Water flow at the field scale

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Abstract

In this introductory paper I try to summarize some major features of water flow at the field scale relevant for the subsequent discussion of P-losses. After the definition of the field scale as a hydrologically arbitrary scale between the plot and the hillslope scale the flow mechanisms at the field scale are discussed. It is emphasized that it is crucial to understand the interplay between the spatial patterns of the flow paths and the pools of mobile solutes in the soil. The differences between surface and subsurface flow are discussed as well as the main factors enhancing surface runoff. Despite the substantial differences between flow in the soil and on the soil surface I argue that it is important to treat the two processes together because they are mutually dependent and the flow path out of a field may well be a sequence of subsurface and surface flow. In the last part the spatial and the temporal heterogeneity are discussed. The paper concludes with the proposition to compare the P-losses in different areas of Europe based on conceptual models containing the most important processes and controlling factors for different regions.

Key words:

heterogeneity, subsurface flow, overland flow, drainage systems

Introduction

Water is the main agent of transport of all P-forms from fields into waters. A proper knowledge of the water fluxes is needed in order to understand P-losses. In the following I try to summarize some major features of water flow at the field scale relevant for the subsequent discussion of P losses. The focus is on experimental field work and the conceptual model that come out of this research. This shall be a background for evaluating the actual state-of-the-art in assessing and modeling P-losses at the field scale.

Modeling is an essential part of scientific work. However, the notion of a model is not always unambiguously used. In the following I use "model" for a well-defined mental representation of a natural phenomenon. We can distinguish between different levels of models:

- conceptual models
- mathematical models
- simulation models.

Conceptual models represent the phenomenon of interest by the structures of the entire system, the main processes occurring and the relevant boundary and initial [Tsang, 1991 #1058]. All mathematical and numerical models rely on an underlying conceptual model (even if this model is not formulated explicitly). In a mathematical model the quantities contained in the conceptual model, their relationships and the processes are written down in a mathematical form (e.g., partial differential equations). In soil physics or hydrology these mathematical model are often too complex to be solved analytically. Therefore, they are often translated into numerical approximations that can be solved as a numerical algorithm.

Models can be looked at as (complex) scientific hypotheses. Applying a simulation model implies therefore that one accepts the underlying hypotheses to be true or to come close enough to reality to be useful. However, as scientific hypotheses models never can be proven to be correct. At most they can be validated properly. This means that a model could not be rejected against a null-hypothesis for many different situations. If the conditions for which the models are used are within the range of the situations used for validation it is reasonable to accept the model. If a model fails in a validation process, there are two basically different possibilities:

1. Parameterization problems: The model may be right, but its output is wrong due to erroneous parameters. In soil physics and hydrology to obtain correct parameters is often a major problem.
2. The underlying conceptual model is wrong.

If the model is wrong, the model results will in general not be in accordance with independent measurements. However, the effects of erroneous parameters and models may compensate for each another. If one uses inverse parameter estimation procedures, it may be possible to fit a wrong model to a measured output with wrong parameters. Instructive examples are given by [, 1990 #408, p.43] or [, 1992 #1033]. Nevertheless, it may also turn out during an inverse parameter estimation that no parameter set can describe the observed field results. This is strong evidence for the underlying model to be false or incomplete (e.g., Schmied et.al. , 2000) .

In our context it will be of special importance to test whether or not the conceptual models underlying existing simulation codes are in agreement with the findings of experimental field work. Therefore, this article concentrates on demonstrating the complexity involved in water and solute transport at the field scale. This shall be used as a background against which one may judge

1. the agreement between the conceptual models of existing simulation models and those resulting from field studies
2. for which conditions the simulation models may be applied successfully

3. the main scientific problems related to measure and model P-losses at the field scale.

