Theory and Applications of Transport in Porous Media

Vyacheslav G. Rumynin

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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March 31, 2015

Vyacheslav G. Rumynin

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Part I
Response Mechanisms of Hydrological Processes in the Near-Surface Environment

To describe the flow and contaminant transport, induced by rainfall or snowmelt, through the landscape media, one is to consider several coupled processes occurring in the near-surface environment represented by soil and vadose zone in contact with a periodically forming movable water domain or with the atmosphere through the surface (Chow et al. 1988; Brutsaert 2005; Shaw et al. 2011). Thus, rain or snow-melting events intensify several mechanisms and processes, including: (a) the formation of a water body on the landscape; (b) the accumulation of pollutants of natural or anthropogenic origin in this layer after their release from the surface or from soil solution; (c) flow of polluted water over the surface; (d) the descending infiltration of a part of this water through the porous medium under the effect of capillary and gravity forces – a process, which controls the flow depth and, accordingly, the degree of water saturation with solutes, as well as the rate of water flow; (e) the development of paths of rapid pollution transport through macropores and fractures in the vadose zone and from depressions on the land surface toward water table, and, finally, (f) lateral contaminant transport through temporary or permanent phreatic horizons (sloping shallow aquifers).

The relevant hydrological analysis shall account for the differences between the space and time scales of the processes in the near-surface domains in contact with aquifer materials. Thus, the time scale for the conditions of runoff formation and solute migration is commonly of the order of hours, rarely a few days, while those of flow and solute transport in aquifers are of the order of months or years. The length of water flow paths in such systems is of the order of hundreds of meters or some kilometers. In terms of the time a water particle spends in it, the soil and vadose zone, with rare exceptions, occupy an intermediate position; however, unlike the systems involving surface and subsurface runoff, the vertical flow paths are much shorter in the sediments above the water table. For example, at such combination of time scales, a description of subsurface flow and solute transport can be based on the mean annual values of groundwater recharge and solute inputs, because the long pollutant residence time in the aquifer smoothes the effect on the solution of transport problem caused by daily and seasonal fluctuations in water flux and concentration functions on the upper aquifer boundary. From the viewpoint of stochastic analysis (Duffy and Gelhar 1985), for systems with large residence times (such as phreatic aquifers), small input correlation scale variations in continuous flow and solute inputs will produce little variation in the outflow characteristics. Under the same condition, the nearsurface domains are much more sensitive to small-scale changes in the flow and solute input characteristics. Therefore, to properly model the behavior of such system, in some practical situations it is important to use rainfall records with high temporal resolution.

The large differences in the time and space scales between the flow of water within the surface and subsurface domains allow a researcher to formalize the interaction between the domains through the transfer of boundary conditions from one domain into another, thus avoiding the solution of fully coupled equations of surface and subsurface flow (Furman 2008). In this part of the work, the relevant decoupling of the hydrological processes in the two domains is based on the raincontrolled infiltration interface approach allowing analytical solution of flow and solute transport problems with the assumption of prescribed infiltration rate or depth.

In this, first, part of the book, the behavior of the near-surface system under rainfall conditions will be analyzed based on an analytical framework at the column and hillslope scales. Mega-scale system's behavior is the subject of the second part of the book.

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Chapter 1
Surface Runoff Generation, Vertical Infiltration and Subsurface Lateral Flow

In this and the following three chapters, we will focus explicitly on the dynamic (transient, short-time-scale) hydrological processes that determine the partitioning of rainfall into runoff and infiltration and control the flow and chemical response of a catchment or its segments to the anthropogenic impact. Two principal components of runoff, surface and subsurface, which differ remarkably in their response time to precipitation or snow-melting events, are considered; however we do not present here a general mathematical framework for coupling the surface and subsurface flow equations, relying instead on an approach based on the transfer of boundary conditions (from one model domain to another). Soil infiltration theory, as discussed here briefly, plays the central role in such approach as well as in the solution of various problems of the surface and subsurface hydrodynamics. With this in view, special attention will be paid to some nonlinear and threshold phenomena in structured (discontinued by macropores and cracks) soils having a major impact on hydrological processes as well.

However, before we pass to the substantive part of the chapter, it is reasonable to discuss the key terminological issues and the description of individual mechanisms that govern the flow of water over the surface and within the shallow subsurface domains.

1.1 Key Definitions

Rain falling onto land surface is accompanied by rainwater partitioning into the surface and subsurface components in different proportions, depending on the rainfall rate, the properties of the cover deposits (their permeability and capillary characteristics), and their initial moisture content. This process can be considered at different space and time scales with different degree of detail or, conversely, generalization of the processes governing it. Thus, many problems can be analyzed at scale 1D of a soil profile. The next scale of hydrological process consideration is

