore flow initiation. The proportion factor is the difference between rainfall intensity and infiltration into the soil matrix.

A model was developed, which incorporates the considerations of the last paragraph, to simulate the distribution of the MDA for a given soil surface and macropore density. The model consists of the following units:

1. The reproduced, relatively smooth surface topography derived in the previous section is overlaid with a rough surface representing the micro-topography (Figure 6.3). The micro-topography stands for the roughness formed by vegetation or soil aggregates. The micro-topography is generated by a power-law spectral technique and shows fractal spatial properties. The fractal dimension is set to 2.85 (equal to a Hurst coefficient of 0.85). The relative deviation, which is similar to the relative roughness, is set to 1.5 mm.

![Fig. 6.3 Example of the micro-topography (shaded relief, area = 1 m²)](image-url)
(2) The flow direction of every cell of the new surface is calculated. Starting at the local minimum (no flow cell), the extent of depressions is determined iteratively (Figure 6.4). A depression is the area where ponding occurs. Contiguous depressions are then merged and the topography underlying the depressions is raised to the height of the outlet of the depression. Additionally, the topography within the depression is slightly inclined to the outlet to ensure flow to the outlet.

(3) The model generates a defined number of macropores with a spatial random distribution (Figure 6.5). It has been proven in Ch. 6.1.3 that the point pattern of macropores at the experimental sites are random. The surface area of every macropore depends on the resolution of the topography and is set to 1 cm$^2$. After the macropore distribution is generated, the location of macropores is compared to the location of depressions. A macropore that lies within a depression will capture all water flowing into the depression. To account for this process, the macropore is moved to the outlet of the depression. Now the macropore will receive all water flowing into the depression.

(4) The flow accumulation for every cell is calculated according to the method of Holmgren (1984):

$$A_i = \frac{A(tan \beta_i L_i)^h}{\sum_{i=1}^{n} (tan \beta_i L_i)^h}$$

(6.5)

where $n$ is the total number of directions to downhill neighbouring cells, $A_i$ is the amount passed onto the $i$th downhill cell, $A$ is the total up-slope area accumulated in the current cell, $\tan \beta_i$ is the gradient and $L_i$ is the contour length in the $i$th downhill cell and $h$ is a
weighting factor. If \( h = 1 \), the equation is equal to the multiple-flow-direction algorithm, that allows water flowing in all neighbouring downhill cells. For \( h > 100 \) it is similar to the single-flow-direction algorithm, that allows only water flowing in the deepest neighbouring cell. (Quinn et al., 1991). Because the flow behaviour is assumed to be dispersed at the soil surface, \( h \) was set to two. If the flow accumulation for a macropore cell is calculated, the actual accumulated area will be transferred to the macropore cell. This value is then the macropore drainage area (MDA). Afterwards the flow accumulation of this surface cell is set to zero. Figure 6.6 shows the colour coded flow accumulation (as square root of accumulated area) of a 100 cm by 100 cm surface. The black circles represent the macropores and their individual MDAs are indicated by the diameter of the circle.

Results

**Total macropore drainage area (MDA)**

In a first step the model was used to calculate the total MDA. The total MDA is the accumulated MDA of all macropores. A 1 m\(^2\) part of each of the reproduced surface topographies of the four sites (see previous section) was used as a representative example. To account for different spatial distributions of the simulated macropores, 25 different macropore distributions for the same surface topography were realized and the median of the total MDA was calculated. For the four sites, the influence of the macropore density on the relative total MDA (equal to total MDA divided by the surface area) is illustrated in Figure 6.7. Additionally, the values of a plane surface with a gradient of 20% were calculated.

![Graph showing influence of macropore density on total macropore drainage area](image)

**Fig. 6.7** Influence of the macropore density on the total macropore drainage area
Figure 6.7 shows a strong influence of the macropore density on the total MDA. The values are quite similar for the four sites. The simulations with the real world surface result in values similar to the realizations using a plane surface. Thus, the total MDA of a real surface is equal to the total MDA of a plane surface. This consistency, however, is no longer valid, if the extent of the depressions increases (higher surface roughness and lower slope).

The influence of boundary effects was also studied. The limited area of 1 m² will probably alter the MDAs of the upper part compared to the lower part of the slope. Using a larger area of 2 m² and a plane surface, only the total MDA of the lower part (0–1 m) was calculated. The relative total MDA of the lower part is significantly higher than the total MDA with boundary effects (Figure 6.7). Hence, the real MDA without boundary effects is probably equal to the MDA of the lower part of the simulation area. Since the total MDA of a real world surface is comparable with the MDA of a plane surface, this agreement can be used to estimate the proportion of surface runoff that drains into the macropores. Léonard et al. (2000) have also derived a relation for macropore density and total MDA with a hydraulic model solving the 2-D St. Venant equation. Their values, which are similar to the simulations without boundary effects, are additionally shown in Figure 6.7.

Other potential factors influencing the total MDA are the slope and the roughness of the surface. These factors in particular change the proportion of ponding areas to the surface area. If the ponding areas are larger, the probability is higher that macropores are within the ponded areas. Thus, the total MDA will increase because the MDA of macropores within a depression is larger than the MDA of macropores outside a depression. Consequently, the MDA increases at lower slopes (<10%) and at a higher surface roughness, especially for low macropore densities.

The variance of the total MDA of different realizations is an indicator of the degree of constancy for a given macropore density. The variance is higher for low macropore densities (~0.1) and lower for high macropore densities (~0.05). The variance, furthermore, increases for surfaces with a low gradient and for surfaces with a high channelling behaviour (e.g. the Koblenz site in Figure 6.8).

**Probability distribution of MDA**

The probability distribution of the MDA is important to understand the interaction variability and, consequently, the macropore flow variability. The difference of the MDA of each macropore depends on its location and the overall accumulation pattern of the surface. For each realization, the distribution of the MDA was fitted to a theoretical probability distribution using a non-linear least square fitting procedure. The Weibull distribution was chosen because it is an extreme value distribution and it can have exponential or symmetrical behaviour. The cumulative distribution function (cdf) takes the form:

\[
F(x) = 1 - \exp\left[-\left(\frac{x}{\lambda}\right)^\beta\right]
\]  

(6.6)
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MDA (cm²)

• <5 • 10 to 20
• 5 to 10 • >20

Fig. 6.8 Examples of the flow accumulation pattern of the four sites of one realization with a macropore density of 100 m² for an area of 1 m² (white lines are the contours with an elevation distance of 1 cm)

with the two parameters β and λ > 0. For comparison, the range of estimated Weibull distributions for the experimental sites and for the plane surface is illustrated in Figure 6.9. The MDA is standardized to the expected MDA of a macropore.

The cdf for the real surface shows an exponential behaviour. The cdfs are similar at the four sites. However, the cdf of the plane surface differs significantly from the cdf of the sites. The
flow accumulation of the plane surface is more homogeneous and regular. Therefore, the cdf is more symmetrical. The cdfs for a site differ slightly due to the influence of the macropore density. For a higher macropore density the variance decreases because the probability for high MDAs decreases. The mean is more or less constant. Since the cdfs are very similar for the sites and for different macropore densities, an average cdf with $\beta = 0.66$ and $\lambda = 0.55$ can be assumed.

**6.2.3 Subsurface initiation**

The initiation of macropore flow in a saturated horizon can be described with the following assumptions. The saturated horizon has a spatially constant saturated hydraulic conductivity and the slope of the lower boundary is zero. The horizon is on top of a horizon with a significantly lower permeability. The water infiltrating into the horizon can freely drain to the macropores. The hydraulic head in the macropores is zero. Thus, the total flow from the saturated horizon into the macropores is given by the infiltration. The infiltration can be limited by the hydraulic conductivity of the saturated horizon. But the infiltration must be higher than the hydraulic conductivity of the subjacent horizon in order to generate a saturated area.

The water will always flow to the nearest macropore in order to follow the maximum gradient. Hence, a macropore will drain the area that is closest to it. This partition of the macropore
drainage area is described by the Voronoi diagram (Thiessen polygons). More details about Voronoi diagrams can be found in Aurenhammer (1991).

It could be shown that the spatial distribution of macropores at the four sites is random (Ch. 6.1.3). The simplest possible stochastic mechanism for the generation of a random spatial point pattern is the Poisson process (Diggle, 1983). The areal density of the generated random points \( \lambda \) is equal to the macropore density. Thus, the distribution of the macropore drainage area (MDA) for randomly distributed macropores is achieved by Voronoi diagrams. The size distribution of random Voronoi segments for one dimension can be derived rigorously and is given as (Kiang, 1966):

\[
f(x) = \frac{c}{\Gamma(c)} (cx)^{c-1} e^{-cx}
\]

This distribution is a Gamma distribution where the shape parameter \( c = 2 \) for the 1-D case and \( x \) is the standardized length. For the two dimensional case, the distribution becomes difficult to establish and no rigorously derived result could be found in the literature. However, simulations with a randomly generated point pattern showed that for every areal density \( \lambda \) in Equation 6.7 \( c \) is equal to 4 (Kiang, 1966 and own simulations).

The distribution of the MDA for subsurface initiation can be calculated with Equation 6.7. The result has to be divided by the macropore density to get the area distribution in square meters. Thus, the shape of the distribution does not depend on the macropore density. The distribution of MDA for subsurface initiation is compared with distributions of MDA for surface initiation to illustrate the differences of the two initiation processes on the frequency distribution of macropore flow (Figure 6.10).

### 6.2.4 Conclusion

Initiation of macropore flow at the soil surface or from a saturated or partially-saturated soil horizon shows some interesting characteristics. For surface initiation, the total macropore drainage area (MDA) and therefore the proportion of overland flow that can drain into macropores is strongly influenced by the macropore density. A macropore density of 100 m\(^{-2}\), which is a low value compared to field observations, is sufficient to capture over 70% of the overland flow. The total subsurface flow initiation is mainly influenced by the hydraulic conductivity of the saturated soil layer, by the hydraulic conductivity of the subjacent horizon, and probably by heterogeneities of the soil.

The probability distribution of the MDA and therefore the distribution of macropore flow for surface initiation is mainly influenced by the surface topography. Only a few macropores contribute significantly to the water flow. For example, 10% of the macropores drain 25% of the surface. Other studies also showed that the distribution of MDA initiated from the surface shows an exponential behaviour (Ela et al., 1992). Trojan & Linden (1992) measured a sig-
significant increase of macropore flow in macropores located in micro-depressions, since their MDA is larger than for macropores located on ridges. The probability distribution of the MDA for subsurface initiation is more symmetrical and has a lower variance. Thus, the distribution of macropore flow is also more symmetrical. The subsurface initiation works like a filter equalizing the macropore flow.

The real macropore flow distribution is probably between the distribution of initiation only at the soil surface and initiation in a saturated soil horizon, as the surface infiltration into the soil matrix is heterogeneous. The two macropore initiation processes, however, generate the envelope of the macropore flow distribution.

Finally, the flow rate of every macropore for surface and subsurface initiation is calculated to compare this flow rate to the measured flow rate in the macropores (see Ch. 6.1.2). Two different total initiation rates of 10 and 60 mm h⁻¹ combined with a macropore density of 200 and 100 m⁻², respectively, are assumed. The number of macropores and the resulting flow rate are given in Figure 6.11.

For the lower initiation rate independent of the initiation process, the maximum macropore flow rate does not exceed 0.05 cm³ s⁻¹, which is only 0.7-5% of the measured macropore flow rate (see Table 6.1). Even for a very high initiation intensity and a low macropore density, the estimated maximum macropore flow rate is only 5-40% of the measured macropore flow rate. Consequently, the flow rate of macropores does not limit the infiltration process even under unpropitious conditions.
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**Fig. 6.11** Number of macropores and flow rate distribution for surface and subsurface initiation with (a) an initiation intensity of 10 mm h⁻¹ and a macropore density of 200 m⁻² and (b) an initiation intensity of 60 mm h⁻¹ and a macropore density of 100 m⁻² (scale is different)

6.3 INTERACTION

6.3.1 Introduction

Interaction is the water transfer from macropores into the surrounding soil matrix. It was also referred to as lateral infiltration from the macropores into the surrounding soil matrix (Beven & Clarke, 1986). The interaction is one of the critical processes describing water flow in macroporous soils (Logsdon et al., 1996; Faeh et al., 1997). Interaction is not only influenced by soil properties and soil water content, as for example vertical infiltration into a homogeneous soil, but also by the geometry of the macropores, the macropore density and the lining material in the macropores.