The European context

Within this COST action 832 it should be kept in mind that there exists a large variability within Europe concerning the factors influencing water flow and P-losses. The area of agricultural production covers an area of almost 30° of latitude (Crete, 35° N to about 63° N at the northern end of the Gulf of Bothnia) with climatic conditions varying from Mediterranean to almost arctic and a large variability in soil conditions (see Tab. 1). The agricultural practice is also highly differentiated according to the natural and the socio-economic situations. For example, we can distinguish regions of intensive dairy farming like Denmark with predominant grassland cultivation and regions dominated by arable land. Subsurface drainage systems as important management tools are found mainly in the northern parts of the continent according to the soil and climatic conditions [, 1999 #997], whereas the risk of soil erosion is in general much higher in many parts of the Mediterranean region due to more intense rainfall, often sparse vegetation and steep terrain.

Characterization of the field scale

Because transport is dominated by different factors at different scales it is useful to start with a description how the field scale differs from the (generally) larger hillslope (or subcatchment) and catchment scale as well as from the smaller plot scale. From a hydrological point of view hillslopes and catchments are natural units. They are separated by no-flow boundaries. This means that the delineation of hillslopes or catchments is not arbitrary and the flow processes within a single unit are independent of the processes in the neighboring ones. In contrast, fields and plots are arbitrarily delineated, and the fluxes within a field or plot are generally influenced by the surrounding areas. From an agronomic perspective however, the field scale is a logic one since at this scale a certain part of the landscape is managed in a homogenous way.

Table 1: Soil types in Europe. After FAO [, 1993 #1013].

Soil type	Area [km2]
Leptosols	648360
Cambisols	1572880
Calcisols	566570
Gleysols	176410
Luvisols	1426580
Regosols	268480
Podzols	2136240
Kastanozems	555980
Fluvisols	402500
Podzoluvisols	1616840
Histosols	32824
Chernozems	98551
others	456710

Plots are the most arbitrary units in our context. They are delineated and located in the landscape mainly based on practical aspects related to the experimental goals and methodological possibilities. Nevertheless, scientifically the plot scale is very important allowing to study processes inaccessible at larger scales but relevant for entire fields, hillslopes or catchments. One of the large problems pertinent to this scale is the question how to relate results to fields or even larger units.

This scaling problem is closely linked to the spatial variability of soil properties and water fluxes. The heterogeneity at the plot scale is due to small-scale variability in the pore structure. At the field scale, additional factors may contribute to the spatial variability. Apart from a natural random heterogeneity there may exist deterministic trends (e.g., due to topography) of soil properties within fields that are not relevant at the plot scale. Technical installations like subsurface drains also contribute to the artificial, deterministic variability that has to be considered at the field scale but which can often be neglected at the plot scale.

Going from the field to the hillslope or catchment scale new factors get relevant. The position in the landscape may strongly influence the runoff behavior due to the differences in soil moisture status or due to changes of the soil type along a catena. This effect may also exist for fields but is much more important for hillslopes covering the entire continuum from the hill-crest to the lower parts along the river. The human impact causes also spatial variability not existing at the field scale by fields managed by different farmers. To understand the response of entire hillslopes or catchments one has to consider also that the out-flowing water from single fields may be affected by artificial channelization or remediation measures like buffer belts [, 1997 #1035]. Such factors come into play only at scales larger than fields. In erosion research this aspect is well known as the problem of the delivery ratio linking the on-site erosion rates to the sediment yields at the catchment scale [, 1990 #1034]. Recent publications show that the problems still remains to be settled [, 2000 #1057].

To conclude this section, I would like to mention another important difference between the plot and field scale: their ratios between the lateral, horizontal extension and depth. For the plot scale this ratio is in many cases in the order of about one and the main flow direction is vertical. In contrast, for the field-scale this ratio is in the order of about 10 to 100 or even larger. For transport into surface waters lateral transport is the dominant flow direction.

Flow mechanisms at the field scale

The classical scheme of flow processes at the field and hillslope scale differentiates between surface and subsurface runoff. They differ in many important aspects like in the travel times or the different parts of the soil getting into contact with the flowing water. The physics of transport are also quite different. Subsurface flow is mainly laminar due to the restricted size of most pores and can be described by Darcy's law [, 1856 #590] except for very large pores like soil pipes. In contrast, surface runoff may cover the entire range from laminar sheet flow to fully turbulent rill flow [, 1990 #1018] and is described by the Saint Venants equation [, 1990 #1019]. Due to these differences between surface and subsurface processes it is often necessary to use different theoretical and experimental approaches. This may create problems of compatibility for experimental and modeling purposes. The adequate temporal and spatial resolution for measuring and model calculations may be quite different. Despite the physical differences between surface and subsurface flow processes a comprehensive analysis of the transport phenomena at the field scale shows that they are closely linked together. In the following I try to give an overview on the dominant flow paths at the field scale and to show how surface and subsurface flow may interact.

