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PHYSICAL ASPECTS OF SOIL QUALITY

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1   RELATIONSHIP BETWEEN SOIL PHYSICS AND SOIL FUNCTIONS

Soil has different functions as was shown in the previous chapters. For the soil to function well, soil physical behaviour plays a crucial role in the soil environment. This is implicit in the 'loose' definition of soil physics encompassing the statics and dynamics of the soil matrix, energy and interstitial fluids (gas, liquid). In the next few paragraphs we discuss the soil physics in relation with selected soil functions.

1.1   Soil Physics in Relation with Crop Production

The physical behaviour of soil is controlled by the complicated interaction of water, gas, and heat dynamics, which depend heavily on the nature of the soil matrix in a static and dynamical sense. As an illustration, the matrix may be regarded as a medium with low heat conductivity. Because of soil porosity, and the heat capacity and heat conductivity of resident fluids which differ in this respect from the matrix, heat transmission depends critically on the composition of the pore system. At low moisture contents, water disks surrounding solid phase contact points control the overall heat transmission. At higher moisture contents the net heat flux at the soil surface (as affected by evaporation, radiation and reflection) depends among others on the nature of the solid phase, water flow to the surface, and the soil surface roughness. These processes may affect the sustainability of crops or vegetation under given climatological conditions. The hydraulic and thermal response of the topsoil to atmospheric conditions normally control the warming up of the seed bed and of the sub soil, and may have important implications for water conservation in arid regions. Thus, daily variations of temperature in combination with germination physiology of seeds (both crop and weeds) affect seedling emergence. The balance of heat and water controls whether seedlings and plants grow or wilt. In the root zone the temperature is an important factor for root physiology, microflora growth, chemical equilibria in the soil solution, and microbiological, as well as chemical transformation rates, which may be important for the availability of nutrients (and contaminants). The relevance of water supply to plant growth is also well established. For optimum growing conditions, water supply and soil aeration have to remain within limits which depend on the crop. Dependent upon the status of the soil matrix, high moisture contents (which vary with time) may lead to periodic partial anaeroby, which affects both soil chemistry and microbiological activity (e.g. denitrification). Thus soil physical behaviour, in combination with external factors, may have considerable effects on soil as an agricultural resource.

1.2   Soil Physics in Relation with Transport

Even considering the matrix to be rigid, transport may occur in soil via the pore system. The geometry and saturation of the pore system with fluids, in combination with potential gradients, control movement of the fluids. In conjunction with concentration gradients of solutes this implies the soil surface roughnesstransport of these solutes. Moreover soil physical conditions may in part determine the chemical environment, e.g. with respect to the redox potential (aeration) or temperature. Mechanical aspects, such as the presence of crusts at the soil surface, compacted layers, clogged pores, may induce resistances to flow and significantly affect the transport of heat, of fluids (Ten Berge, 1986) and of suspended or dissolved matter. Alternatively, considering a non-rigid matrix, cracks formed by shrinking of the soil matrix upon drying, and the presence of macropores, among others may lead to transport bypassing a large part of the pore system. This bypassing may occur between soil surface and ground water, or between the soil system and the atmosphere or the ground water (Van Genuchten et al., 1984). To a smaller extent, aggregation may lead to the same effect.

2   SOIL PHYSICS IN RELATION WITH SOIL QUALITY STANDARDS

Soil quality standards are set to provide rules for soil protection. This requires assessing the environmental risks in a broad sense, associated to perturbations of the natural soil ecosystem. One aspect in such risk analyses is related to exchange rates of mass and heat in soil and between soil and the environment (Van Riemsdijk et al., 1987). Soil physics play a central role in the nature and magnitude of such exchange rates.

3   SCOPE OF SOIL PHYSICS RESEARCH IN RELATION WITH SOIL QUALITY

For a risk analysis of perturbations of the soil system, and for the design of remedying actions the following steps may be distinguished:

(i)   definition of the perturbation in physical, chemical or biological terms

(ii)   gaining understanding of the phenomena (accounting for mutual interactions) controlling the effects of the perturbation.