Since this study investigates the hydrological effects of infiltration into natural soils containing macropores with field experiments, the processes should be described in a model with a minimum degree of complexity in order to compare the uncalibrated simulations with the results of the field experiments (Logsdon et al., 1996). The description of interaction can be very complex due to the high number of influencing factors. However, a reliable and process-oriented approach tries to concentrate on the most important factors that can be measured in the framework of this study. The factors influencing interaction will initially be described in more detail and then factors chosen for simulating interaction will be highlighted.

Factors influencing interaction can be subdivided into properties of the soil matrix and properties of the macropores. Horizontal water flow in an unsaturated soil matrix is governed by
the soil water characteristics, the unsaturated hydraulic conductivity, and the initial conditions of the soil. These properties also describe the vertical infiltration into the soil matrix. In order to simulate the water flow of natural soils containing macropores, the properties of the soil matrix and its water content have to be considered.

The main features that describe the macropore system were already introduced in Ch. 6.1. The major characteristics relevant for interaction is the macropore density and the geometry of the macropores. The macropore density in combination with the geometry determine the surface area of the interface between the macropores and the soil matrix. Because this study concentrates on macropores that were formed by anecic earthworms, the geometry of the macropores can be simplified by vertically oriented, circular tubes. It was shown that the macropore density can be determined in the field or derived from additional information (Ch. 6.1.4).

An additional factor of the macropore system that can influence interaction is the lining material at the wall of the macropores (Faeh et al., 1997). Different types of macropores have different lining material. Earthworm deposits produce a lining material high in clay and silt content (Banse & Graf, 1968). Macropore lining in holes formed by root decay is created from bark material or translocated clays and oxides (Schoenberger & Amoozegar, 1990). A lining material of clay, silt or humus particles is created by deposition of downward moving particles from the soil surface in hydrologically active macropores. The lining material usually reduces the hydraulic conductivity of the interface between the macropores and the soil matrix and, subsequently, the interaction (Faeh et al., 1997). However, the hydraulic properties of the lining material cannot be measured directly and its degree of influence on interaction is not well understood. Therefore, the influence of macropore lining is not implicitly considered in this study. The effects of the lining material will be considered, if the simulations do not capture the processes that were observed with the experiments (Ch. 7).

To describe interaction in the framework of this study, the model should implement the soil water characteristics of the soil matrix and a simple geometrical representation of the macropores. Two different approaches to model horizontal infiltration with radial symmetry can be distinguished: (1) saturation deficit of the soil matrix or (2) the potential gradient between the macropores and the soil matrix determine the infiltration. The first approach relies on constant boundary conditions at the macropore wall (Beven & Clarke, 1986; Jarvis et al., 1991; Chen & Wagenet, 1992a). The second approach describes interaction as a linear function of the driving potential in analogy to the Darcy equation (Workman & Skaggs, 1990; Faeh et al., 1997) or as a steady state flow from a water filled borehole (Smettem, 1986). The second approach has the advantage, that a hydrostatic pressure in the macropores can also be considered, but this requires a numerical scheme solving the Richards equation in the head form. Due to this major disadvantage in combination with the demand of a simple hydrologically infiltration model and because the macropores are usually not filled during infiltration, the saturation-deficit-based approach is chosen.
A Green-Ampt approximation was chosen to simulate the water transfer from macropores into the surrounding soil matrix (Beven & Clarke, 1986). Apart from the above mentioned advantages, the following points were taken into consideration:

- The Green-Ampt approach has been widely used for modelling infiltration in a hydrological framework. The parameters of the model are physically-based and can be derived from soil properties.
- The Green-Ampt approach will also be used to simulate the vertical infiltration into the soil matrix (Ch. 7.1.1). Therefore, a consistent theory describing vertical infiltration and horizontal infiltration from the macropores is guaranteed.
- The distance between the wetting front and the macropore wall after the rainfall event can also be calculated. This value can be compared with the measured extension of the stained areas around the macropores of the experiments (Ch. 4.3).
- Because the analytical solution of the Green-Ampt approach allows a stable and fast computation of the interaction of a single macropore, the approach can also be used to calculate the individual interaction of a high number of macropores. Thus, the inflow rate distribution due to the initiation process can be linked with the interaction model and the related effects can be studied.

This chapter initially outlines the theoretical background for the interaction model based on the Green-Ampt approach. Then the model set-up is described in detail and a verification of the interaction model is performed. Finally, results of different model simulations are compared between the case where the initiation process is neglected and the case where the initiation process is implicitly considered.

6.3.2 Theory

As mentioned in Ch. 6.1.2 the macropores are usually not completely filled during rainfall events and, therefore, the hydrostatic pressure in the macropores is zero. Only under certain circumstances (saturation of the soil matrix or very low interaction), the pressure in macropores, where the initiation is high enough, can be above zero (filling of macropores). Assuming a cylindrical shape of the macropores and a predominant horizontal movement of water from the macropores into the soil matrix, the Green-Ampt assumptions for horizontal infiltration with radial symmetry are valid (Beven & Clarke, 1986):

$$\frac{dy}{dt} = \frac{K_s r (h + \psi_f)}{y \Delta \theta(y - r)}$$

(6.8)

where $y$ is the radial distance of the wetting front from the centre of the channel, $r$ is the radius of the macropore, $h$ is the pressure head in the macropore, $\Delta \theta$ is the change of water content across the wetting front, and $\psi_f$ is the wetting front suction. The Green-Ampt model further assumes that the soil matrix is initially uniformly dry with a water content of $\theta$, that a distinct
wetting front during infiltration exists, that the wetting front suctions remain constant in time and space, and that the soil behind the wetting front is uniformly wet with a constant hydraulic conductivity (Beven & Clarke, 1986). For \( y = r \) at time \( t = 0 \) Equation 6.8 can be solved for any \( t > 0 \):

\[
t = \frac{\Delta \theta}{K_s r (h + \psi_f)} \left( \frac{y^3}{3} - \frac{y^2 r}{2} + \frac{r^3}{6} \right)
\]  

(6.9)

For Equation 6.9 a real solution can be found for the radial distance of the wetting front \( y \) at a given time \( t \):

\[
y(t) = \frac{1}{2} \frac{c^{1/3}}{\Delta \theta} + \frac{1}{2} \frac{b}{c^{1/3}} + \frac{1}{2} r
\]  

(6.10)

\[
a = t \ k_s (h + \psi_f)
\]  

(6.11)

\[
b = \Delta \theta r^2
\]

\[
c = r \Delta \theta^2 (12a - b + 2\sqrt{6a(6a - b)})
\]

Besides the wetting front suction, all parameters can be directly determined from soil properties and initial conditions (Table 5.3 in Ch. 5.5). The wetting front suction will be calculated by an approach of Mein & Larson (1973) that uses the soil water retention curve and unsaturated hydraulic conductivity curve of the soil:

\[
\psi_f = \int_{K_{ro}}^{1} h(K_f) dK_f
\]  

(6.12)

where \( h(K_f) \) is the inverse function of the relative hydraulic conductivity \( K_f(h) = K(h)/K_s \) and \( K_{ro} \) is the relative hydraulic conductivity at the initial soil water content \( \theta \) of the soil. Thus, the wetting front suction is a function of the initial soil water content and the shape of the water retention curve and of the unsaturated hydraulic conductivity curve. The wetting front suction will be highest at the residual water content and zero at saturation. The maximum wetting front suction can be calculated for given soil properties which were estimated for different soil textures (Schaap et al., 1998). The results are illustrated in Figure 6.12a. Hence, the wetting front suction can be multiplied with the saturated hydraulic conductivity to receive the parameter of the Green-Ampt equation that depends on the soil texture (Figure 6.12b). The initial water content of the soil reduces the wetting front suction and the fraction \( \Delta \theta / \psi_f \) is almost linearly related to the saturation deficit. Thus, the horizontal infiltration increases almost linearly with the saturation deficit.

Equation 6.10 gives the solution of the radial distance of the wetting front \( y \) for any time. The interaction \( q_{int} \) (water flux from the macropores into the soil matrix) for any time \( t \) can be cal-
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Fig. 6.12 Maximum wetting front suction (a) and square root of maximum wetting front suction multiplied by saturated hydraulic conductivity (b) in the soil texture diagram

culated for a soil layer with a given height $\Delta z$ and a given macropore density $n_{mac}$ of vertically oriented macropores with:

$$q_{inf}(t) = \pi \left[ y(t)^2 - y(t-\Delta t)^2 \right] \frac{\Delta z \Delta \theta n_{mac}}{\Delta t}$$  \hspace{1cm} (6.13)

where $\Delta t$ is the time step and $y(t)$ is the radial distance of the wetting front at time $t$ and $y(t-\Delta t)$ is the radial distance of the wetting front at the previous time. An example of the function $q_{inf}(t)$ with the parameter $K_s = 5 \text{ mm h}^{-1}$, $\psi_f = 10 \text{ mm}$, $\Delta \theta = 0.1$, $r = 3 \text{ mm}$, $n_{mac} = 200 \text{ m}^{-2}$ and $\Delta z = 500 \text{ mm}$ is illustrated in Figure 6.13.

6.3.3 Simulating interaction

Model description

In a first step, the factors influencing interaction and therefore the macropore flow will be studied by means of a simple model using the Green-Ampt assumptions for horizontal infiltration with radial symmetry. This Interaction Model (IM) is a building block of the INfiltration-INItiation-INteraction Model (IN$^3$M), that will be used in Ch. 7 to simulate infiltration into macroporous soils.

The model is conceptualized in Figure 6.14. The soil matrix is equally parameterised for all elements by the variables of the equation of VAN Genuchten (1980). A uniform saturation def-
Fig. 6.13 Function of interaction and cumulated interaction

Fig. 6.14 A schematic representation of the Interaction Model (IM)

Explicit is assumed. The macropore system is characterized by the macropore density and the average macropore radius. Only vertical flow is assumed in the macropores. In the soil matrix, flow can only be horizontal. The input into the macropores of the upper element is fixed.
6.9 and Equation 6.10 are then used to calculate the interaction $q_{int}$ for every element. For every time step $t$ the following calculations for every element $i$ are performed from top to bottom:

- If the cumulative interaction of element $i$ is greater than the initial saturation deficit, the soil matrix is saturated and, therefore, all water flowing into element $i$ is transferred to element $i+1$.
- If the inflow $q_{in}(t)$ into element $i$ is the first time greater than zero, the initiation starts. The time for calculating the interaction for this element is set to $t = \Delta t$. The potential radial distance of the wetting front $y_{pot}(t)$ is calculated with Equation 6.10. The radial distance of the wetting front that is limited by the inflow into the element $y_{in}(t)$ is calculated with Equation 6.13, which is solved for $y(t)$ with $q_{int}(t) = q_{in}(t)$.
- The potential radial distance of the wetting front $y_{pot}(t)$ and the actual radial distance of the wetting front $y_{in}(t)$ are compared:
  - If $y_{in}(t) > y_{pot}(t)$, the inflow into the element is greater than the potential interaction and, therefore, the actual interaction $q_{int}(t)$ is calculated with Equation 6.13 with $y(t) = y_{pot}(t)$. The time for calculating the interaction of this element is set to $t+\Delta t$. The outflow of this element is equal to the inflow of element $i+1$ is calculated with $q_{in}(t,i+1) = q_{in}(t,i) + q_{int}(t,i)$.
  - If $y_{in}(t) \leq y_{pot}(t)$, the inflow into the element is smaller than the potential interaction and, therefore, the actual interaction has to be reduced to the inflow by adjusting the time for calculating the interaction. This time is calculated with Equation 6.9 with $y = y_{in}(t)$. The actual interaction $q_{int}(t)$ is equal to the inflow $q_{in}(t,i)$ and the outflow $q_{in}(t,i+1) = 0$.
- Water flowing out of the lowest element is the macropore outflow at the lower boundary of the model.

The temporal and spatial discretisation of the IM model does not influence the results. Additionally, the explicit formulation of the problem does not introduce any numerical error or numerical instabilities, which would probably occur for a numerical solution of the interaction. Hence, the IM is a robust and accurate model for a hydrological consideration of interaction. The flow velocity in the macropores does not need to be considered in the model because the high flow velocity occurring in macropores (Ch. 6.1.2) does not significantly change the simulations, whereas the water is transferred within one time step from the inflow to the outflow. The macropore flow distribution, which is caused by the initiation process, can also be simulated. For this purpose, the model calculates the interaction separately for each macropore or a group of macropores. For each macropore or group of macropores, the flow rate is calculated according to the flow distribution of the initiation process (Ch. 6.2). The results of these more complex simulations will be discussed in the next sections.