As mentioned above, lateral transport is the main flow direction at the field scale if we are concerned with surface waters. Therefore I focus on saturated water flow, which dominates lateral transport. We may group different flow systems according to the temporal scale of the lateral flow process and according to the depth of the lateral flow paths into two broad categories: continuous and event-based lateral transport. For continuous lateral flow to exist a persistent ground water table has to be present. Precipitation can infiltrate completely through the vadose zone feeding the groundwater.

As well in the vadose or unsaturated soil as in the subsoil the hydraulic conductivity has to be sufficientely large to convey all the precipitation downwards and laterally towards the open channel. In general, continuous lateral transport occurs in permeable subsoils. Event-based lateral transport occurs when the hydraulic conductivity for vertical infiltration and / or lateral saturated transport in the subsoil is limited. If the vertical hydraulic conductivity at a given depth of the unsaturated zone is too small a perched water table builds up causing lateral transport. Sometimes the thin compacted plow pan is sufficient to cause saturated lateral flow in the topsoil [, 2000 #1009].

If the infiltration is limited right at the soil surface overland flow occurs. There are several causes limiting the infiltration and inducing surface runoff:

- High intensity rainstorms. If the rain intensity exceeds the infiltration capacity of the soil surface runoff occurs. This process was the basic mechanism Horton proposed in the early 30's to explain storm flow [, 1933 #1083]. Under European conditions this probably not the main factor causing surface runoff in undisturbed soils.
- Saturated soil conditions. If the soil is already saturated prior to a rain event all the additional water has to flow on the surface. This mechanism causes surface runoff to occur mainly in the wet, lower parts of field.
- Surface sealing. Especially on arable land with poor soil cover the plash effect of rain-drops may destroy the soil structure causing a sealing of the soil surface. With its dense structure [, 1990 #1017] the infiltration rates decreases strongly enhancing surface runoff. Sealing may also be caused by manuring or by the crop residues left on the fields [, 1984 #701].
- (Temporal) Hydrophobicity. If soil dries out strongly its physico-chemical surface properties change and it may get water-repellent. This is observed on many different soils [, 1992 #990]. It can induce finger flow in the soil and reduce the infiltration

capacity to only about one percent of the capacity under wettable conditions. Therefore hydrophobicity may also cause surface runoff and severe erosion [, 1964 #994]. In Europe, it has been intensively studied for sandy soils under Dutch conditions [, 1996 #1078] but it is also known from other regions [, 1997 #566].

- Frozen soil. Soils freeze regularly in many agricultural areas of northern Europe. The infiltration capacity of a soil is substantially reduced during the frozen conditions. Hence, melting snow or rain will often flow on the surface. This can cause erosion or transport of solutes that were applied on the frozen soil or stem from a tiny layer of unfrozen soil above the frozen bulk soil. An example of the relevance of freezing on the hydrological regime is given in Øygarden [, 1997 #877].
- Soil compaction. Grazing animals or management of machinery may cause surface compaction [, 2000 #1009] reducing the infiltration capacity substantially.

The quantitative importance of surface and subsurface flow depends on soil conditions, climate, topography but also on soil cover and management practices. The relative amounts of the two main flow paths vary within broad boundaries. Table 2 summarizes some results from the literature without pretending to be a representative overview.

