WATER AND SOLUTE TRANSPORT IN THE VADOSE ZONE

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Contents

Summary

Water and solute transport processes throughout the unsaturated zone are intimately connected to soils and soil properties. These, in turn, form parts of the most complex natural systems known to science. They are highly nonlinear, highly variable, and feature an infinite number and variety of chemical and biological, as well as hydraulic, phenomena. In order to manage and maximize the long-term productivity of soil and minimize environmental pollution it is no longer possible to regard soil from the standpoint of any one scientific discipline. A more unified and interdisciplinary approach, that considers the most pertinent physical, chemical, and biological processes operating at the various solute transport scales of interest, is needed.

A critical point in any future environmental or agricultural change of soils is the proper management of water and solute transport processes throughout the unsaturated zone. An interdisciplinary approach is essential for this, as is an appropriate balance of effort between research and education.

Observations of soil water and solute transport processes made at appropriate scales form a foundation for both management and research and education activities. These in turn will help the development of new and better prediction techniques for (for example) pollutant transport patterns.

1. Introduction

The transport of water and solutes through the soil poses one of the most serious threats to our environment at present, as well as to the possibility of a sustainable future. The vadose, or unsaturated, soil zone is situated between the soil surface and the groundwater table. The vadose zone consists of three phases:

- soil particles, or the *solid phase*
- the solute or *liquid phase*, containing water and its dissolved constituents, and
- the *gas phase*, constituted by open voids between the solid and the liquid phase

The soils and the vadose zone are constituents of a complex system of inorganic and organic compounds that covers almost the entire land surface of the Earth. Sustainable management of this system is essential for safe food production and clean water supplies in the future, as well as for a clean recreational environment.

The soils through which water and solute transport take place may be seen as a life support system that acts as a protecting filter between atmosphere and groundwater, plants and water, and/or pollutants and food. Soil water and solute transport in the unsaturated zone have become key issues in managing pollutant transport from waste deposit sites and agricultural land, and in other environmental and food production concerns. The transport of water and solutes is largely governed by the textural and structural components of the soil. Textural classes of soils are defined according to the size of the mineral particles. In some soils peds, or aggregates, are formed, leading to a heterogeneity defined as *soil structure*. The pore domain can be divided into *matrix pores*, which are the spaces between the individual soil particles, and *macropores*, which refer to both the voids between structural elements and pores created by organisms such as root channels and wormholes. Several soil properties are related to soil formation. For example, sedimentary soils are generally more homogeneous than other soils. In most temperate and sub-Arctic climates of the Northern Hemisphere, soils have been formed by glaciation and are relatively young (less than 10 000 years). In contrast, some parts of the Malacca Peninsula rainforest are thought to represent the oldest ecosystem on Earth, one that has remained unchanged for about 200 million years. The soils in this region are ancient, and have not been altered by volcanic activity or glaciers.

Soil often contains horizons or layers that develop according to the texture and chemistry of the soil and the climate, especially temperature and rainfall. These horizons are characterized by their chemical and physical properties. Several soil types have been defined, depending on which horizons the soil profile contains.

The unsaturated zone, situated between the soil surface and the groundwater table, plays an important role in an ecosystem as it is the base upon which the food chain is built. Plants take up nutrients and water from the unsaturated zone. Vegetation, in turn, is consumed by animals and human beings. Thus, harmful substances in the soil can pose a threat to human health. Another important role of the unsaturated zone is in the recharging of groundwater. Groundwater constitutes an important water supply component for (for example) domestic, industrial, and agricultural use, and is often considered a clean water resource. However, pollutants from the soil surface can be transported down through the soil, thus contaminating the groundwater. Describing solute transport is more complicated in the unsaturated zone than in groundwater. For instance, pore water velocity depends on water saturation, and chemicals can exist in both aqueous and gaseous phases.

In this article first we present and discuss some potential obstacles to the future sustainable use of soils in the light of water and solute transport processes in the unsaturated zone. After this, we describe possible ways of mitigating these problems. It is not our intention to cover all aspects of water and solute transport processes fully, but rather to highlight a few areas that are important for societal development. The article closes with a summary and discussion.