**Verification of the model**

To verify the interaction model, measurements should be carried out, where the temporal water balance of a soil containing macropores, which can drain at the bottom, is measured. Data of
a corresponding experiment were kindly provided by Glenn Brown of the Oklahoma State University (Brown et al., 1999). They carried out experiments for the NSF funded project, “Experimental Measurement of Macropore Flow in Porous Media”. A uniformly wetted silty loam was packed in 63.2 mm inside diameter columns consisting of 15, 10 mm high acrylic rings, held together by tape. For the selected experiments, a single vertical macropore with a radius of 2 mm was cored into the centre line of the column. The macropore was connected to an outflow drain to allow excess water to exit the column. Water was initiated directly into the macropore with a flow rate of 60 ml min\(^{-1}\) for durations of 1.5, 2 and 2.5 min. Immediately after the experiment, the column was sectioned into 10 mm slices and the gravimetrical water content of every slice was determined.

The parameters necessary to run the model were estimated. The hydraulic conductivity was determined using an infiltration experiment without macropores. The initial and saturated water content were measured. The van Genuchten parameters were estimated using reasonable values for a silty loam. The resulting potential interaction was compared with a radial sorption experiment also performed by Brown et al. (1999). The resulting parameters are \(a = 5.0 \text{ m}^{-1}\), \(n = 1.15\), \(k_s = 180 \text{ mm h}^{-1}\), \(\theta_s = 0.4\), \(\theta = 0.15\), \(q_{in} = 1147 \text{ mm h}^{-1}\).

The simulation results and the experimental measurements are compared in Figure 6.15. The simulated cumulative outflow shows a similar behaviour to the outflow measurements of the three experiments (Figure 6.15b). The change of the water content profiles for two time steps is illustrated in (Figure 6.15c). Especially for the 2.5 min experiment, the water content change distribution varies significantly. However, the average water content change is correctly simulated. The variations measured in the experiment are probably due to boundary effects near the surface of the column, measurement errors (the initial water content was only determined for the whole column), and heterogeneities. In conclusion, the simulations describe the same processes as observed in the experiments.

Simulating interaction neglecting the initiation process

Because the IM reproduces the interaction process, the main characteristics and influencing factors of interaction can be studied. The IM was parameterised for a common field soil in Switzerland. The relations of inflow to average interaction rate and the initial water content were varied. Basically, two different control conditions were considered:

• Soil properties control interaction.
• Soil water content and thus the saturation controls interaction.

For all simulations the following parameters were kept constant: \(\alpha = 3.0 \text{ m}^{-1}\), \(n = 1.5\), \(\theta_s = 0.41\), \(n_{mac} = 100 \text{ m}^{-2}\), \(\Delta z = 20 \text{ mm}\) and \(r = 4 \text{ mm}\). To see the influence of the two control conditions, the saturated hydraulic conductivity \(k_s\) and the initial water content \(\theta\) were varied. The inflow into the macropores \(q_{in}\) was varied to study the effects where the inflow is higher or lower than the interaction. The simulation time was adjusted to a constant total inflow. Table 6.5 shows the parameter setting for the simulations.
Macropore flow, initiation and interaction

Fig. 6.15 Results of interaction simulation compared with the experiment of Brown with (a) simulated vertical flow in macropores in different depth, (b) measured and simulated cumulative outflow, and (c) changes of water content profiles

Table 6.5 Parameter settings for the different simulations of interaction

<table>
<thead>
<tr>
<th>No.</th>
<th>$q_{in}$ (mm h$^{-1}$)</th>
<th>$\Sigma q_{in}$ (mm)</th>
<th>$\theta_s - \theta$</th>
<th>saturation deficit (mm)</th>
<th>$k_s$ (mm h$^{-1}$)</th>
<th>$\psi_f$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15.0</td>
<td>60.0</td>
<td>0.3</td>
<td>150.0</td>
<td>7.0</td>
<td>75.6</td>
</tr>
<tr>
<td>B</td>
<td>30.0</td>
<td>60.0</td>
<td>0.3</td>
<td>150.0</td>
<td>7.0</td>
<td>75.6</td>
</tr>
<tr>
<td>C</td>
<td>60.0</td>
<td>60.0</td>
<td>0.3</td>
<td>150.0</td>
<td>7.0</td>
<td>75.6</td>
</tr>
<tr>
<td>D</td>
<td>15.0</td>
<td>60.0</td>
<td>0.06</td>
<td>30.0</td>
<td>30.0</td>
<td>48.2</td>
</tr>
<tr>
<td>E</td>
<td>30.0</td>
<td>60.0</td>
<td>0.06</td>
<td>30.0</td>
<td>30.0</td>
<td>48.2</td>
</tr>
<tr>
<td>F</td>
<td>60.0</td>
<td>60.0</td>
<td>0.06</td>
<td>30.0</td>
<td>30.0</td>
<td>48.2</td>
</tr>
</tbody>
</table>
If only the soil properties of the matrix control the interaction, the simulation results are illustrated in Figure 6.16. The figures on the left show the vertical flow in the macropores at different depths. The figures on the right show the water content changes for different time steps. If the total interaction is higher than the input into the macropores, the water will be completely absorbed by the soil matrix (Figure 6.16 A). However, the water in the macropores will finally reach the outlet. This behaviour can be seen in case B, where the total interaction is approximately equal to the total input. The outflow starts after filling 26% of the saturation deficit. When the inflow into the macropores increases to 60 mm h\(^{-1}\), the outflow starts after 8% of the saturation deficit is filled (Figure 6.16 C). The water content change in the soil matrix decreases and the wetting front moves more vertically.

The control of the soil properties is limited to situations, in which the soil is very dry or the total water input into the macropores is low compared to the saturation deficit. Usually, a combination of soil properties control and saturation control will occur (Figure 6.17). If the interaction is high compared to the input into the macropores (Figure 6.17 D), the outflow will increase very rapidly after the available pore volume is filled from top to bottom. The cascaded increase of the macropore flow is due to the vertical discretisation of the elements. If the inflow and the interaction is more balanced (Figure 6.17E), soil properties will control the interaction to a depth of 300 mm. Then the saturation controls the overall behaviour of the interaction and the outflow. Figure 6.17F shows the result, in which the interaction is smaller than the inflow. The wetting front will first reach the outlet without being influenced by the saturation. Therefore, the outflow will slowly increase. Once the inflow exceeds the saturation deficit by 120%, the interaction is limited by saturation and the outflow increases rapidly until the soil matrix is completely saturated. Thus, the saturation deficit triggers the interaction process and, therefore, macropore flow. The saturation control is strongest for soils with a high interaction.

Assuming that the macropores at the bottom end are closed or the outflow is limited and the inflow is larger than the interaction, the macropores will be filled. The filling will increase the hydrostatic pressure in the macropores and the interaction will increase with higher pressure in the macropores (Equation 6.8). However, the change of interaction cannot be calculated, because the Green-Ampt model assumes a constant wetting front suction. After the macropores are filled, the difference between inflow and interaction will create overland flow. Thus, the outflow capacity of macropores is relevant, if the excess water flows either on the soil surface or in the subsurface.

Simulating interaction in consideration of the initiation process

The IM model does not consider the influence of the initiation process on interaction. It is already known that macropore flow initiation changes the inflow rate distribution in the macropores. Therefore, the simulations were also performed with macropore initiation at the soil surface and in the subsurface. The distributions compared in Figure 6.10 were used to calculate the distribution of flow rate in the macropores. The parameters of the model are the same as
Macropore flow, initiation and interaction

**Fig. 6.16** Soil properties control interaction (parameter settings for A-C see Table 6.5)
Fig. 6.17 Soil properties and saturation deficit control interaction (parameter settings for D-F see Table 6.5)
for the simulations neglecting the initiation process. The results are illustrated for the cases, when saturation and soil parameters control interaction (Table 6.5 D-E), since those cases show the whole range of controlling conditions.

Figure 6.18 shows the simulations for subsurface initiation. The results are still comparable with those neglecting the initiation process (Figure 6.17). However, there are important differences: firstly, the depth profiles of the water content change (right column) show a tailing. The shape of the water content profiles depends on the distribution of flow rate in the macropores. The faster penetration of water in some macropores affects the starting time of the outflow. Even for a high initiation compared to the inflow (Figure 6.18 D), the outflow starts after filling 45% of the saturation deficit. For the other two cases, the outflow starts nearly immediately with the start of the inflow. Macropore initiation also changes the shape of the outflow hydrograph. The increase of outflow is slower compared to the cases neglecting the initiation process. If saturation controls interaction, the outflow increases also slower because the soil matrix is wetted more simultaneously with depth.

Figure 6.19 shows the results for surface initiation. Because only a few macropores receive a high inflow rate, the outflow starts immediately after the inflow. The outflow increases rapidly, especially in the cases E and F. The saturation control is reduced for all simulations since the total outflow is higher. The water content changes in the soil matrix show an exponential shape similar to the inflow rate distribution for surface initiation. Some macropores receive as much water whereby the interaction is lower than the inflow into these macropores. Therefore, the water can flow very rapidly in deeper soil layers. The interaction within the whole soil profile and the outflow start simultaneously.

### 6.3.4 Conclusion

The results show that the initiation process considerably changes the interaction. Therefore, it is important to combine initiation and interaction in order to describe macropore flow. Subsurface initiation slightly changes interaction because the flow rate distribution has a low variability. Surface initiation, however, considerably alters interaction since the flow rate distribution has a high variability.

A flow rate distribution within macropores resulting from macropore flow initiation and an immediate start and fast rise of the outflow was also observed in several experiments. In order to study the spatial and temporal variability of water and solute movement through intact soil blocks, it is necessary to interface the block with solution collection systems. Andreini & Steenhuis (1990) and Shipitalo et al. (1990) constructed for the first time a grid lysimeter using a grid collector system. All studies showed a very high variability of water and solute flux among individual grid cells. Andreini & Steenhuis (1990) measured water flow from only 30% to 40% of the total grid cells. Bowman (1993) found that over 99% of the water flow was conducted through only about 26% of the basal area of the soil block regardless of the application rate. He also estimated from the results of a tracer experiment with bromide that
Interaction

Vertical flow in the macropores

Water content change in the soil matrix

Fig. 6.18 Subsurface initiation, soil properties, and saturation deficit control interaction (parameter settings for D-F see Table 6.5)
Vertical flow in the macropores

- $q$ within $\Delta z = 50$ mm
- $q_{out}$

Water content change in the soil matrix

- $\theta$ within $\Delta t = 0.1 t_{max}$
- $\theta$ at $t_{max}$

Fig. 6.19 Surface initiation, soil properties, and saturation deficit control interaction (parameter settings for D-F see Table 6.5)
approximately 85% of the water in the soil block was bypassed by the bromide. Quisenberry et al. (1994) also used different application rates (5-31 mm h\(^{-1}\)) and measured water flux and chloride concentration. They found for all application rates that 50% of the water and chloride appeared within 20% of the cross-sectional area. They always detected one grid cell in which the water flux was 3 to 30 times higher than the application rate. Macropore flow was initiated at the grass covered soil surface. The water flux measurements of these experiments correspond to the flow rate distribution of surface initiation derived in Ch. 6.2.2. Edwards et al. (1992) measured in one grid cell 30% to 60% of total percolate for a soil block with macropores formed by Lumbricus terrestris. Similar values were found by Shipitalo & Edwards (1996) who also studied the influence of the initial soil water content. They concluded that the number of cells contributing to flow did significantly increase with increasing soil water content and argued that under dry condition macropore flow was initiated at the soil surface, and under wet conditions from a saturated zone near the soil surface. These results confirm the two different flow rate distributions derived for surface and subsurface initiation.
Macropore flow, initiation and interaction
7.1 MODELLING PROCEDURE

7.1.1 Infiltration-Initiation-Interaction Model (IN$^3$M)

The Infiltration-Initiation-Interaction Model (IN$^3$M) consists of the Interaction Model (IM) (Ch. 6.3.3) and a module that describes the vertical infiltration into the soil matrix, the initiation of macropore flow at the soil surface or from a soil layer, and the formation of overland flow and subsurface flow (percolation of water below the simulation domain). The IN$^3$M uses the dual-porosity approach to describe flow in the macropores and in the soil matrix separately. Basically, it assumes a one-dimensional vertical flow in the soil; however, the interaction and initiation is treated as horizontal flow. The vertical infiltration in the soil matrix is calculated like the horizontal infiltration using the Green-Ampt approach (Green & Ampt, 1911):

\[ i = K_s \frac{\psi_f + h_0 + z_{wf}}{z_{wf}} \]  

where \( i \) is the infiltration rate, \( K_s \) is the hydraulic conductivity, \( \psi_f \) is the wetting front suction, \( h_0 \) is the depth of the surface ponding, and \( z_{wf} \) is the depth of the wetting front. The wetting front suction is calculated with Equation 6.12 in Ch. 6.3.2. Since IN$^3$M should be applicable to natural soils that consist of soil layers with different hydraulic properties, the approach of Schiffler (1992) was used to apply the Green-Ampt equation to a multi-layer soil. Between successive rainfall events or during times at which the infiltration front did not reach a soil layer, the soil water is redistributed by the Buckingham-Darcy law of vertical water flow:

\[ j_w = K(\theta) \left( 1 + \frac{d}{dz}h \right) \]  

where \( j_w \) is the volumetric water flux and the potential gradient is estimated using the geometric mean of the matric potential in the layers (Schiffler, 1992).
Initiation of macropore flow in IN\textsuperscript{3}M takes place if the upper inflow into a soil layer exceeds the infiltration capacity. The excess water is transferred to the macropore domain of the layer boundary and distributed into the simulated macropores according to the distributions derived for surface and subsurface initiation (Ch. 6.2.4). Surface initiation occurs only at the upper boundary of the top layer, subsurface initiation at the other boundaries. The number of simulated macropores can be chosen independently from the macropore density of each layer. The simulated macropores are used to calculate the differences in interaction according to the differences in macropore flow (details in Ch. 6.3.3).