The depth, at which lateral transport occurs, determines to a certain degree the travel time of the water and the solutes from the soil surface to the outflow from the field. Overland flow seems to interact with only the topmost mm to cm of the soil [, 1986 #1070], and the travel times are very short. With increasing depth of the vadose zone, where transport is mainly vertical, the mean travel time increases. However, it is not only the depth of the unsaturated zone that determines the travel time for the vertical transport. In many field soils it has been observed that the flow paths are highly variable in space often causing fast transport of water and solutes through a very limited portion of the soil volume. Under such preferential flow conditions, the travel time distributions typically shows a double peak behavior. There is a mostly small first and a large second peak. A smaller portion of the water passes through the profile in a very short time of minutes to few hours. Most of the water flows through the soil matrix with much longer residence times of weeks to even years. Preferential flow has been shown to be widespread in very different soils under various climatic conditions [, 1994 #213]. It may be caused by biopores or cracks [, 1982 #17], wetting front instabilities causing fingering [, 1973 #791] or by textural changes causing funneled flow [, 1990 #790; , 1990 #789].

Many of the physical structures like worm-holes or cracks extend mainly in vertical direction and cannot cause preferential flow in lateral direction. However, there are also examples reported in the literature, where fast lateral transport was observed [, 1988 #1046]. One may distinguish between two soil structures relevant for lateral preferential flow: networks of laterally connected cracks extending into the depths of groundwater and so-called soil pipes. In heavy clay soils it has been observed that cracks may extend to considerable depths and well below the groundwater table. At least in some cases these cracks are sufficiently connected in lateral directions to allow for substantial water flow [, 1991 #1066; , 1993 #428]. Soil pipes are products of subsurface erosion [, 1997 #1049]. They are especially important in organic soils of humid uplands, dry badlands and degraded rangelands. In Europe, evidence for soil piping in agricultural areas are reported for Spain [, 1997 #1050].

Whereas vertical preferential flow has been investigated very intensively over the last 20 years lateral preferential flow has received much less attention. One obvious reason for this is the relative ease to study vertical preferential flow at the plot scale compared to the experimental difficulties encountered by research on lateral transport at the field scale. However, it should kept in mind that the observation of vertical preferential flow

Table 2: Flow partitioning between subsurface and surface runoff.

Land use (country)	Texture	Slope [%]	Drainage [% precipitation]	Surface runoff [% precipitation]	Special observations	Reference
Arable land (Finland)	Clay	- 1.5	5 - 54 (total flow yr^{-1})	6 - 53 (total flow yr^{-1})	large variability due to changes in the drainage system^{-1}	Turtola & Paajanen (1995)
Grassland (Switzerland)	Loam	10 - 18	-	3.0 - 4.7	flow weighted average for 16 events, no drainage	von Albertini et al. (1993)
Arable land (Norway)	Silty clay loam	4 - 8.5 %	7 - 39 (total flow yr^{-1}) Median: 18	14 - 31 (total flow yr^{-1}) Median: 25	Influence of frozen soil	Øygarden et al. (1997)
Arable land (Germany)	Loamy sand to sandy loam	7 - 17 %	-	0.6 - 1.3 43.2 - 49.9	undisturbed field soil traffic rut	Fleige & Horn (2000)
Arable land (Finland)	silty / heavy clay	4 %	10 - 18	10 - 12	surface runoff incl. snow melt	Paasonen-Kivekäs et al. (1999)
Arable land (USA)	Loam	0 - 4 %	- -	0 - 3.4 0.9 - 3.1	rainfall surface runoff snow melt surface runoff	Ginting et al. (2000)
Arable land (Japan)	Heavy Clay	-	51.5 - 53.5 11.4 - 90.0	5.4 0.0 - 40.7	Annual values Event values	Inoue (1993)
Arable land Grassland (Finalnd)	Heavy Clay	0.6 - 1.5 %	21 - 26 15 - 19	17 - 42 22- 35	Annual values Annual values	Turtola & Jaakkola (1995)

at a given site doesn't imply the occurrence of lateral preferential flow as well. Further, one should notice that a fast hydrological response doesn't imply fast water and solute transport neither. Most studies have shown that even during peak flow conditions most of the water discharged by subsurface drainage systems or open streams is so-called old or pre-event water. Preferential flow may be involved in this context as the transport mechanisms conveying substantial amounts of water quickly through the unsaturated soil increasing the water table, forcing the old water to be pushed out downstream by a steeper hydraulic gradient.