(iii)   development of means required for a prediction of effects when no actions are undertaken

(iv)   and development of understanding how remedial actions influence the perturbed sys-
       tem's behaviour

For each of these steps a number of cycles need to be gone through, sometimes iteratively, to
ascertain that the system level of interest is compatible with the process level at which under-
standing is required (Van der Zee and Bolt, 1988, Bourg, 1989) and to ascertain that all relevant
processes were taken into account. Soil physics research has to furnish the instruments on the
physical side of steps i-iv.

Another methodological aspect also lies predominantly in the physics field, though it is not
restricted to it. Each topic of soil quality research is confronted with the problems of measurement
resolution and scale. Most process oriented measurements are being carried out on soil samples,
i.e., they are point measurements. For an accurate description of the process it is needed to
know exactly which phenomena are measured and how these relate to the process of interest.
This problem was considered from the theorist's point of view by Cushman (1986, 1984). An
example is e.g. the relation between the hydraulic conductivity measured in a soil core and the
in-situ conductivity of a cracked soil (Bouma, 1981). The resolution of measurement should agree
with the process of interest. When the process level considered for basic understanding differs
from the system level, this therefore does not mean that the two are unrelated, but instead that
these should be compatible.

Practically, the compatibility between governing processes and system behaviour may be a
demand that cannot be met. This is the case in predicting flow or dispersion in aquifers, for which
only a number of measurements are available. These local measured properties must be inte-
grated into spatially averaged properties. The averaging procedure, however, depends on the
property and processes of interest as well as on the magnitude and scale dependence of soil or
aquifer heterogeneity (Baveye and Sposito, 1984, Bear, 1972).

A fundamental framework with respect to measurement resolution and appropriate averaging
theory was considered by e.g. Cushman (1986, 1984), Whitaker (1986), Bear (1972), pre-
dominantly from the point of view of transport, and e.g. (geo) statistics schools in different
countries (De Marsilly, Matheron in France, Webster and co-workers in the UK, etc.). To develop
a practical useful framework for this problem area, stripped from formalistic 'ballast' may perhaps
be undertaken best from the soil physics field. This hypothesis is based on the use of such
theories which is most advanced in the soil physics/hydrology research areas (of the areas
considered in this report). Moreover the mathematical foundation, that uses systems analysis,
stochastic analyses etc., is perhaps more compatible with mathematical branches of soil physics
than with the other areas distinguished in this report. Obviously, the testing, refinement and
further use and development of these techniques for particular applications can only be
undertaken successfully through interdisciplinary research.

4   THE STATE OF THE ART OF SOIL PHYSICS

The dynamics of heat and mass transfer in (plastic) soil are in principle coupled. In practice, a comprehensive review is impossible. Therefore, and in view of the limited space, a more general topic-oriented and fragmentary review is presented, mainly restricted to the contaminants considered in the introductory chapter (De Haan, 1989).

4.1   Soil Water Physics

Despite this sub-heading, soil water consists not just of water but is a dilute solution that sometimes contains solid particles and dissolved gases. Because of the surface charge of the matrix (Van Riemsdijk, 1989) and the intricate, irregular pore structure among others, soil water (i.e., the carrier fluid) is subject to different forces, that in combination lead to a complicated water potential function.

Work devoted to electrochemical and osmotic contributions to the water potential has either been highly fundamental (Groenevelt and Bolt, 1969, Ten Berge and Bolt, 1988) or has focussed on 'special effects', viz. ice lens formation, swelling pressures, coupled heat/water flow, salt sieving in e.g. very fine textured soils, (Kemper, 1960,). This work may be useful with respect to artificial clay linings or bentonite screens used for insulation of waste. Such rather fundamental aspects may have to be reconsidered in relation with capillarity problems as discussed later in this section and in section 4.3.