The lower boundary condition of the matrix domain depends on the hydraulic properties of the lowest soil layer. The boundary condition of the macropore domain is determined by a variable describing the maximum outflow of the macropores. If the calculated outflow of the macropore domain is larger than the maximum outflow, the macropores will fill up. If the water table in the macropores reaches the soil surface, overland flow will start. The number of dead-end macropores are calculated from the difference of the macropore density between two layers.

The input parameters of IN\textsuperscript{3}M can be subdivided into parameters describing the soil properties and parameters describing initial and boundary conditions. The soil properties are parameterised by:

- number and thickness of individual soil layers;
- soil hydraulic properties of each layer, characterised by the van Genuchten parameter \( \alpha \), \( n \), \( \theta_s \), and \( \theta_f \) (or the maximum saturation deficit) and the saturated hydraulic conductivity \( K_s \);
- macropore properties of each layer, characterised by the macropore density \( n_{mac} \) and the average macropore radius \( r \) or the macroporosity.

The parameters describing initial and boundary conditions are:

- precipitation duration and intensity;
- saturation deficit \( SD \) or \( \Delta \theta \) of each layer at the beginning of the simulation;
- maximum outflow of the macropore domain at the lower boundary.

The input parameters of IN\textsuperscript{3}M were derived from different sources. However, with the exception of one parameter, all parameters were determined prior to the simulations and had not to be fitted. The soil properties were derived from the soil survey at each site and the resultant soil hydraulic properties (Ch. 5.5). The macropore properties were estimated from the images of the horizontal sections (Ch. 6.1.3). The duration and intensity of the precipitation is listed in Table 5.1. The saturation deficit of each layer was determined from the water content measurements and from the matric potential measurements. Only the maximum outflow of the macropore domain at the lower boundary could not be directly determined. This value was estimated from observations of subsurface flow listed in Table 5.2.

### 7.1.2 Multi-criteria validation

A primary goal of modelling physical processes in hydrology is the prediction of one or more variables in time and/or space for a given set of inputs (Legates & McCabe Jr., 1999). The
ability of a model like IN$^3$M to predict a hydrological process like infiltration into macroporous soil depends firstly on the implementation of the processes in the model and secondly on the parameterization of the process. However, the simulation results have always to be tested in a validation strategy regardless of the complexity of the model, the kind of physical or conceptual description, and the ways to parameterize the model. The power of a validation strategy is its ability to distinguish between good and bad model hypotheses. The validation depends on what kind of data are available and how the data are used to challenge the hypothesis (Mroczkowski et al., 1997).

The validation of modelling results have always been a topic of discussion in the scientific community (Klemes, 1986). Nowadays it is more or less accepted that validation using multiresponse data, also called multi-criteria validation, is the best way to check the model hypothesis. However, the methods to determine how well a model fits the observed data are still doubtful. Usually a "goodness-of-fit" measure is used to determine the degree to which the model simulations match the observations. But these measures are over-sensitive to extreme values and are insensitive to additive and proportional differences between model predictions and observations (Legates & McCabe Jr., 1999). Additionally, these measures can only be applied to numerical data. Furthermore, it is necessary that the observations can be directly compared with the model predictions. But the observations are commonly not in the same space and time scale as the model predictions. Also the limitation of the device to measure the observed values should be taken into consideration. Consequently, a "goodness-of-fit" measure is not the only way to compare observed and simulated values. A qualitative description of the "goodness-of-fit" can also be used in some cases.

A multi-criteria validation strategy was applied to check the hypothesis and the parameterization of the IN$^3$M. The strategy was built on three different criteria. The agreement of the simulated with the observed criteria was qualitatively checked. In the following, each criterion and the way to determine how well the simulation fits the observed data will be described:

**Water balance criterion**

Overland flow (OF), infiltrated water (I) and soil moisture changes within the soil profile (ΔSM) of the measured water balance (Ch. 5.2) were compared with the simulation. Additionally, the percentage of water in the macropores that was initiated at the soil surface was calculated and compared to the observations in Ch. 5.4. All fluxes and water content changes from the IN$^3$M simulations of a soil profiles are visualized and labelled in Figure 7.1. The soil profile is subdivided into the macropores (dark grey) and the soil matrix (light grey). The total water content change of the profile is indicated in black vertical letters (all values are in mm), the measured value is added in brackets. The ΔSM of each simulated soil layer is indicated in black. The total water exchange from the macropores to the soil matrix (interaction) for each layer is given in red with red arrows. The blue values are the total subsurface initiation of macropore flow. The red values on top of the grey area indicate the input into the macropores (surface initiation) and the soil matrix at the soil surface. The uppermost value is the infiltrated
water with the measured values in brackets. The purple values in the upper right corner show the simulation and measurement of overland flow. The blue values at the bottom of the grey rectangle represent the total outflow of each domain at the lower boundary. The percentage of water in the macropores that was initiated at the soil surface is given in black to the left of the graph. The "goodness-of-fit" of the water balance criterion was evaluated with the three parameters, where simulated and measured values were available. Due to the inaccuracies of the ASM measurements, this parameter was less considered. In addition to the total overland flow, the progression of overland flow was also considered, if it was observed.

**Water content change criterion**

The depth-time plot of measured water content changes for each experiment (Ch. 5.3) was compared with the simulated water content changes in each soil layer. The simulations were visualized in a similar way as the measurements in Ch. 5.3; however, the extent of each layer is different (Figure 7.2 left). Additionally, the simulated water content changes for each layer at the end of the rainfall application were compared with the TDR measurements (Figure 7.2 right). The grey area indicates the simulated water content change and the black bars show the measured change. The black framed area in the depth-time plot shows the saturation of the soil matrix. This result can be indirectly compared with the saturation measured with the tensiometer (Ch. 5.4). The "goodness-of-fit" of the final water content change profile can be directly quantified. The depth-time plot is compared in a qualitative way with emphasizes on the timing of the beginning of water content changes and the saturation of the soil matrix.
**Modelling procedure**

**Dye pattern criterion**

The simulation results were used to generate an artificial dye pattern which was then classified and compared with the measured and classified vertical dye patterns (Ch. 4.2.3). For the generation of the dye pattern, the following steps were performed:

- The stained soil block was reproduced by a 3-dimensional array with a horizontal resolution of 1 mm and a vertical resolution of 10 mm. The horizontal size was 800 mm by 400 mm and the vertical size was 1000 mm.
- An artificial macropore network in the soil block was generated using the parameterised macropore density of each soil layer (see example in Figure 7.3). A point pattern of spatial randomly distributed macropores at the top border was generated. Then the position of each macropore in the layer below was determined. The horizontal displacement was calculated by two independent normally distributed random numbers $X$ and $Y$ with a mean of zero and a standard deviation of 0.4 times the vertical resolution. The angle of the macropore from the vertical $\alpha$ is also a random number and calculated with:

$$\alpha = \arctan(\sqrt{X^2 + Y^2})$$  \hspace{1cm} (7.3)

Figure 7.4 shows the resulting cumulative probability distribution of the macropore network inclination. This distribution corresponds with the measured distribution of inclination from nine casted earthworm burrows at the Niederweningen site (Ch. 6.1.3). The simulated distribution also corresponds with the frequency distributions of inclination of macropore networks measured with computer tomography (Perret et al., 1999) and from excavating and recording the macropore networks (Ligthart & Peek, 1997).

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*Fig. 7.3 Example of an artificial macropore network with a macropore density of 100 m$^{-2}$ and a length of the cube of 700 mm*
Starting from the centre of the macropores, the staining around the macropores was generated. Staining around the macropores is based on the probability distribution of the radial distances of the wetting front of each soil layer (Figure 7.5). This distribution is a result of IN3M, where the radial distance of the wetting front $y$ for each simulated macropore is calculated for each time step and thus the probability distribution can be derived for each soil layer at the end of the simulation. The radial staining distance $y_{st}$ is then calculated by:

$$y_{st} = (y - r) \frac{\Delta\theta}{(\theta_s - \theta_r)} \frac{1}{\eta} + r$$

(7.4)

where $\eta$ is the effective fraction of the maximum saturation deficit, in which the transport of the tracer took place. The calculation of the staining distance assumes only advective transport of the tracer. The values of the probability distribution of the resulting staining distances determine the radius of the circle that is used to define the staining around the macropores. The allocation of a staining distance to a macropore is random. The number of stained macropores is determined from the macropore density and from the fraction of numbers where interaction takes place (Figure 7.6).

Finally, the depth of the homogeneous staining of the soil matrix from the soil surface was calculated. The depth depends on the input into the soil matrix and the maximum soil moisture deficit. Only advective transport is assumed.

The resulting dye pattern is a 3-dimensional array with stained and unstained marked voxels. In Figure 7.7 an example of the rendered interface between stained and unstained voxels illustrates the homogeneous staining at the top and the four layers with different staining distance.
Modelling procedure

1. Modelling procedure

2. Example of probability distribution of the radial distance of wetting front of four different soil layers

3. Examples of staining patterns around macropores with different probability distributions of radial staining distances

4. Distributions. This 3-dimensional array was then sliced into five vertical sections and the depth function of stained path width (SPW) was calculated as described in Ch. 4.2.3. The simulated depth function of SPW was compared with the measured one (Figure 4.5) in terms of the depth function of volume density and the distribution of the SPW. Figure 7.8 shows two examples of the simulated SPW depth functions. Finally, the simulated SPW distribution was finally classified into profiles of flow processes. The profile was also compared with the measured and
Modelling infiltration into macroporous soils

Fig. 7.7 Example of an artificial dye pattern with a horizontal scale of 400 mm by 300 mm and a vertical scale of 1000 mm. The radial staining distance distribution is different for the four layers.

Fig. 7.8 Examples of simulated depth functions of stained path width and the corresponding classified flow processes using the results of IN3M.

classified flow processes. Mainly the vertical extent of a flow process and the similarity of flow processes were checked.
7.2 APPLICATION OF IN\textsuperscript{3}M

7.2.1 Simulation without calibration

In a first step of the simulations with IN\textsuperscript{3}M, the input parameters were derived from the parameterization of the soil properties and the initial and boundary conditions as described in Ch. 7.1.1. Hence, the model was parameterised without calibration. Because the maximum outflow of the macropore domain cannot be directly measured, two simulations were carried out. The value of the maximum outflow of the macropore was set to zero in the first case and to 100 mm h\textsuperscript{-1} in the second case. The value for the second case ensures an unlimited outflow. Thus, the sensitivity of the simulation results to this parameter was determined. Additionally, the results were validated in order to check the "goodness-of-fit" of the first parameterization. Table 7.1 lists the main parameters of the water balance of each simulation and ranks the agreement of the simulations using the three validation criteria.