By the mechanism of preferential flow most of the sorbing soil matrix is by-passed. This is one of the mechanisms explaining how even strongly sorbing solutes like P or pesticides may get transported from the soil surface to groundwater. Based on the assumption of well-mixed flow conditions as expressed by the convection-dispersion equation this is excluded under most conditions.

The flow paths within a field is not just influenced by the hydraulic conductivities of different horizons or the connectivity of macropores. In many agricultural soils the hydraulic conditions are strongely influenced by artificial drainage systems. They may strongely change the hydraulic response of a field and the relevant flow paths. Due to the lowered water table they may reduce surface runoff [, 1999 #997]. But drainage systems are not only large preferential pathsways in lateral directions. Due to their field installation and often artificial backfill they are also large vertical preferred flow paths and may redirect surface runoff or lateral flow in the plough layer into subsurface drains. The most obvious example is the draining of ponded depression into tile-drains [, 1980 #1051]. But mole drains and the trench above deeper drainage systems may have similar effects [Øygarden, 1997 #877; Stamm, 1997 #826; Addiscott, 2000 #1011].

In order to understand the solute losses from fields it is not sufficient to have a proper knowledge on the relevant flow paths and transport processes. The crucial point to understand is, how the relevant flow paths are coupled in space and time to the pools of mobile solutes, colloids or particles. Two examples shall demonstrate how the water quality is determined by the interplay between flow paths and pools of mobile nutrients.

In a field study on drainage water in grassland soils we have observed that the P-concentrations increased always with discharge during flow events [, 1998 #825] whereas the nitrate concentration normally decreased [, 1995 #1014]. This result can be explained by the different position of the pools of mobile P and nitrate in the profile. Due to the high sorption capacity of the loamy soil matrix high concentrations of mobile P were limited to the topsoil receiving substantial amounts of surplus P in form of manure. Hence, an increase in P concentration occurred during high-flow periods due to fast transport of P-enriched water from the topsoil down to the tile drain. In contrast, nitrate as a mobile, non-sorbing anion was leached through the entire profile and normally, the topsoil was not the main pool of nitrate. Hence, along the fast flow paths, the water normally didn't get into contact with pools of high nitrate concentrations and preferential flow caused a decrease of the nitrate concentration during high flow periods. However, the relationship between flow rate and solute concentration is not specific for a given solute but depends also on site-specific bio-geochemical conditions. In wet soils where nitrate gets denitrified in the lower parts of the profile and where the nitrate pool is mainly in the vicinity of the macropores of the topsoil due to atmospheric deposition, fertilization or mineralization the nitrate losses may be strongly connected to preferential flow [, 1999 #1064].

Based on this overview on the flow paths at the field scale I would like to draw following conclusions:

- Although often investigated separately in field experiments and often not included in the same simulation models subsurface and surface flow are closely coupled and can hardly be understood one without the other. For example, it has been demonstrated that the flow volume of surface and subsurface runoff may be dependent on each another [, 1999 #997]. Furthermore, the traditional separation between the two flow mechanisms can be quite arbitrary. In certain occasions, water leaving a field as subsurface flow was transported at or at least close to surface within the field. Hence, instead of having two alternative flow-paths there may be a sequence of both of them.

- One should recognize that drainage systems impose special, spatially defined boundary conditions to the flow processes in the undisturbed soil in-between. The often expressed belief subsurface drains were ideal measuring devices for transport into shallow groundwater [, 1999 #995; 1998 #1038] neglects that the transport behavior observed at the drainage outlet is the combined effect of the soil properties and the characteristics of the drains. It should be remembered that there are different drainage systems like shallow mole or deep pipe drains that may influence the hydrology of a soil quite differently (see below). Therefore, for modeling purposes it is not sufficient to parameterize the soil properties properly but one has to consider the site specific drainage properties as well.

- To understand the export behavior of a field it is not sufficient to know the flow paths of water. It is essential to understand the spatial and temporal coupling of flow paths and the solute pools.

Influence of heterogeneity on flow processes

Precipitation falling on a given field encounters mostly a very heterogeneous flow system. Spatial heterogeneity is an important aspect but variability is even more complex in that important soil properties may change over time scales relevant for practical or experimental purposes.