Water flow is usually described as the resultant (sum) of flow due to gradients in each potential term (e.g., pressure, gravitational). Usually the assumption is made that flow is proportional to the gradient of the potential in question. When more potential terms show gradients the assumption is often made that these terms are uncoupled (Bolt,1982). Coupling is due only through the effect of state variables (moisture content, temperature, etc.). For a discussion of the validity of this assumption for non-isothermal conditions see Ten Berge (1986). In those conditions the relationships between potential gradients and flux density may become very complicated (Raats, 1975, Nielsen et al., 1972). While osmotic and electrochemical terms may not be neglected in saline soils (Bresler et al., 1982) their omission for most other field studies may be appropriate. Practically, the gradient in water potential is most often restricted to the pressure (or matric) term and the gravitational term.

Combination of the flux equation (usually Darcy's Law, for its validity see e.g. Bear, (1979)) with the continuity equation yields Richard's equation. This equation does not account for water or soil matrix compressibility and it may therefore lead to unacceptable results for ground water systems (Verruijt, 1969). Spatial differences in water density are also not accomodated in this

equation (Lusczynski, 1961, De Josselin De Jong, 1969). Of main interest for this report is that Richard's equation does not account for the gas phase (i.e., the second fluid) (see section 4.3), reducing the problem to a monofluid one.

Assuming Richard's equation to hold for (unsaturated) soil, much work has been done on the assessment and description of the water retention curve and the hydraulic conductivity curve, but most of the methods of measurement used are costly and time consuming. This has been the incentive for further research on measurement methods. Reviews given by Klute (1972), Bouwer and Jackson (1974) and research papers by Morrison (1983), Fluehler et al (1976) and Van Grinsven (1988) give an indication of the experimental problems and innovations in this topic, for field and laboratory measurements. Of interest are methods to asses both curves simultaneously (Dane and Hruska, 1983, Kool et al., 1985, 1986) and elegant methods to measure the matric flux potential (Ten Berge et al., 1987).

Classic works devoted to describing the hydraulic properties of soil were presented by Childs and Collis-George (1950), Marshal (1958), Millington and Quirk (1961), Brooks and Corey (1964) and Mualem (1976). This work was reviewed by Van Genuchten and Nielsen (1985). Several models for retention curves were proposed, the most widely used currently being Van Genuchten's (1980) model which may be combined with Mualem's (1976) conductivity model. The characterization of soil water properties becomes complicated due to hysteresis phenomena (Childs, 1969, Nielsen et al., 1972, Everett, 1954, Mualem, 1974, 1984, Kool et al., 1986) and their temperature dependence. The latter was often ignored through it may be considerable (Hopmans and Dane, 1986, Ten Berge et al., 1987). Explanations may be sought in changes of surface tension of water upon changes of temperature (Philip and De Vries, 1957, Ten Berge and Bolt, 1988), effects of entrapped air, chemical composition and viscosity effects (Constantz, 1982). For reviews of chemical effects, see Shainberg (1984) and Bresler et al (1982).

Rather amazing is the very limited work done with respect to temporal changes in soil water properties, due to e.g. crust formation, tillage, freezing/thawing cycles that may control changes over a much wider range than those receiving most attention to date. Flow in swelling soils was considered among others by Stroosnijder (1976), Philip (1969), Smiles (1974), Sposito and Giraldez (1976), Giraldez and Sposito (1985), and Russo and Bresler (1977).

An immense number of analytical solutions and numerical models has been developed for Richard's equation and for flow in saturated ground water For reviews see Narasimhan and Witherspoon, (1976), Oster, (1982), Van Der Heijde et al., (1985) and for papers consult Philip (1955,1957), Parlange (1971), Freeze (1969, 1971a,b), Javandel and Witherspoon (1968), Huyakorn et al.(1984), Pinder and Gray (1977) among others. For the monofluid flow problem the solution of the equations does not seem to pose a serious problem, except perhaps for special effects such as for hysteresis and temperature gradients. For the applied soil quality field this line of research does not seem to be of the most urgent priority.

4.2   Gas Transport and Exchange

Gas movement in soil has received less attention in soil research than has water flow. The role of gas upon water flow is most often disregarded. Nevertheless, as indicated in the previous section, transient water flow implies bulk flow of gas. When this flow is impaired, gas pressures may build up which reduce the infiltration rate (Raats, 1984, Stroosnijder, 1976) and lead to unexpectedly large water table fluctuations (Bianchi and Haskell, 1966).