Table 7.1  Simulation results of IN\textsuperscript{3}M with limiting and maximising subsurface flow

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil moisture</th>
<th>Original, no SSF</th>
<th>Validation criterion *</th>
<th>Original, max SSF</th>
<th>Validation criterion</th>
<th>Marked influence of SSF?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intensity</td>
<td>simul. water balance</td>
<td>(\Delta SM)</td>
<td>WB</td>
<td>WC</td>
<td>DP</td>
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<tr>
<td>Rietholzbach</td>
<td>high dry</td>
<td>11.7 73.4</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>11.7 73.4 1.8</td>
</tr>
<tr>
<td></td>
<td>high wet</td>
<td>14.9 57.0</td>
<td>-</td>
<td>(\pm)</td>
<td>-</td>
<td>12.7 57.0 4.2</td>
</tr>
<tr>
<td></td>
<td>low dry</td>
<td>0.0 91.6</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>0.0 91.6 0.0</td>
</tr>
<tr>
<td></td>
<td>low wet</td>
<td>0.0 58.6</td>
<td>+</td>
<td>(\pm)</td>
<td>+</td>
<td>0.0 58.6 1.1</td>
</tr>
<tr>
<td>Heitemberg</td>
<td>high dry</td>
<td>30.9 46.3</td>
<td>(\pm)</td>
<td>(\pm)</td>
<td>+</td>
<td>1.6 46.3 31.8</td>
</tr>
<tr>
<td></td>
<td>high wet</td>
<td>58.3 19.1</td>
<td>(\pm)</td>
<td>+</td>
<td>+</td>
<td>1.8 19.1 59.0</td>
</tr>
<tr>
<td></td>
<td>low dry</td>
<td>12.2 57.3</td>
<td>(\pm)</td>
<td>(\pm)</td>
<td>+</td>
<td>0.0 57.3 14.8</td>
</tr>
<tr>
<td></td>
<td>low wet</td>
<td>42.7 32.9</td>
<td>(\pm)</td>
<td>+</td>
<td>+</td>
<td>0.1 32.9 45.1</td>
</tr>
<tr>
<td>Koblenz</td>
<td>high dry</td>
<td>23.3 49.0</td>
<td>-</td>
<td>+</td>
<td>?</td>
<td>1.6 49.0 24.3</td>
</tr>
<tr>
<td></td>
<td>high wet</td>
<td>57.8 17.2</td>
<td>-</td>
<td>+</td>
<td>?</td>
<td>2.0 17.2 58.4</td>
</tr>
<tr>
<td></td>
<td>low dry</td>
<td>14.2 56.7</td>
<td>-</td>
<td>+</td>
<td>(\pm)</td>
<td>0.6 56.7 16.2</td>
</tr>
<tr>
<td></td>
<td>low wet</td>
<td>40.8 17.7</td>
<td>-</td>
<td>+</td>
<td>(\pm)</td>
<td>0.8 17.7 42.5</td>
</tr>
<tr>
<td>Niederweningen</td>
<td>high dry</td>
<td>3.0 71.8</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>3.0 71.8 0.8</td>
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<tr>
<td></td>
<td>high wet</td>
<td>3.4 69.7</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>3.4 69.7 3.2</td>
</tr>
<tr>
<td></td>
<td>low dry</td>
<td>0.5 69.6</td>
<td>+</td>
<td>(\pm)</td>
<td>-</td>
<td>0.5 69.6 0.0</td>
</tr>
<tr>
<td></td>
<td>low wet</td>
<td>1.2 69.3</td>
<td>+</td>
<td>+</td>
<td>(\pm)</td>
<td>1.2 69.3 0.0</td>
</tr>
</tbody>
</table>

\* agreement of the simulated with the observed criteria that was ranked to three classes: + agreement, \(\pm\) partly agreement, - disagreement, ? no data available. WB = water balance criterion, WC = water content change criterion, DP = dye pattern criterion

\(\dagger\) Vertical subsurface flow of the macropores
The parameterization of the maximum outflow of the macropore domain shows a marked influence on the results of all experiments at the sites of Heitersberg and Koblenz. A low value of the maximum outflow results in significant overland flow (OF), whereas a high value results in significant subsurface flow (SSF). The soil moisture changes within the soil profile (ΔSM) are similar in both cases. Considering the validation criteria for these sites, the water content change criterion (WC) and the dye pattern criterion (DP) show the same agreement class in both cases and, therefore, they are inappropriate to decide for one case. Only the water balance criterion (WB) can be used to decide for the maximum outflow of the macropore domain for these sites. For the Koblenz site, a high value of the maximum outflow and, thus, an unlimited drainage of the macropores results in an agreement of the water balance criterion. A fast drainage of the macropores complies with the observation during the experiments (see also Table 5.2), where the neighbouring creek at 110 m distance from the site was stained within several hours after starting the experiment. An additional tracer experiment was used to verify the high conductivity of these lateral preferential pathways in the bedrock (WEILER & NAEF, 2001). For the Heitersberg site, the value of the maximum outflow of the macropore domain lies somewhere between the two extreme cases. It is possible to fit the simulated to the observed overland flow by fixing the maximum outflow to 45 mm h⁻¹. However, the measured overland flow is strongly influenced by boundary effects (see Ch. 5.2 and WEILER & NAEF, 2001). Without boundary effects the overland flow would increase significantly, as measured by SCHERRER (1997) with sprinkling experiments on a 60 m² hillslope plot at the same location. Therefore, a low value of the maximum outflow of the macropore domain of 5 mm h⁻¹ is assumed. This value complies with the measured soil properties and results in a significant overland flow generation. However, it should be noted that the drainage of the macropore domain is a very sensitive parameter controlling the runoff generation as overland flow or as subsurface flow. The other two sites, Heitersberg and Niederweningen, do not show a marked influence on the parameterization of the macropore outflow because for all the experiments the applied water is either stored in the soil profile or is hindered to infiltrate into the soil by a low permeable soil surface.

The agreement between the simulated and observed values, which is shown by the three criteria, is generally very good, if the macropore drainage is properly chosen. Some discrepancies are obvious for the experiments with a high rainfall intensity at the Rietholzbach site. A water repellent soil surface causes these discrepancies (WEILER & NAEF, 2001). Also, the simulations for the experiments with low rainfall intensity under dry conditions at the Rietholzbach and Niederweningen sites do not comply for the dye pattern criterion. The main reasons for discrepancies at the sites are:

- **Rietholzbach** – the low permeability in top layer due to hydrophobic effects is not reproduced by the model.
- **Heitersberg** – the aggregation and structure of the top soil layer generates a higher permeability as estimated.
• Koblenz – the saturated hydraulic conductivity at the soil surface should be slightly lower parameterised because the simulated infiltration into the soil matrix is too high for low rainfall intensities.

• Niederweningen – the saturated hydraulic conductivity at the soil surface should be slightly lower parameterised because the simulated infiltration into the soil matrix is too high for low rainfall intensities.

The listed reasons for the divergences lead to the following conclusion. Firstly, the parameterization of the soil surface is crucial to reproduce the correct initiation of macropore flow. Experiments using different rainfall intensities are necessary to capture the parameterization of the surface. Secondly, an undisturbed soil surface is necessary to simulate the infiltration as naturally as possible. Mainly, the vegetation and roots significantly alter the properties of the upper soil layer. Unfortunately, these factors are usually not implemented in pedo-transfer models to estimate soil hydraulic properties. The capabilities of IN* to predict water flow in macroporous soils are very good, except for cases in which processes that were not considered by the model play an important role (e.g. water repellent top soil). This result is remarkable because the parameterization depends only on directly measured values for the macropore system and estimated values for the soil hydraulic properties.

7.2.2 Reference simulations

The reference simulations with IN* are performed with the proposed changes for the hydraulic conductivity in the upper soil layer. Table 7.2 lists the used input parameters. Figure 7.9 to Figure 7.12 show the results of the four experiments, arranged in rows, at each site for each validation criterion. In the first column, the results of the water balance criterion are shown, followed by the water content change criterion and the dye pattern criterion. In the last column, the observed profiles of classified flow processes can be compared with those simulated.

The results of the simulations for the Rietholzbach site reveal disagreement in some validation criteria (Figure 7.9). The main discrepancies are obvious for the water content change criterion and the dye pattern criterion for the experiments with high rainfall intensity. Despite the simulated dye pattern showing also the high interaction that was observed at this site, the profile of the classified flow processes is different. The simulated final water content change profiles also do not comply with that measured. The water repellent soil surface probably influenced the initiation and interaction in the upper soil layer and because IN* did not account for these effects, the simulations show the mentioned discrepancies. The simulation results for the low rainfall experiments agree better because the influence of the water repellency was reduced for longer rainfall events.

In general, the infiltration process at the Rietholzbach site was mainly controlled by initiation of macropore flow at the surface and a high interaction. Since infiltration into the soil matrix was limited, the water had to flow into macropores open to the surface. The macropore density at the surface is relatively low and, thus, the relative macropore drainage area is 80% (see also
Modelling infiltration into macroporous soils

Table 7.2  Input parameters of the reference simulation with IN3M

<table>
<thead>
<tr>
<th>Site</th>
<th>Thickness (mm)</th>
<th>$r$ (mm)</th>
<th>$n_{mac}$ (m$^{-2}$)</th>
<th>$SD_{max}$ (mm)</th>
<th>$K_s$ (mm h$^{-1}$)</th>
<th>$n$ (-)</th>
<th>$\alpha$ (-)</th>
<th>$\Delta \theta_{dry}$ (m$^{-1}$)</th>
<th>$\Delta \theta_{wet}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhetholzach</td>
<td>150</td>
<td>3.1</td>
<td>0.38</td>
<td>4.0 (16.0)</td>
<td>1.44</td>
<td>2.7</td>
<td>0.28</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>3</td>
<td>0.34</td>
<td>13.0</td>
<td>1.38</td>
<td>1.4</td>
<td>0.22</td>
<td>0.10</td>
<td></td>
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<tr>
<td></td>
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<td>2.8</td>
<td>0.28</td>
<td>10.0</td>
<td>1.41</td>
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<td>0.20</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>2.6</td>
<td>0.28</td>
<td>5.0</td>
<td>1.43</td>
<td>0.65</td>
<td>0.15</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2.4</td>
<td>0.33</td>
<td>24.0 (12.0)</td>
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<td>2.1</td>
<td>0.14</td>
<td>0.05</td>
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</tr>
<tr>
<td></td>
<td>200</td>
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<td>0.31</td>
<td>5.0</td>
<td>1.3</td>
<td>1.67</td>
<td>0.10</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>2.6</td>
<td>0.29</td>
<td>1.5</td>
<td>1.3</td>
<td>2.0</td>
<td>0.06</td>
<td>0.01</td>
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<tr>
<td></td>
<td>350</td>
<td>2.6</td>
<td>0.29</td>
<td>1.5</td>
<td>1.3</td>
<td>2.0</td>
<td>0.04</td>
<td>0.01</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2.0</td>
<td>0.36</td>
<td>5.0 (7.0)</td>
<td>1.47</td>
<td>2.1</td>
<td>0.17</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>2.5</td>
<td>0.36</td>
<td>10.0</td>
<td>1.47</td>
<td>1.06</td>
<td>0.08</td>
<td>0.02</td>
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<tr>
<td></td>
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<td>0.30</td>
<td>2.5</td>
<td>1.4</td>
<td>0.9</td>
<td>0.02</td>
<td>0.01</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>2.5</td>
<td>0.36</td>
<td>5.0 (8.0)</td>
<td>1.38</td>
<td>2.2</td>
<td>0.20</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
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<td>3.0</td>
<td>0.14</td>
<td>0.07</td>
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<td>0.34</td>
<td>24.0</td>
<td>1.52</td>
<td>3.4</td>
<td>0.15</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
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<td>0.36</td>
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<td>1.84</td>
<td>4.1</td>
<td>0.20</td>
<td>0.17</td>
<td></td>
</tr>
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<td></td>
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<td>0.34</td>
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<td>4.3</td>
<td>0.19</td>
<td>0.16</td>
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</tr>
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<td>maximum outflow of the macropore domain = 60.0 mm h$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Values in brackets indicate the initial parameter values that were directly derived.

Figure 6.7). Therefore, not all water could enter the macropores and overland flow was generated, especially for the high rainfall intensities. The ratio between infiltration at the soil surface into the soil matrix and into the macropores depends mainly on the rainfall intensity and less on the initial water content. The high permeability of the soil matrix leads to a generally high interaction observed and simulated for all four experiments. The experiments with the dry soil moisture conditions show a higher interaction than those with the wet soils. For example, the classified flow processes for the low rainfall intensity experiments are dominated by high interaction for dry initial conditions and by mixed and low interaction for wet conditions. Significant outflow of the macropore domain at the lower boundary was only simulated for the high rainfall intensity which agrees with the observation of a complete staining of the bedrock below 100 cm depth (Table 5.2).