Spatial heterogeneity

It is useful to separate spatial heterogeneity into a deterministic and random part. The deterministic heterogeneity can be explained by factors like topography, texture or management practices. In contrast, the random part of heterogeneity cannot be inferred from other quantities. Furthermore, it should be recognized that part of the heterogeneity is due to natural variability, but human impact may also contribute.

The deterministic variability may be due to natural factors like topography or soil type. For surface runoff or erosion topography is the major controlling factor since it directly determines the flow direction on the surface. Often, the same holds for subsurface flow also, causing depressions to be especially wet. Since soil-forming processes are strongly influenced by the water regime soil properties vary frequently according to the topographical position. In a classical way this is expressed by the catena principle. A less obvious relationship between topography and soil properties was found by *[, submitted #1084]* for earthworms in a German loess area. The worm abundance was correlated with the position within the hillslope. Higher densities were observed in the wetter colluvium areas enhancing the tendency for preferential flow.

Agricultural management causes also spatial variability in a deterministic way. An important factor influencing water and solute transport are drainage systems. As mentioned in the previous section, subsurface drainage systems may have a large influence on preferential flow by intersecting and draining these pores in a restricted area. This has been recently demonstrated by Shipitalo et al (submitted) by injecting smoke into a drainage system. The soil surface connected by preferred flow paths to the tile drain was only a narrow band of about one meter width. We have found similar results in a grassland soil [, 1997 #826]. This means that the hydrological role of preferred flow paths depend on their connectivity to subsurface drains. A few studies have also demonstrated that the backfill material may be an important flow path for water and solutes into the subsurface drainage systems [Øygarden, 1997 #877]. Chow et al. [Chow, 1993 #1067] have reported that with natural soil used as backfill material the hydraulic properties were persistently altered above the drains. For mole drains it is reported that the neighboring soil is changed as well [, 1968 #1075. p. 286].

Wheel traffic due to agricultural management is a second important factor causing spatial heterogeneity. On arable land, the hydraulic properties often vary according to their position as traffic lines, row or interrow areas. Compactions affects the infiltration behavior into soils [Kulli, 2000 #1010] and may enhanced surface runoff or interflow on the plough pan [, 2000 #1009].

Apart from the deterministic variability many soil properties exhibit a strong random spatial heterogeneity. The hydraulic properties belong to the quantities varying most and the variability at the field scale can be enormous. As can be seen from Tab. 3, a mean value may be almost meaningless given the large coefficients of variation.

Table 3: Spatial variability of some soil properties.

Properties	Coefficient of variation (%)	Sample size	Study area [ha]	References
Physical properties:				
Sand content	55 7 49	0.34 dm3 - -	150 0.19 -	Nielsen et al. (1973) Wagenet (1981) Coelho (1974)
Silt content	27 12 22	0.34 dm3 - -	150 0.19 -	Nielsen et al. (1973) Wagenet (1981) Coelho (1974)
Clay content	23 7 18	0.34 dm3 - -	150 0.19 -	Nielsen et al. (1973) Wagenet (1981) Coelho (1974)
Bulk density	7 11	- -	0.19 -	Wagenet (1981) Coelho (1974)
Saturated hydraulic conductivity	60 - 106 52 147	6.5 m2 0.09 m2 0.11 m2	150 0.19 -	Nielsen et al. (1973) Wagenet (1981) 0.11 m2
Unsaturated hydraulic conductivity	106 - 452	6.5 m2	150	Nielsen et al. (1973)
Transport				
Drainflow	33 - 55	0.24 ha	5	Addiscott et al. (2000)
TP losses	36 - 85	0.24 ha	5	Addiscott et al. (2000)
MRP losses	50 - 60	0.24 ha	5	Addiscott et al. (2000)
Cumulative infiltration	25	0.09 m2	-	Starr (1990)
Chemical properties:				
pH	2 - 15	-	-	Mulla & Bratney (2000)
Organic matter content	21 - 41	-	-	Mulla & Bratney (2000)
Soil available P	39 - 157	-	-	Mulla & Bratney (2000)
Agricultural properties:				
Crop yield	8 - 29	-	-	Mulla & Bratney (2000)

In contrast to classical statistical problems soil properties are spatially autocorrelated. Therefore, special methods, mostly taken from geostatistics, are needed to deal with kind of data [, 1991 #1085]. The correlation length for different soil properties may vary within abroad range. For soil hydraulic properties they may be correlated over fairly short distances of few meters only, whereas chemical properties like organic matter content tend to have longer spatial dependences of up to several hundred meters [, 2000 #1005].