Convection of gas may occur in soil, but its importance is not always clear. Significant water vapor flow may be very relevant with respect to the water and heat balance (Ten Berge, 1986). Driving forces may be gradients in the pressure (due e.g. to density differences implied by different temperatures or gas composition) and may be relevant for the rate of gas exchange with the atmosphere. Whereas this process is often modeled assuming a diffusion type first order mass transfer, convective flow may well be more important. As far as known this subject has not been sufficiently explored, and a better understanding is needed for describing ammonia volatilization (Singh and Nye, 1986), gaseous losses of volatile pesticides (Jury et al., 1983,1984) or the aeration status of soil. Gaseous convection may also be of important for the transport of volatile organic contaminants present in pure form as liquids (Abriola and Pinder, 1986). In principle the flow of gases through soil follows the same general laws as water flow. The problem in evaluating gas flow and its relevance is therefore more one of uncertainties with respect to e.g. conductivity, than the formulation of the transport equation.

A major complication is the relatively high diffusivity of gas. The level of both convective and diffusive exchange or transport depends critically on soil moisture content. This parameter governs the interconnectivity of pores and should therefore be taken into account in the description of gas transport (Collin and Rasmuson, 1988, Fluehler,1973, Groenevelt and Lemoine, 1987, Van Brakel and Heertjes, 1974). Additional complications arise when the compound of interest is dissolved in the carrier gas (soil air) and is also soluble in water. In those cases diffusion through water pockets hindering gas phase transport may be significant (Leffelaar, 1979, 1986, 1987). Moreover, the formulation of gas diffusion is then commonly a multi-solute diffusion problem, which manifests itself on a microscopic scale (compared with the field scale of prime interest). Very important phenomena such as partial anaeroby and gas exchange between the top soil layer and the atmosphere thus depend on a complex interplay of matrix properties, and gas, heat and water dynamics on a microscopic scale (Singh and Nye, 1986, Leffelaar, 1979). The relatively simple analysis of Jury and co-workers (1983, 1984) based among others, on the continuity of water-filled and gas-filled pores, permit therefore only simplifying illustrations of the situation in the field. The effects of moisture on gas diffusivity have been treated by Collin and Rasmuson, (1988).

4.3   Multifluid Transport

The multifluid nature of unsaturated flow has be mentioned briefly in previous sections. While in the past the effect of the gas phase could most often be neglected in describing water flow, the contamination of soil and ground water reservoirs by organic (non aqueous, NA) fluids has been the incentive to study the multifluid (water/NA, water/gas/NA) systems in soil and ground water. This research borrows heavily from petroleum engineering. Illustrations were given by Schwille (1984), Schiegg (1985), and by a number of research groups in the USA (Anderson, 1986).

The multifluid transport problem is dominated by differences in density, capillarity and mobility of the fluids. NA phases lighter than water tend to move on the phreatic level, while NA phases denser than water will move through water to greater depths. Moreover, differences in mobility (e.g. differences in viscosity) may lead to unstable displacement, physically and mathematically, also when density contrasts are absent. When two fluids move through a porous medium we may assume capillarity effects to be absent (piston type displacement) or present (dispersion type displacement). In earlier work capillarity effects where usually neglected (Scheidegger, 1961, Mull, 1971, Hochmuth and Sunada, 1985), as were the usually low solubilities of NA-phases in water and volatilities in soil air. In summary, we are confronted with the problem to develop models for the simultaneous flow of different fluids, taking the above effects into consideration, while only scarce data on the transport and accumulation properties of these fluids in the porous media soil or vadose zone are available.

Disregarding the complex interplay that may be expected in case several NA-phases are present, the NA/water/gas system should be characterized by setting up mass balance equations for each compound (NA, water, carrier gas) for each phase (NA, water, gas, solid). Constitutive relations are needed to ascertain that mass fractions of compounds in each phase sum up to one, just like the fractions of the pore volume occupied by each phase add up to one. This leads to a number of equations which may be solved without or with additional (usually simplifying) assumptions (e.g. rigid matrix, immobility of the gas phase, relationships between parameters). At present the full problem remains to be solved.