Figure 7.10 shows the simulations for the Heitersberg site. The maximum outflow of the macropore domain is only 5 mm h$^{-1}$ resulting in a significant generation of overland flow that does not concur with the observations and is due to the already discussed boundary effects.
However, the very good accordance of all criteria except for the overland flow justifies that the flow processes were correctly simulated. The water content change criterion illustrates the observed mechanism at this site whereby initially the upper soil layer is saturated and then the water content increases in the deeper soil layers. The simulated final water content change reasonably fits the measured values. The dye pattern criterion is compatible. The depth of the
homogeneous matrix flow approximately corresponds to the observed change from matrix flow to low interaction. The observed continuous change from the homogeneous matrix flow to heterogeneous matrix flow cannot be simulated with INM because the model only accounts for homogeneous infiltration into the soil matrix. The observed low interaction in the subsoil is also correctly simulated for all experiments. The simulation of the low rainfall experiments indicate that the initiation of macropore flow mainly occurred in the soil. Overland flow is generated after the soil is saturated and therefore depends on the rainfall amount and initial soil moisture content. The simulations also illustrate that under low rainfall intensity conditions the lower outflow of the macropores is larger than for the high rainfall intensity because the out-

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**Fig. 7.10** Results of reference simulation for the Heitersberg site (Legend see Figure 7.10)
flow is regulated by a constant value. The low percentage of surface initiation, especially for the low rainfall intensity, is also validated by the results of the horizontal dye pattern analysis (Ch. 4.3). Since nearly all macropores were stained, water flow in the macropores was relatively similar due to subsurface initiation.

**Fig. 7.11 Results of reference simulation for the Koblenz site (Legend see Figure 7.10)**

Figure 7.11 shows the simulation results of the Koblenz site. The water balance criterion shows a good agreement. All simulations indicate that a large amount of the applied rainfall leaves the soil profile by the lower outflow of the macropore domain. Overland flow is generated because the macropore density is not sufficient to capture all water by the surface initiation.
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process (Figure 6.7). Surface initiation dominates especially for high rainfall intensity. The interaction is high in the upper soil layers, if the soil is dry. The water content change criterion shows a good agreement not only for the final water content change but also for the onset of saturation within the soil profile. The comparison of the dye pattern criterion is only possible for the low rainfall intensity experiment (see Ch. 4.2.2). The classified flow processes show homogeneous matrix flow in the upper soil layers and low interaction in deeper soil layers. However, the observed transition zone could not be simulated exactly with IN3M, but the average depth of the transition zone agrees. The simulations point out that the outflow of the macropore domain depends more on the initial soil moisture conditions than on the rainfall intensity.

Fig. 7.12 Results of reference simulation for the Niederweningen site (Legend see Figure 7.10)
Figure 7.12 illustrates the simulations for the Niederweningen site. Comparable with the other sites, all criteria show a good agreement. The overland flow and macropore outflow generation are very low corresponding to the observations. Only for the low rainfall intensity and wet initial conditions matrix outflow at the lower boundary is substantial. The water content change simulations generally agree with the observations except for the high rainfall intensity and dry initial condition. In this case the final water content change in the subsoil is simulated too high.

At a first glance, the agreement of the dye pattern criterion is not very good. However, a more detailed investigation shows that the general and important processes are reproduced, especially the low interaction between 20 cm and 40 cm depth and the high interaction in the deeper soil layers. The slight disagreement mainly results from the discretization of the soil layers in IN$^3$M. The depth function of the volume density of the generated dye pattern always underestimates that observed. A possible reason is that the calculation of the staining distance assumes only advective transport of the tracer generally resulting in a lower staining distance compared to the observed advective and dispersive transport of the tracer.

The high percentage of surface initiation is also validated by the results of the horizontal dye pattern analysis (Ch. 4.3). The lower values of the cumulative stained distance distribution at zero distance means that only a small percentage of the macropores were hydrologically active. Because surface initiation produces very little flow in many macropores, staining surrounded only some macropores.

A multi-criteria validation procedure was applied to compare the reference simulations of IN$^3$M with the observed data. This validation procedure is an adequate method to compare the complex output and information of IN$^3$M with experimental data derived from soil water measurements and dye pattern analysis and to justify the simulation results. The simulations of all sites generally agree with the observations, and the major flow processes and the resulting runoff generation was reproduced with only minor adjustment to the hydraulic conductivity of the uppermost soil layer. Consequently, IN$^3$M was capable of predicting flow processes in soils with macropores.

### 7.2.3 Sensitivity analysis

The validation of the simulation results of IN$^3$M was quite successful. However, the sensitivity of the model parameters and the implemented flow processes have to be evaluated in order to better understand the correspondence between the model and the physical process being modelled. In general, sensitivity is the measure of the effect of change in one factor on another factor (McCuen, 1973). The relative sensitivity of a parameter is frequently observed as a measure of the importance of that parameter for the physical process. The effect of the input data error or the error in the evaluation of the initial state of a model component is also estimated. Usually the sensitivity of a model is tested by changing the input parameters within a specified range and calculate either the relative change of a selected output value or the change in a "goodness-of-fit" measure, if the output of the model is more complex.
Since the output information of \text{IN}^3\text{M} is complex and a calculation of one "goodness-of-fit" measure was not sufficient, the sensitivity was evaluated with another approach. Two different input parameters of \text{IN}^3\text{M}, the macropore density and the saturated hydraulic conductivity, as well as the initiation process were selected to examine the sensitivity. The macropore density was selected as a representative parameter of the macropore domain and as a parameter that directly influences interaction and initiation. The saturated hydraulic conductivity was chosen as it has frequently shown a high sensitivity in infiltration models (e.g. Baumhardt et al., 1990) and its determination has large inaccuracies. Two output values were chosen to evaluate the sensitivity, the total interaction and the runoff. The depth function of the total interaction is a measure of the influence of macropore flow and bypassing of soil layers. The total and subsurface runoff is a measure of the runoff contribution of the plot. Both values were compared with the results of the reference simulations (Table 7.2).

**Sensitivity to the choice of the initiation process**

The influence of the initiation process was first examined by not considering the probability distribution of surface and subsurface initiation. The same flow rate in every macropore was assumed. Figure 7.13 shows this effect on the depth function of total interaction for all experiments. The gray bars show the total interaction for the reference simulation and the hatched bars show the values for the simulation without initiation process. The values give the change of the total interaction of the whole soil profile. For the simulations, the vertical resolution was increased (thickness of soil layers is equal to 100 mm) in order to have a more detailed depth function of interaction. The results indicate that with the same flow rate in every macropore, interaction for the whole soil profile increases, especially for the high rainfall intensity. The depth function of total interaction also changes. Interaction in the upper soil is frequently higher and the percolation depth of macropore flow and, thus, the depth of interaction is significantly lower for the Rietholzbach and Niederweningen sites.

Figure 7.14 shows the sensitivity of the runoff generation to the initiation process. The gray shaded area again shows the results for the reference simulation. The hatched areas show the total runoff and the cross-hatched area the subsurface runoff for the simulations without considering initiation. In this case, subsurface runoff is the combined outflow at the lower boundary of the macropore and the matrix domains. The difference between total runoff and subsurface runoff is overland flow. The runoff is normalized to a runoff coefficient that is the total runoff at a time divided by the total rainfall at the same time. In order to compare the experiments with the different rainfall intensity, the runoff coefficient is plotted against the total rainfall. The results indicate that the runoff is sensitive to initiation. If a change in runoff occurs, runoff is always lower with the same flow rate in every macropore. Especially for the experiments with a high interaction (Rietholzbach and Niederweningen), modelled subsurface runoff is strongly reduced. For the Koblenz site, where the water in the macropores bypasses the soil
matrix and thus produced subsurface runoff, the modelled subsurface runoff is considerably delayed for the experiments with high rainfall intensity.

The sensitivity of the infiltration in soils with macropores to the initiation process can be summarized as follows:

- Without considering the initiation process, total interaction is overestimated because the same flow rate in every macropore leads to a maximum possible interaction, whereas modelling a flow rate distribution in the macropores results in a limitation of interaction in part of the macropores.

**Fig. 7.13** Effect of the initiation process on the depth function of total interaction
Especially for soils with a high potential interaction, the interaction is higher in the upper soil profile and, thus, without initiation, the runoff generation is simulated with delay. The effects are more pronounced for surface initiation than for subsurface initiation because the flow rate distribution for surface initiation tends to produce more extreme values.

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**Fig. 7.14 Effect of the initiation process on the subsurface runoff and total runoff**

- Especially for soils with a high potential interaction, the interaction is higher in the upper soil profile and, thus, without initiation, the runoff generation is simulated with delay.
- The effects are more pronounced for surface initiation than for subsurface initiation because the flow rate distribution for surface initiation tends to produce more extreme values.
Sensitivity to macropore density

The sensitivity analysis of the macropore density was evaluated by increasing the macropore density by 300% compared to the values in Table 7.2. Usually the sensitivity is tested by changing the input parameter within a specified range, but due to the detailed evaluation of the simulation results, only one parameter change is shown. Only an increase was considered, as the chosen values for macropore density more likely represent the lower limit. A decrease of the macropore density or even a reduction to zero was not considered, as the experiments demonstrated the existence and importance of macropores. Figure 7.15 shows the sensitivity of the interaction to an increased macropore density. A higher macropore density is directly related to a higher interaction, whereas the significant increase of the macropore density by 300% only resulted in an increase of the total interaction between 6% and 80%. Despite the proportional relationship between the macropore density and the interaction (see Equation 6.13), the depth function of interaction usually did not change too much. Only for some experiments a decrease of the maximum depth where interaction occurred was simulated. Figure 7.15 shows the results for the runoff generation. For all experiments, a delay and a reduction in runoff was simulated. The change is significant for the experiments where a low interaction controlled the macropore flow and the runoff generation (e.g. Heitersberg), but also for experiments where a low macropore density at the soil surface reduced the total infiltration rate (e.g. Rietholzbach).

In general, the sensitivity of the infiltration in soils with macropores to macropore density can be summarized as follows:

- An increase of macropore density results in an increased interaction. However, the relative change of interaction is considerably lower. The flow rate distribution in macropores due to initiation, a limitation in interaction due to saturation, and an already high interaction partly explain the relatively low sensitivity of interaction to macropore density.
- The sensitivity of the runoff generation to the macropore density is higher, especially for the high rainfall intensity. If macropore density in IN²M is increased, a reduced bypassing of the soil matrix, an increase in the total infiltration, and a higher total interaction result in a reduction and delay of runoff.
- The low significance of the macropore density indicates that a simulation of infiltration in soils with macropores is also feasible if the macropore density can only be roughly estimated.

Sensitivity to saturated hydraulic conductivity

Finally, the sensitivity to the saturated hydraulic conductivity was examined. The hydraulic conductivity within the whole soil profile was increased by a factor of 3 and reduced by a factor of 0.33. As justified in the previous section, the sensitivity was only studied for two parameter changes. The relatively large changes account for the high uncertainties in estimating or measuring the saturated hydraulic conductivity in soils. It is expected that a higher hydraulic con-
Modelling infiltration into macroporous soils

Fig. 7.15 Effect of a 300% increase of the macropore density on the depth function of total interaction

ductivity results in an increase in the total interaction. Figure 7.17, however, shows a general decrease in the total interaction, especially for the experiments with low rainfall intensity. For high rainfall intensity, the relative differences were only minor, especially if the proportion between rainfall intensity and hydraulic conductivity of the upper soil layer is high. For low rainfall intensity, the depth function of interaction gives a different picture. A decrease in the hydraulic conductivity has the more or less reverse effect as an increase in the hydraulic conductivity (Figure 7.18). The total interaction increases for the low rainfall intensity, because a higher amount of water flows in the macropores. The total interaction decreases for high rain-
Fig. 7.16 Effect of a 300% increase of the macropore density on the subsurface runoff and total runoff

fall intensity since the interaction is reduced by lower hydraulic conductivity. The general shape of the depth function of interaction does not change, but a more pronounced interaction in the subsoil can be observed.

The sensitivity of runoff to hydraulic conductivity is not directly related to the changes observed for the interaction. An increase of hydraulic conductivity results in a reduction and delay of runoff, independently from the change of interaction (Figure 7.19). Only for the low-wet experiment at the Niederweningen site, runoff increased due to a higher percolation of the wet soil matrix. In general, changes are lowest under wet initial conditions and highest under
Modelling infiltration into macroporous soils

Fig. 7.17 Effect of a 300% increase of the saturated hydraulic conductivity on the depth function of total interaction

dry initial conditions and high rainfall intensities. The proportion between subsurface runoff and total runoff often changes by increasing the relative proportion of subsurface runoff. Figure 7.20 shows the results for a decrease of the saturated hydraulic conductivity. The changes are most significant for the high rainfall intensity where the interaction decreases. The runoff increases most for experiments in which runoff is controlled by the infiltration rate of the upper soil layer (Rietholzbach) and the interaction (Heitersberg and Koblenz). For low rainfall intensity subsurface runoff mainly increases due to a higher bypassing of the soil matrix in macro-
Fig. 7.18  Effect of a decrease to 33% of the saturated hydraulic conductivity on the depth function of total interaction

pores. The changes at the Niederweningen site are minor because hydraulic conductivity is still sufficient to infiltrate simulated rainfall intensities.