Temporal heterogeneity

Many soil properties change over time scales relevant for practical applications. However, the relevant time scales differ considerably. There are fast processes like the crust formation at the soil surface occurring during single storms. Soil freezing changes soil properties also very rapidly once it occurs.

Other processes governed by climatic conditions induce changes more slowly exhibiting an obvious seasonality. The vegetation cover is a well-known example influencing the risk of erosion, the amount of intercepted water by the vegetation or the flow resistance to overland flow. However, weather conditions may influence soil properties also in a more erratic way. It has been shown for Danish conditions that during a single vegetation period the soil surface may switch from wettable to water repellent and back [, 1999 #989].

There are also changes to be observed on the time scale of several months or years. It has been demonstrated for example that the type of management (e.g., plowing against tining) influences the drainage behavior over several months after the treatment [, 1995 #999]. During a crop rotation of several years including grassland cultivation it has been observed that the infiltration pattern of a field changed considerably [, 1995 #1008]. These changes can be caused by abiotic processes like drying or by activities of organisms like earthworms. For a drainage system, it has been shown that its effect on water flow is not stable over time [, 1995 #878] but may change over several years.

Many of these temporal changes affect the soil surface, which is exposed most to external natural and anthropogenic influences. However, shrinking and swelling in heavy clay soils affect larger depths and the structural changes are not confined to the topsoil [, 1998 #1068].

Combined effects of spatial and temporal heterogeneity

The impacts of temporal and spatial variability have not to be independent. An instructive example relates to the influence of frozen soil on the infiltration behavior. It has been shown experimentally [Baker, 1997 #979; Derby, 1997 #980] that local topographic depressions may act as hot spots for infiltration as long as infiltration is inhibited by a frozen soil surface. Same effects may occur under heavy rainfall when surface runoff occurs that is retained by depressions.

Agricultural practice has also a strong influence on soil properties. Several studies have shown that the hydraulic conductivities of arable land change substantially during the season. Furthermore, it seems that the spatial correlation structure of the heterogeneity also varies in time [, 1996 #882].

Drainage systems often consist of different types of drains within a single field. Installed at different depths and directions lateral and the main drains may influence the transport behavior differently. An example is given by Schmied and Kohler [Schmied, 1999 #1052] for a 7 ha field. The lateral drains at 70 to 100 cm depth were almost noneffective for most of the time. The majority of the water was drained by the main drains at 150 cm depth. Only during periods of very high water table the lateral drains lowered the water table. Hence, depending on the hydraulic conditions the spacing of the active drains changed from 100 to 20 m only. Furthermore, the flow direction switched for 90°.

Conclusions for assessing / modeling P losses at the field scale

It has been shown above that water flow and solute transport at the field scale is governed by a fairly large number of different factors. Some of them like topography or soil type are time invariant, others like the surface conditions, change in time due to natural processes and human impact. Furthermore, the relevant factors like soil hydraulic properties are often spatially very heterogeneous.

For the assessment of water and solute fluxes this means that it is very important to measure the soil properties and the solute and water fluxes at the right time and the right locations. A sufficient understanding of the flow regimes, that is an apriori conceptual model, is required therefore prior to field measurements or modeling. Such an apriori model should contain the most important factors relevant at a given site. In the framework of an European-wide COST action it might be worthwhile to establish conceptual models for P-losses for different regions in order to compare the processes contributing to these losses over whole Europe. This could be a basis to decide which existing simulation models can be applied for what kind of problems or what kind of measurements are needed to compare the risk situation of different areas.

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