Continuum based fluid flow models require (section 4.1) knowledge of relationships between fluid pressures, saturations and permeabilities. Such relationships are difficult to assess. Simplifications, such as assuming that relative permeabilities are independent of phase composition (Pinder and Abriola, 1986), methods that predict three-phase relationships from two phase relationships (Aziz and Settari, 1979) and scaling methods as used by Parker and co-workers (1987, 1988) may not always be valid. Validation of these simplifications for different media and organic compounds is needed. Examples of experimental data needed are the imbibition pressure (needed to displace one fluid by the other fluid), the extent of hysteresis, the validity of

three phase relationships in case of limiting situations (where one phase vanishes), partition coefficients for three phase systems, and relationships between system parameters and diffusion-dispersion coefficients.

As was argued by Pinder and Abriola (1986) the numerical solution of their reduced problem may still lead to significant difficulties. Analogues for the air/water system were given by e.g. Morel-Seytoux (1973) and Touma and Vauclin (1986). Three phase problems were modelled numerically by Faust (1985), Parker et al. (1988), and Abriola and Pinder (1985a,b). Alternatives to the approaches given are needed (Pinder and Abriola, 1986).

Additional complications may arise in case of unstable flow. Due to microscopic permeability and porosity differences in combination with density and mobility differences of the displacing and displaced fluids, such instability (fingering) may develop. At present this process is poorly understood, no doubt due to the physico-mathematical complexity of the problem and the difficulties to relate experimental results to existing theory (Schwille, 1984, Chickhliwala et al., 1988). In view of the relevance for transport of organic compounds commonly found in the environment and their partitioning into ground water, experimental and theoretical work is badly needed in this area.

4.4   Solute Transport, Miscible Displacement

Transport of solutes in water has received much attention in soil science and hydrology, among others. Most work was based on the convection-dispersion equation (CDE) amended with reaction terms or adaptions to account for non-Fickian displacement, as predicted with the mono-continuum CDE. In early work most emphasis was given to understanding and quantifying the hydrodynamic dispersion term (De Josselin De Jong, 1958, Bachmat and Bear, 1964, Pfannkuch, 1963). Later work extended in different directions, either considering non-reactive transient flow (Wierenga, 1977, Smiles et al., 1978), in some cases taking hydraulic hysteresis into account (Curtis et al., 1987), or concerning reactive transport. To organize conceptual developments for the many feasible soil conditions and solutes, this area relied heavily upon mathematical formulations. As most experimental results were obtained in the laboratory, they were to a certain extent biased, and this bias affected conceptual developments until recently (Section 4.5).

In general, numerical and analytical solutions for the transport equations no longer pose problems for the modelling of transport for the mono-solute problem. Research should focus on concepts and not on modelling techniques. Conceptual changes can sometimes be attributed to known shortcomings of the mathematical formulation. Thus, microbiological transformations for the mono-solute system described with empirical rate laws (Van Genuchten and Wierenga, 1976, Parlange and co-workers, 1984,1986) are known to be too limited with respect to reality (McLaren,

1970, see also Iskandar, 1981), which in part causes the deviations between measurements and predictions. Significant bypass effects, due to aggregation or cracking of soils, were accounted for by e.g. dual porosity models since about 2 decades (Coats and Smith, 1964, Van Genuchten and co-workers, 1976, 1984). Emphasis with respect to the empirical dual porosity concept is nowadays based primarily on understanding of the underlying concepts for regular systems, such as soils with well defined aggregate sizes and geometries or rock with well defined fracture patterns (Van Genuchten and Dalton, 1986, Parker and Valocchi, 1986, Rasmuson 1985, 1986). Based on these studies concerning soil analogons sometimes more far reaching conclusions can be drawn concerning the soil's behaviour with respect to transport or sorption (Van der Zee et al., 1989).

