

# Theory and Applications of Transport in Porous Media

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# Overland Flow Dynamics and Solute Transport

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# Preface

It is generally recognized that overland flow (runoff), surface–subsurface mass transfer, and subsurface water and solute fluxes are key processes governing contaminant transport in the landscape environment. The relevant interdisciplinary studies have been a prime focus of the hydrological society from the past century to the present, resulting in an enormous number of publications dedicated to model development, both conceptual and site-specific. Moreover, in the recent decades, a number of observations were made, evidencing the presence of anomalous phenomena enhancing or restraining water and chemical runoff from contaminated watersheds. However, it is not yet fully understood how both the natural and human-induced mechanisms, controlling these processes, interact and how the temporal and spatial-scale effects control these interactions under different watershed conditions and at different characteristics. Such understanding may help improve the reliability of assessment and prediction of the large-scale human impact on the environment, in particular, for areas contaminated by radioactive fallout from damaged nuclear units, such problems being among the most important applications of this work.

In this context, the purpose of this work is to contribute, marginally at least, to the theoretical framework of the link between overland flow dynamics and water quality, with a special focus on the challenge the author faced in dealing with the ambiguity of existing approaches to conceptualization of some particular transport mechanisms and field conditions. Thus, the main subjects include (1) extension of the theoretical concepts regarding the connection between overland flow dynamics and water quality, with a special focus on the transient system behavior; (2) study of anomalous behavior of the mass transfer accompanying the overland flow, which stems from both the peculiarities of the physicochemical interactions and the overlapping of several transfer mechanisms; and (3) collection of field data required to quantify the parameters and processes controlling the radionuclide transport in the near-surface domains which is closely related to the risk assessment of soil and water contamination through radioactive fallout.

More specifically, this book is aimed to emphasize analytical tools, supported by numerical modeling and illustrative field materials, providing assessment and prediction of contaminant transport in runoff, interacting with the shallow subsurface environment, represented by soil, vadose zone, and phreatic aquifers. The topics discussed here are related to the land surface hydrology and cover a wide range of coupled hydrological processes across a range of scales from hillslope to watershed. Overland dynamics and solute transport are presented and discussed through the application of both physically based models (mostly, using methods from the kinematic wave theory) and the empirical (effective lumped-parameter) approach. Such combination provides a better understanding of the mechanisms of flow and transport and would assist in the development of effective methods to control and predict changes in water components of the environment.

The fundamental problem of studying the formation of surface runoff and its chemistry under anthropogenic pollution of the soil and precipitation contains three major aspects:

First, the identification and description of runoff generation mechanisms providing rain and snowmelt water conversion into water bodies on the landscape

Second, the development of hydrodynamic models, describing water flow over land surface toward an outlet

Third, the development of hydrological models, describing the transfer of contaminants accumulated on the land surface or in the soil profile into water flow and their lateral transport in the form of dissolved species and particulate matter toward an outlet

The variable rainfall conditions, one of the most common features of the synoptic environment, determine the transient effects of rainfall–runoff–infiltration partitioning and chemical response of catchments to excess precipitation. Therefore, special attention is given to the analysis of the coupled transient flow and solute transport with the aim to more precisely formulate the physical and mathematical problem. To simplify the mathematics and reduce the number of required variables and parameters, other lumped runoff and solute transport models are also considered.

Another priority of this book is the focus on the anomalous behavior of mass transfer accompanying the overland flow. Such phenomenon stems from both the specifics of physicochemical interactions (e.g., sorption kinetics and irreversibility) and the overlapping of several transfer mechanisms (infiltration, soil erosion, the flow-focusing or channeling effects of microtopography, etc.). The relevant illustrations are concerned mostly with the model and experimental study of the regional-scale radionuclide transport with runoff induced by radioactive fallout from damaged nuclear reactors or nuclear weapon tests in the atmosphere since 1952.

In the latter respect, special attention is paid to the analysis of the consequences of the Chernobyl 1986 and Fukushima 2011 NPP accidents, supplemented with analysis of the less known Kyshtym 1957 accident, from the viewpoint of fallout radionuclide mobility and retention in the shallow subsurface environment, surface

water bodies, and groundwater reservoirs. Monitoring data supported by theoretical findings are used as a basis for coupling NPP accident scenarios (source-term and fallout deposition specification) with a set of hydrological models aimed at prediction of hydrological system response to soil contamination by radioactive materials in the areas of potential influence of existing or designed nuclear power units. To test the methodology, a distributed parameter watershed model of the Beloyarsk NPP location (Middle Urals, RF) was developed and calibrated basing on monitoring data.

This book is organized into seven chapters. The first two Chaps. (1 and 2) consider the runoff generation and water flow dynamics as a mathematical background of the near-surface solute transport (Chaps. 3 and 4) based on distributed parameter approach. Then, in the next two Chaps. (5 and 6), watershed lumped-parameter models for both water flow and solute transport are discussed. The conclusive Chap. 7 illustrates both the applicability of the above risk assessment strategy and the applicability of a selected numerical code for watershed modeling to the investigation of urgent issues related to radioactive fallout after hypothetical accidents at engineered nuclear power units. Monitoring data and data from field-site characterization experiments are also discussed in this chapter.

The author very much appreciates the help of Dr. Leonid Sindalovsky in the implementation of many numerical algorithms and codes considered in the book, as well as the contribution of Dr. Anton Nikulenkov and Elena Vereschagina, who shared their data on regional study of soil and surface water systems in the influence area of the Beloyarsk NPP. The author also appreciates the attention to his work and fruitful discussions with other colleagues – researchers from E.M. Sergeev Institute of Environmental Geology, St. Petersburg Division, RAS, and staff from St. Petersburg State University, Institute of Earth Sciences. Finally, the author deeply thanks Gennady Krichevets for his help in the professional translation of the book and many useful comments from him allowing the author to make certain improvements to the book.

Thus, this book, along with theoretical findings, contains field information, which will facilitate the understanding of near-surface solute transport and the development of a methodology for practical application in watershed hydrology. This book addresses scientists and engineers who are interested in the quantitative approach to studying contaminant transport processes. The book can also be profitably read by students.

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