In general, the sensitivity of the infiltration in soils with macropores to the saturated hydraulic conductivity can be summarized as follows:

- An increase in the hydraulic conductivity often results in less runoff generation. However, the changes are relatively small. Under wet conditions and low rainfall intensities, subsurface runoff by percolation of the soil matrix becomes more important. The presence of
macropores reduces the effects of an increasing hydraulic conductivity, since the soil permeability is controlled rather by macropores than hydraulic conductivity of the soil matrix.

- A decrease in hydraulic conductivity often results in a higher runoff generation, especially subsurface runoff, since water is additionally forced to flow in the macropores and to bypass the soil matrix. A lower interaction supports bypassing of the soil matrix.
- Sensitivity to hydraulic conductivity is only recognizable, if the analysis is carried out with different rainfall intensities and different initial soil moisture contents. Depending on the
Application of IN3M

Fig. 7.20  Effect of a decrease to 33% of the saturated hydraulic conductivity on the subsurface runoff and total runoff

proportion of rainfall intensity to hydraulic conductivity, the results become sensitive to saturated hydraulic conductivity.

Conclusion

The sensitivity analysis pointed out that IN3M is generally less sensitive to changes in the input parameters than an infiltration model neglecting macropore flow would be since a single soil
layer always controls the behaviour in soil without macropores. However, effects of changes in the input parameters are more difficult to predict for a more complex infiltration model. The analysis also showed that the initiation of macropore flow and the resulting flow rate distribution in macropores has to be considered by a macropore flow model in order to correctly simulate interaction and the onset of runoff. The sensitivity analysis also demonstrates that the flow processes within the soil never completely changed and, thus, the general hydrological behaviour of a soil can be predicted independently of the uncertainty of the input parameter estimation. Therefore, the first simulation results of IN$^3$M were quite satisfactory, despite the estimation of the soil properties being based on pedo-transfer functions.

### 7.3 ARE THE EXPERIMENTAL SITES REPRESENTATIVE?

The selection of the experimental sites was based on different criteria (Ch. 2.2.1) influencing the flow processes in the soils. It can be argued that this selection of specific sites with a unusually high or low interaction may not be representative for other sites in Switzerland. In order to check this conjecture, the results of the experimental sites were compared with results from other sites in Switzerland. IN$^3$M was used to simulate infiltration with similar boundary conditions as for the experimental sites. Six reference sites in Northern Switzerland where informations on soil properties and soil classification was available from the Swiss Federal Research Station for Agroecology and Agriculture were selected. In Table 7.3 some important features of the reference sites are listed. The sites are characterized by different geological parent material and by different land-use.

#### Table 7.3 Selected reference sites from the Swiss Federal Research Station for Agroecology and Agriculture

<table>
<thead>
<tr>
<th>No.</th>
<th>Soil classification</th>
<th>District</th>
<th>Altitude (m a.s.l.)</th>
<th>Geological parent material</th>
<th>Land-use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tb 188</td>
<td>Gleyic Cambisol</td>
<td>Kirchberg, SG</td>
<td>745</td>
<td>Conglomerates (Molasse)</td>
<td>Meadow</td>
</tr>
<tr>
<td>Mh45</td>
<td>Orthic Luvisol</td>
<td>Möhlin, AG</td>
<td>350</td>
<td>Loess</td>
<td>Farmland</td>
</tr>
<tr>
<td>Mi 308</td>
<td>Fluvic Eutric Gleyso</td>
<td>Waltenschwil, AG</td>
<td>426</td>
<td>Alluvium (fluvial deposits)</td>
<td>Farmland</td>
</tr>
<tr>
<td>KE 8</td>
<td>Gleyic Cambisol</td>
<td>Malters, LU</td>
<td>610</td>
<td>Molasse</td>
<td>Pasture</td>
</tr>
<tr>
<td>WI 26</td>
<td>Eutric Gleyso</td>
<td>Will, AG</td>
<td>520</td>
<td>Clay (Opalinus)</td>
<td>Farmland</td>
</tr>
<tr>
<td>DS 13</td>
<td>Gleyic Cambisol</td>
<td>Urdorf, ZH</td>
<td>465</td>
<td>Moraine (Würm)</td>
<td>Farmland</td>
</tr>
</tbody>
</table>

The soil texture of the reference sites as percentages of sand and clay fraction are shown in Figure 7.21. Compared to the experimental sites, the soil texture of the reference sites is higher in clay and silt. The database does not hold a more sandy soil. Many of the selected reference sites are frequently influenced by groundwater or waterlogging, which is very common for soils in the Swiss midland and Swiss pre-alpine regions. The detailed descriptions of the soil properties
was then used to determine the input parameters for IN3M, whereas the macropore density was estimated from a qualitative description of the soil profile. The maximum outflow of the macropore domain was estimated from the properties of the geological parent material. The initial conditions of the soil water content were determined by assuming a matric potential of 100 kPa in the topsoil and 20 kPa in the subsoil for dry initial conditions and 10 kPa in the topsoil and 3 kPa in the subsoil for wet initial conditions. The high and low rainfall intensity was simulated based on the chosen values in Ch. 2.3.1.

The simulation results for runoff generation at the six reference sites are illustrated in Figure 7.22. Total runoff and subsurface runoff can be compared for all experiments under the four different initial and boundary conditions. The results of site Tb 188 are similar to the results of the Rietholzbach site because infiltration into the soil was reduced by a low permeable topsoil and the macropore density was not sufficient for all excess water to flow into the macropores. The influence of the initial and boundary conditions is relatively low. The soil properties of site Mh 45 are comparable to properties of the Koblenz site. Also, the pronounced subsurface flow generation due to bypassing of water in macropores is comparable. However, for dry initial conditions, rainfall is completely retained in the soil matrix, whereas the Koblenz site also produced runoff under dry initial conditions. The results of the Mi 308 site, a clay-loam soil over alluvium, also showed distinct bypassing of the soil matrix in macropores, resulting in recharge into the groundwater. Below 80 cm depth, the water reached a high permeable layer and the interaction strongly increased. The properties of this site are comparable to the Obfelden site where a dye tracer experiment also showed bypassing in the soil and a complete staining below 80 cm (Flury et al., 1994). The results of the KE 8 site show a delayed overland flow generation. The water infiltrated into the high permeable topsoil layer and after this layer had been saturated, macropore flow was initiated and the overall infiltration was controlled by the interaction. Therefore, overland flow was also controlled by interaction. The results of the WI 26 site show a very strong overland flow reaction with a final runoff coefficient of around 80% for the wet initial conditions. Due to a low permeable bedrock material (clay) and a low permeable soil, macropore flow was rapidly ini-
Modelling infiltration into macroporous soils

tiated, but the macropores just filled up and overland flow started because interaction was very low. The results of the DS 13 site are similar to the WI 26 site. However, runoff generation is more moderate.

![Subsurface runoff and total runoff for six reference sites in Switzerland](image)

**Fig. 7.22** Subsurface runoff and total runoff for six reference sites in Switzerland

Figure 7.23 shows a direct comparison between the results of the experimental sites and the six reference sites in terms of interaction and initiation processes. The percentage of total interac-
Are the experimental sites representative?

...tion on the total flow in macropores plotted against the total flow in macropores illustrates the variety of total macropore flow and the bypassing of the soil profile of the experimental and reference sites (Figure 7.23a). Bypassing means the proportion of water that drains macropores at the lower boundary to water that enters the macropores. This value is reciprocal to the percentage of total interaction on the total flow in macropores. The scatter of data suggests independence of the total flow in macropores from the interaction for the simulated sites. The experimental sites tend to have a higher interaction for high macropore flow than the reference sites. In Figure 7.23b the percentage of surface initiation is also plotted against the total macropore flow which is equal to the total input into macropores. The majority of simulation results shows a high percentage of surface initiation independent from the total macropore flow. Only the simulations for the Heitersberg site and the WI 26 site result in subsurface initiation. The minority of sites showing subsurface initiation reflects the specific conditions necessary for this initiation process.

![Figure 7.23](image)

**Fig. 7.23** Comparison of interaction (a) and initiation (b) between the simulations results of the experimental sites and the reference sites

In general, the results of the experimental sites show a similar behaviour and the same variety of processes as the reference sites. Therefore, the experimental sites can be considered to be representative for agricultural soils on hillslopes in Northern Switzerland.
Modelling infiltration into macroporous soils
8.1 DISCUSSION

8.1.1 Credits and limitations of the field experiments

The field experiments were designed to study the important processes governing infiltration in macroporous soils and the selected experimental sites contained a wide variety of different properties influencing macropore flow. Nevertheless, the question arises whether the experiments were appropriate to study macropore flow processes, to identify the main factors influencing these processes, and to generalize the relevant processes.

Combined sprinkling and dye tracer experiments with different rainfall intensities on different initial soil moisture conditions were performed. The artificial rainfall experiments allowed the addition of dye tracer to the sprinkling water and was definitely necessary to simulate extreme rainfall events of a low recurrence probability. The high spatial and temporal variability of the macropore flow processes was captured by the simultaneous measurements of water fluxes, soil water content, and matric potential, and by the preparation of horizontal and vertical soil sections to obtain the dye patterns. The measurements of the soil water regime allowed the characterisation of the temporal behaviour of infiltration, although they suffer from a poor spatial resolution (point measurement and low density). By the simultaneous use of tensiometer and TDR probes the shortcomings of one system were compensated by the other system. For example, the low sensitivity of the TDR probes for water flow in macropores within their region of influence is compensated by the immediate reaction of the tensiometers to flow in a macropore that is connected to the tensiometer cup. To counteract the low spatial resolution of both measurements, horizontal and vertical dye patterns assisted the analysis. Due to their high spatial resolution, the dye patterns allowed to quantify the interaction, to draw conclusions about macropore initiation, and to qualify subsurface runoff. As dye patterns show only one picture of the cumulative flow pattern at the end of the experiment, only integrative statements about the important flow processes are possible. Furthermore, adsorption of the tracer can influence the results. However, the dye tracer results in combination with the soil water regime
Discussion and Conclusion

provided a good basis to analyse macropore flow processes and to develop and verify the infiltration model IN$^3$M.

The experimental set-up is less appropriate for studies focusing on the exact measurement of overland flow. Because the plot size of 1 m$^2$ can show influences of boundary effects, overland flow due to saturation excess may be incorrect (Ch. 5.2). Moreover, for the measurement of runoff within a permeable top soil layer, another approach for water collection needs to be considered for future applications. In this set-up, the measurement of water percolating below a certain depth (100 cm) is not possible and only qualitative information on percolation was obtained by the staining of macropores and bedrock. Water drainage in lysimeters or water drainage to tile drains provide possibilities to measure percolation within field experiments, but their application is also limited (Villholth et al., 1998).

As the experiments were carried out on sites where the macropores were predominately vertically oriented, continuous earthworm channels, macropores formed by decay of plant roots (root channels), wetting and drying process (cracks), etc. were not explicitly studied. Most likely for soils with these macropores, initiation and interaction likewise are the relevant processes controlling macropore flow, but their conceptualisation and parameterisation might be different. As the presented experiments allowed a consistent quantification of the macropore flow processes, a similar set-up could be designed to study flow processes for other macropores.

The experiments in this study are very well suited to study macropore flow processes in field soils if their limitations are taken into account and the results are coherently analysed. It would now be useful to carry out these experiments on additional sites with different macropores or boundary conditions to identify the factors for macropore flow under these conditions in more detail and to supplement the results of this study.

8.1.2 Generalisation of the experimental results

Although the experiments were carried out under specific conditions such as size of the plot, constant rainfall application, drop size distribution of the sprinkling water, etc. (discussed in Ch. 2.3.2 and Ch. 7.1.2), these should not affect the identification of the general macropore processes and influencing factors. Various measures were considered to increase the general significance of the results. The experiments were carried out under different initial soil moisture conditions and rainfall intensities. Consequently, they are representative for different natural conditions. The contrasting experimental results for different conditions at some sites underlines the importance of this approach. Furthermore, the experiments were carried out on field sites without disturbing the soil surface and artificial influences of the measurement devices were minimised. The endeavours also comprised the use of additional hydrological measurements available for the sites in the catchments in which the field experiments were carried out. Weiler & Naef (2001) showed that the major processes observed for the experimental sites could also be confirmed with independent measurements under natural conditions (e.g.
groundwater table fluctuations, continuous matric potential and overland flow measurements, etc.).