The main challenges seem to be the multicomponent nature of solute transport and spatial variability, the latter of which is treated in a separate section. For most contaminants (and even solutes in general) the assumption of non-reactiveness in soil does not hold. Hence, sorption and chemical interactions in the soil solution such as complexation and precipitation, need to be taken into account. Both the equilibrium and the rate of chemical and biological transform-ations over the soil phases affect the transport processes. Although mono-solute formulations may lead to acceptable results in many cases, they may not do so in many other situations. Then the formulation should be based on the presence of different solutes that react or compete with each other. This poses high demands with respect to modelling (Jennings et al., 1982, Kirkner et al., 1984,1987, Cederberg et al., 1985) as well as to data acquisition. With respect to modelling two essentially different approaches have come into perspective. In the integrated approach, the transport and chemistry equations are combined and solved more or less simultaneously. This rather inflexible method which is problem dependent, (Singh and Nye (1986) and Harmsen and Bolt (1982)) may lead to complicated numerical schemes, as analytical approximations are seldomly available. The alternative modular approach solves the chemical equations separately from the transport equations. This more flexible approach may lead to numerical errors that are not always easy to quantify, due to the non-linearity of the problem, and has found until now only limited use for problems taking more than simple adsorption and complexation into account. Multicomponent modelling requires further attention as a basis for understanding the validity of monocomponent formulations of transport and of their limitations (Van Riemsdijk, 1989). In part this implies efforts for soil physics research, in part for multidisciplinary research (physics, chemistry, (micro-)biology).

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4.5   Soil and Aquifer Heterogeneity and Transport

In the past 10 to 15 years much valuable work has been done to develop a conceptual and physico-mathematical basis for transport through heterogeneous media. This work followed essentially two lines, both for soil and for ground water, i.e., deterministic and stochastic models.

i   Deterministic models

Based on fracture models (distinguishing the fluid filled fracture from the microporous solid rock) of Neretnieks, Rasmuson (1980, 1981) and Tang et al. (1981) a number of papers considered dispersive flow in macropores (Van Genuchten et al., 1984), and media consisting of regularly or irregularly shaped aggregates of uniform or variable size (Rasmuson, 1985a,b, 1986, Van Genuchten and Dalton, 1986, Parker and Valocchi, 1986), and in fractured media (Sudicky and Frind, 1984, Schwartz and co-workers, 1983, 1988, Fogden et al., 1988). Similar deterministic bi-continuum models were developed for ground water flow in different geometries (Gillham et al., 1984, Guven et al., 1984, Sudicky et al., 1985, Chen, 1985,1986, Van Duijn and Van der Zee, 1986, among others). In conjunction with kinematic wave type fluid flow models as developed by German and Beven (1985) this line of research has led to a better understanding of transport in well defined media, and to the well known scale dependence of dispersion.

ii   Stochastic models

As porous media have a distributed pore size, they also exhibit irregular features of permeability on larger scales. Because of these variations and of their irregular distribution in space a deterministic treatment is impossible. Besides assuming different layers, inclusions etc. to be uniform in properties, a second approach was used in which relevant properties were assumed to be stochastically distributed. This has resulted in flow and transport formulations in which usually the hydraulic conductivity was assumed to be a random property. This results in stochastic differential equations for transport, which can be solved analytically if certain assumptions are made, such as some degree of stationarity (Gelhar and Axness, 1983, Dagan, 1986). This latter assumption seems to be often met to satisfaction, at least for individual aquifers. When a stratum is sufficiently homogeneous, two scales, for heterogeneity and for the size of the flow domain need to be quantified. In practical situations also scales are needed for averaging measurements and for the numerical grid used for calculations (Dagan, 1986). A detailed review of assumptions made in the solutions available, as well as the method of solution using the spectral or the Green's function approach is beyond the scope of this paper. It can be concluded, though, that the use

water management is therefore needed. Such a practical application also requires additional research on the inverse problem, i.e., the estimation of parameters using stochastic methods. Likewise, in order to ensure a correct interpretation of the results, the assumptions regarding the interpolation of point measurements (continuity or extent of layers) and their effects on predictions deserve further investigation. More complex, real world conditions with regard to recharge, fluctuating flow velocities, and interaction with wells, and data acquisition from properly designed experiments for different geologic strata may be of great interest in validating, and extending theory and characterizing the stochastic nature of natural flow domains. For practical use, the possibilities of generalization and scaling of variability for different strata may be of utmost importance.