2. Obstacles to a Sustainable Future

2.1. Need for Interdisciplinarity

As already stated, soils are components of the most complex natural systems known. At present, there is concern about the need to manage and maximize the long-term productivity of soil, and to minimize environmental pollution. In order to do so, it is no longer possible to regard soil from the standpoint of any single scientific discipline. Unfortunately, however, soils are still usually studied from within different traditional scholarly disciplines. This is a serious obstacle to determining the future sustainability of soils and soil water processes. Instead the soil system—which is never static or in equilibrium—has to be studied from a multidisciplinary standpoint, using knowledge from soil scientists, geochemists, and soil microbiologists as well as from hydrologists, statisticians, and mathematicians (Figure 1). A more unified and interdisciplinary approach is consequently needed, considering the most pertinent physical, chemical, and biological processes operating at the various solute transport scales of interest.

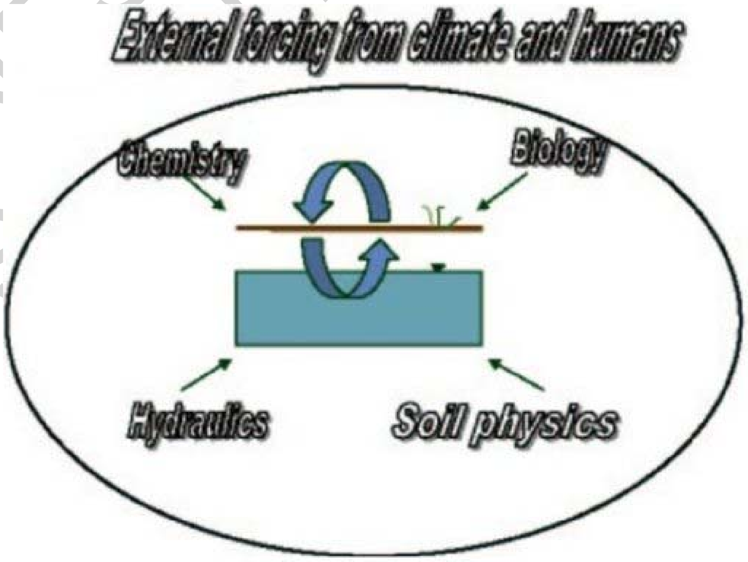

Figure 1. Natural and anthropogenic forces operating on soils; the interdisciplinary approach needed in the study of unsaturated zone processes

2.2. Analysis and Modeling Techniques

Analysis and modeling for field-scale water and solute flux calculations require information on the average values and spatial and temporal structures for various hydraulic, chemical, and biological processes. There are still very few relevant studies here based on soil observations.

Therefore, there is an urgent need for new, carefully planned field soil experiments, especially for the unsaturated zone. New databases of information have a dynamic relationship with evolving analysis and modeling techniques. Increasingly detailed field experiments can give important inputs to more detailed and realistic analyses and modeling techniques.

2.3. Understanding Multidimensional Variability Patterns

Variability in soil properties is a multi-faceted, interdisciplinary issue that ultimately finds expression in spatially varying plant or crop yields. There are many reasons why variability between different agricultural areas and fields is such an important issue. Variations in soil texture govern the transportation of soil moisture as well as solutes.

This is important with regard to nutrient application to crops, as well as to evaluation of the risk of pollutant transport to the groundwater. The variability, both lateral and vertical, inherent in soil water and chemical transport properties seriously limits the applicability of traditional column-scale approaches to analyzing water and solute transport processes.

The chemical properties of the soil interact with the infiltrating solutes, and change the chemical properties of soil water along its direction of movement. Thus, the spatial variation of soil chemical properties and the resulting variation of soil water chemical properties (and *vice versa*) are important issues when considering (among other things) crop yield, management of farmlands, and the prediction of solute interactions and groundwater quality.

Field variability in crop yield and other plant-related properties is a consequence of variation in both the genetic properties of the plants and environmental factors. The variable environmental factors in a single field that result in a particular spatial crop yield may be viewed as stemming from soil properties (for example, hydraulic conductivity and dispersion) and soil variables (such as soil moisture, electrical conductivity, and sodium adsorption ratio).

Applied water, fertilizers, and potentially toxic substances in sludge must also be recognized as a third important source of variability. Each of these components has a specific inherent variability scale that may enhance or cancel out the other superimposed influences.

Variability in soil properties such as hydraulic conductivity has been studied quite extensively; the spatial variability of soil chemical properties rather less so. Spatial variability in crop yield components, and its relation to local soil properties and soil variables, has been investigated by only a few researchers. The field variability of applied sludge and resulting variable rates of toxic substance uptake by crops have, in turn, been investigated even less.

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Biographical Sketches

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