Nevertheless, the temporal variation of factors that may influence the experimental results were not considered, as the experiments were carried out only once on each site and the initial conditions of the experiments were examined for this date. Thus, the experimental and simulation results are in principle only representative for the same time of the year, even though there are causes for a temporal variation of process influencing factors at a site:

- the stability of earthworm casts can change in a seasonal perspective (Hindell et al., 1997) or suddenly during or after rainfall events (Faeh, 1997)
- a change of the continuity of the macropore system, especially a reduction during winter time due to a lower earthworm activity (Carter et al., 1982; Syers & Springett, 1983; Bouchè & Al-Addan, 1997).
- hydrophobic effects of the soil surface, but also within the earthworm burrows, which can temporarily change the initiation and the interaction especially for dry soil moisture conditions and for certain sites (Ch. 7.2.2; Ritsema & Dekker, 1993; Dekker & Ritsema, 1996; de Jonge et al., 1999).

These factors will mainly change the intensity or the degree of influence on the macropore flow, however, the generally observed relevant processes are representative for the whole year. Because macropore flow processes were studied only on four sites, the representativity of the observed phenomena for other sites should be assessed. The results in Ch. 7.3 show that the soil properties of the experimental sites are within the range of variability of the soil properties of other agricultural sites in Switzerland. Simulations for these sites also showed, that they behave similar as the experimental sites and exhibit the same variety of processes. Thus, despite the strict selection of the experimental sites, the experimental results and mainly the observed processes can be considered representative for large regions across Switzerland.

Finally, another factor that can alter macropore flow processes is land use. As all experimental sites were covered by grass, the influence of other land use was not studied. Different land use mainly alter the soil surface and the permeability of the topsoil. Thus, subsurface initiation of macropore flow is probably more pronounced for forested sites and for tilled soils, whereas some field crops (e.g. maize) may increase surface initiation. Also a change of the soil surface by agricultural practices can alter the macropore initiation (e.g. Ehlers, 1975; Bouma, 1992; Ela et al., 1992; Logsdon et al., 1990; Dunne et al., 1991). Even if the parameterisation of some processes may change, the infiltration in macroporous soils of different land use is still controlled by the studied mechanisms. However, additional experiments are necessary to confirm these hypotheses.
Discussion and Conclusion

8.1.3 Appraisal of the infiltration model

Many models describing flow and/or transport in soils containing macropores, like MACRO (Jarvis et al., 1991), QSOIL (Faeh et al., 1997), RZWQM (Ahuja et al., 1995), tipping bucket model (Emerman, 1995), SAMP (Ewen, 1996), LASOMS (Chen & Wagener, 1992b), and PREFLO (Workman & Skaggs, 1990), have been developed, tested and applied in the past years. The models mainly account for macropore flow by a dual-porosity/dual-permeability approach. The physical description of flow and transport in the macropores and the soil matrix and the water exchange between the macropores and the surrounding soil matrix differ significantly. Consequently, it should have been possible to find an existing model satisfying the needs for this study. Why was the new model IN\(^3\)M developed?

The process study and experimental results of Ch. 6 resulted in a description of mechanisms controlling macropore flow which needed to be implemented in the new model:

- the variation of flow rate in every macropore due to the initiation process as it affects the interaction and therefore the runoff response of the soil.
- the flow velocity in macropores formed by earthworms can be neglected because it is always high enough.
- the macropore density and the average macropore radius should be used to parameterise the macropore system, as these parameters can be determined with greater accuracy than the macroporosity using horizontal soil sections (Ch. 6.1.3) or soil-landscape models which can predict different soil attributes such as the macropore density (Gessler et al., 1996).

Finally, the new model IN\(^3\)M was developed, as none of the existing models supported these important considerations.

Additionally, there are other arguments for a new infiltration model. The use of numerical methods to solve the differential equations of flow in variably-saturated porous media often results in instabilities of dual-porosity models (Faeh, 1997) and requires a relatively long computation time, as flow rates can change abruptly and be very high. Therefore, in IN\(^3\)M the Green-Ampt approach was chosen to calculate vertical and horizontal water flow. This analytical solution has been widely used for modelling infiltration in hydrological applications, as its calculation is stable and fast, and the parameters can be derived from soil properties. Due to its fast computation time and its stability, IN\(^3\)M will also be applicable as an infiltration module of rainfall-runoff models.

A separate module of IN\(^3\)M generates dye patterns from the simulation results, hence providing the possibility for comparison with experimental dye patterns. Thus, the validation of the model was not only based on measured water fluxes and soil water content changes, which usually suffer from a low spatial resolution, but also on the measured and classified dye patterns, which are considered to be more reliable for identifying preferential flow processes. A time sequence of artificial dye patterns can also be used to dynamically visualise the flow processes in the soil during the sprinkling experiments.

As IN\(^3\)M was exclusively designed to simulate infiltration in soils containing macropores formed by earthworms, the model does not account for other related hydrological processes.
like interception, evapotranspiration, or lateral flow on the surface or within the soil. It does also not simulate temporal variation of process like hydrophobic effects of the soil surface and within the earthworm burrows and changes of the macropore system.

IN$^3$M, which is still a research tool, was trimmed to simulate the most important processes of infiltration in a soil containing macropores formed by earthworms. Mainly because of its integrative approach, the results were very satisfactory and the factors influencing macropore flow could be well identified. Especially, the possibility of generating dye patterns was found very valuable for validating macropore flow processes. IN$^3$M is a specialized tool and its application is restricted to soils with similar macropore properties. Nevertheless, the concept of IN$^3$M may also be useful to develop an infiltration model for soils with different macropores.

8.1.4 Benefits for catchment hydrology

This study was designed to identify processes related to macropore flow and their influencing factors at the plot scale. Beyond this identification, the results also demonstrate the influence of macropore flow on runoff generation at the plot scale. Therefore, the question arises as to how the findings of this study can benefit problems in catchment hydrology?

If macropores are considered to be relevant for the runoff generation within a catchment, two different approaches to integrate their effects in infiltration models can be found in the literature:

- An effective hydraulic conductivity is introduced combining the permeability effects of macropores and the soil matrix. Bypassing of the soil matrix, however, is not possible.
- A rainfall intensity threshold is defined, above which flow in macropores starts and bypasses the soil matrix. Initiation and interaction of macropore flow are thus not adequately integrated.

Both approaches were applied in rainfall-runoff models. However, their applicability is often restricted by the lack of identifiable parameters and by the non-linearity of the processes themselves, which are not adequately described.

Therefore, an other idea is proposed as to how the results of this study can be used in catchment hydrology. As shown in Ch. 7, the developed IN$^3$M captures the most important processes of infiltration in macroporous soils and thus, enhances the predictability of runoff generation at the plot scale. Hence, with IN$^3$M and the knowledge of the influencing factors of macropore flow, it should be possible to estimate runoff generation processes and their quantity. Once the dominating runoff generation processes can be estimated at the plot scale, their influence on runoff generation at the catchment scale can be studied and simple conceptual rainfall-runoff models, which are based on the identified processes, can be derived (Scherrer & Naef, 2001; Weiler et al., 2000; Seibert & McDonnell, 2000). These models have the advantage that runoff generation of an area is pre-defined according to the identification. The contribution of each area can then be directly verified by a hydrograph separation based on runoff processes. The influence of macropores at the catchment scale can thus be assessed (Weiler et al.,...
2000). Following this idea revealed that the quantification of subsurface runoff is very important and its description and conceptualisation need to be improved in future studies.

8.2 CONCLUSION

Combined sprinkling and dye tracer experiments simulating extreme rainfall events for different initial soil moisture conditions on four sites in Switzerland generated a comprehensive data set of dye patterns and soil water regime measurements. The experimental results demonstrate a large variability of how water infiltrates into macroporous soil. This study was able to explain the observed variability with a new integrative approach combining the most important mechanisms controlling infiltration into macroporous soils:

- Macropore flow is either initiated from the soil surface or within a saturated or partially-saturated soil layer. Macropore initiation provides a different supply of water into each macropore and thus causes a different water flux in each macropore. This flow rate shows large differences especially for surface initiation.
- The water flow in macropores formed by earthworms does not limit the initiation of macropore flow. Although, macropores are in most cases only partly filled, the flow velocity is still very high (>10 cm s\(^{-1}\)).
- Interaction, which is the water transfer from the macropores into the surrounding soil matrix, strongly depends on the flow rate distribution in the macropores and thus, the initiation process.

The interdependencies of initiation and interaction were integrated in the simple but integrative new INfiltration-INitiation-INteraction Model (IN\(^3\)M), which:

- describes vertical and horizontal infiltration with a consistent and stable approach (Green-Ampt),
- uses physically-based parameters that can be derived from soil properties, and
- simulates the vertical wetting front distance of each macropore in order to generate dye patterns from the simulation results which provide a strong verification possibility.

To use dye patterns as a verification tool, a new classification approach was developed which identifies a priori defined flow processes (macropore flow with low and high interaction, heterogeneous and homogeneous matrix flow) for each experiment. The resulting vertical sequences of dominating flow processes in the soil profile concisely characterise the infiltration process.

This study also provided the most important factors influencing the observed variability in the infiltration into macroporous soils. Because most influence factors are inter-related, a sensitivity analysis of IN\(^3\)M together with observations during the experiments provided valuable information:

- The permeability of the top soil layer has a strong influence on the initiation of macropore flow. Therefore, it is important to estimate the permeability using not only soil textural
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information, but also vegetation and soil structure. Due to a change of the initiation process, the infiltration behaviour can switch from one into another regime.

- In soils in which macropore flow notably bypasses the soil matrix, the drainage of the macropore system by subsurface flow is very important. A limited drainage can cause a filling of the macropores and under reduced interaction generates overland flow. A rapid drainage due to fast lateral flow pathways or artificial drainage (tile drains) can cause fast generation of subsurface flow. However, a consistent quantification of subsurface flow is still a problem in hillslope hydrology.

- The water content of the soil matrix has a strong influence on the initiation of macropore flow and interaction. A low saturation deficit in the topsoil results in a rapid initiation of macropore flow (surface or subsurface). If the matric potential of the soil matrix is low, interaction is reduced and thus, bypassing of the soil matrix is enhanced.

- The average saturated hydraulic conductivity of a soil mainly governs the different interaction potential of a site. As opposed to a soil without macropores, in a soil with macropores, a low permeable soil layer does not control the overall infiltration as macropores can open the whole soil profile for infiltration. Thus, the effect of a change in the hydraulic conductivity is less important for a macroporous soil than for a soil without macropores.

This study also has implications for other research areas in hydrology. Although only water flow was explicitly considered in this study, the results also affect the transport of solutes. Especially leaching of solutes in combination with initiation of macropore flow should be studied in more detail, as surface initiation will increase the probability of a fast breakthrough. Related to this area is the question about movement of old and new water in the soil. The percentage of new water in the runoff will increase if rainfall passes the soil by surface initiation in combination with bypassing of the soil matrix. However, subsurface initiation will decrease new water proportion. As both processes strongly depend on rainfall intensity and initial soil moisture content, these factors should be considered when explaining hydrograph separation.

The initial soil moisture profile has a strong influence on macropore flow, but also the final water content in the soil is strongly modified by macropore flow. Macropore flow can generate a very heterogeneous distribution of the water content in the soil. For example, in a macroporous soil, the water content in the topsoil may be lower than expected, which subsequently affects the evapotranspiration and the initial conditions for the next rainfall event. Finally, the macropores can drain a soil more efficiently, which is especially important for the recovery of the saturation deficit in the soil.
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June, 2001

Markus Weiler
## Curriculum Vitae

<table>
<thead>
<tr>
<th>Year(s)</th>
<th>Education/Experience</th>
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<tr>
<td>1971</td>
<td>Born June 17 in Tuttlingen, Germany</td>
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</tr>
<tr>
<td>1994-1997</td>
<td>Hydrology at the Albert-Ludwigs University of Freiburg, Germany Graduation as Diplom Hydrologe (Dipl. Hyd.)</td>
</tr>
<tr>
<td>1997-2001</td>
<td>PhD student at the Institute of Hydromechanics and Water Resources Management, Swiss Federal Institute of Technology (ETH) in Zurich</td>
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