In addition it is worthwhile to consider the unsaturated soil in more detail. Bresler and Dagan in a number of studies (1979, 1981, 1983) illustrated the large effect of the spatial variability of soil-water properties on solute transport. Their line of work was adopted by Amoozegar-Fard et al (1982), Persaud et al. (1985) and others, and indicated that pore scale dispersion was often of secondary importance compared with spatial variability compatible to the flow domain of prime interest (e.g. field scale). In a similar line, close to systems analysis, Jury (1982) and Jury, Sposito and White in their (1986)-papers presented the Transfer Function. Their approach appears suitable to describe field-scale transport, but it lacks predictive power.

The stochastic representations discussed so far were all devoted to non-reactive solutes. The work of Dagan, Bresler and Jury was extended for certain situations by Van der Zee and Van Riemsdijk (1986, 1987) to reactive solutes such as phosphate, copper and cadmium. Their analysis, though simplifying water flow and neglecting layering in soil, gives a good instrument to evaluate the importance of spatial variability with respect to water flow, cumulative contaminant input, and sorption capacity. In related work, the effect of pore scale dispersion and desorption (Van der Zee, 1988, Van der Zee and Bolt, 1988) and of transient flow was evaluated in a field experiment (Van Ommen et al., 1989c).

However, stochastic modelling in this last work did not yield acceptable results. Experiments by Van Ommen et al., (1989a,b) established that preferential flow occurred, even though no difference in moisture content between conducting and non-conducting channels was observed. Such phenomena, that suggest unstable infiltration of water may be as important for solute displacement as the spatial variability of flow described with scaling theory (Van der Zee and Van Riemsdijk, 1987, Bresler and Dagan, 1979). Experimentation, quantification and explanation of such phenomena should have a high priority. Also the assessment whether preferential flow channels are positioned differently for different infiltration events is important because of the consequences for leaching of reactive contaminants to ground water.

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5   CONCLUSION AND RESEARCH PRIORITIES

Much fundamental research has been carried out in soil physics and hydrology in recent decades. The results of this work should assist in defining soil quality and direct work into improving our understanding to the term and the possibility of applying it intelligently. However, there are still many unsolved problems, even when the scope of the problem is restricted, as it is in the first chapter of this survey (De Haan, 1989) to heavy metals and organic pollutants.

5.1   First Priority Research

(i)   Single component modelling, for both inorganic and organic materials, (section 4.4) appears too often to be based upon unrealistic assumptions. Additional chemical and biological studies are needed to establish when modelling of single component sorption or decay is or is not feasible. Additional physical research is needed to provided the theoretical foundation for modelling multi-component transfer processes.

(ii)   The domain of mass transfer has been shown to be heterogeneous, physically, chemically and biologically. This heterogeneity needs to be quantified. Different approaches, both deterministic and stochastic should be tried. The relationships between the scale at which experiments are carried out and the actual size of the field system need to be examined: it has been too readily assumed that there are no effects of scale. Experiments on different scales, including the effects of heterogeneity, are required.

(iii)   Measurement techniques and modeling approaches to describe the non-aqeous organic/water/gas system need to be developed. Techniques for estimating the values of the variables, using simplifying assumptions, require evaluating and testing.

5.2   Secondary Priority Research

(i)   Soil heterogeneity because of factors such as tillage, crust formation, freezing/thawing cycles, affects, mainly through the surface roughness, mass transfer at the soil/atmosphere interface. The importance of these effects on mass transfer (e.g. volatilisation, infiltration) require further studies.

(ii)   Elementary aspects of flow through layered, aggregated or hydrophobic soils and especially the differences between the actual, and the commonly assumed vertical, flow field should be investigated. Such studies should concentrate upon preferential flow paths, the horizontal flow in less permeable or poorly wettable layers and the sideways displacement due to capillary forces.

(iii)   Gas diffusion and gas flow as a function of volumetric water content and the of the composition of the solid phase need additional study.

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