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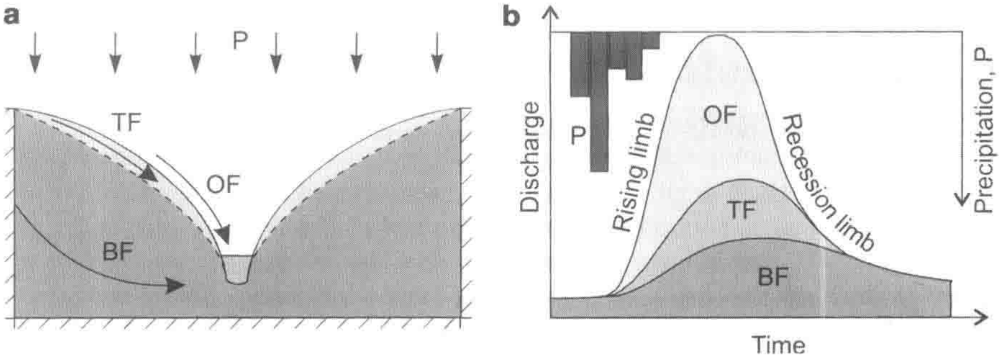

Fig. 1.1 (**a**) A diagram illustrating three major runoff components produced by rainfall: OF overland flow (HOF or/and DOF, see Sect. 1.2), TF throughflow (sometimes in the form of subsurface stormflow, SSF, see Sect. 1.2), and BF base flow; (**b**) corresponding (hypothetical) storm hydrograph. *P* precipitation

the scale of a hillslope (a slope of a river valley or a sloped urban district). Then, of particular importance is the hydrological analysis at the scale of a watershed (catchment) area, a topographic region in which all water drains to a common outlet. According to classical concepts, the entire land surface can be divided into polygons, representing a «matrix» of watersheds of different orders. As a rule, watersheds are associated with stream systems and some of them are identified geographically. In this book, the terms watershed and catchment are used interchangeably without defining the distinctions between them.

The flow of a water layer over the surface and through the pores of soils and sediments that is coming out of the watershed is termed runoff (Fig. 1.1a). There are three components of the runoff from watersheds (Shaw et al. 1994; Dingman 2002; Zhang et al. 2002): (1) surface runoff or overland flow (sometimes termed as direct runoff), (2) subsurface runoff or interflow (throughflow), and (3) groundwater runoff or baseflow. A dynamic form of rapid soil interflow that results from heavy rainfall is associated with subsurface stormflow. Overland flow and soil interflow together are sometimes referred to as quickflow. All three components contribute to the total hydrograph, a plot showing the rate of flow (discharge) versus time (Fig. 1.1b).

The surface runoff is the water that travels over the ground surface driven by gravitational forces in the form of sheet flow (interrill flow), rill and gully flow, towards the stream. It can be generated by different mechanisms discussed below. The water that moves over surface, i.e., surface runoff, rapidly reaches the nearest discharge zones, thus showing a quick response to a rain event or snow melting.

Subsurface runoff or interflow represents the portion of water that moves laterally in the upper part of soil, litter layer covering the soil surface, or in the soil–bedrock interface. Such lateral flow appears when soils have impermeable or semi-permeable layers at shallow depths. Subsurface runoff moves slower than surface runoff.

The water that has been absorbed by soil and has passed through the vadose zone supplements the storage of the topmost aquifer. This process is termed the groundwater recharge. The water flow thus forming in an aquifer is groundwater runoff. It responds to rainfall with a noticeable delay and does not fluctuate rapidly.

The mean annual values of the flow characteristics mentioned above, expressed in terms of volume (L^3, commonly, m^3) or runoff depth (L, commonly, mm), from a unit drainage area, along with precipitation and evapotranspiration, are the main components of water balance. Their values and the ratio between them are determined based on the soil conditions and actual evapotranspiration, as well as landscape–climatic characteristics of the area (Sects. 1.3 and 1.4).

1.2 Surface Runoff Mechanisms: Conversion of Rainfall into Runoff

The development of a functional basis for quantifying the transformation of rainfall to runoff has been a prime target for hydrologists of several generations. Several models (with different degree of physical soundness) are known to describe the transformation of rainfall to overland flow. The models that have the largest recognition and application in the practice of hydrological analysis are (1) the model of infiltration excess runoff (Hortonian overland flow, HOF) and (2) the model of saturation excess runoff (Dunne or saturation overland flow, DOF). Subsurface stormflow (SSF) as a component of runoff has been a subject for much research and discussion over the years as well.

1.2.1 Infiltration Excess Runoff

The physical ideas and the mathematical relationships that form the basis of the infiltration excess model were formulated and developed in the early works (the 1930s) of the well-known American hydrologist Robert Elmer Horton. In his theory, which has become classical, R.E. Horton proceeds from the basic assumption that the surface (slope) runoff forms due to the limited capacity of soil (or rock) to imbibe and pass water that arrives to its surface as rain. This assumption requires the introduction of additional definitions and criteria, enabling quantitative evaluation. To quantify Hortonian overland flow (HOF) generation it is necessary to have a sub-model of infiltration that interacts with the rainfall input (Vieux 2004).

R.E. Horton introduces the concept of soil infiltration capacity, $f = f(t)$, implying the maximal rate at which rainwater can be adsorbed by soil under given conditions. In this case, water is assumed to have unlimited access to the porous surface; therefore, function *f* is also called potential infiltration (by analogy with potential evaporation). Later the term infiltrability was suggested to replace the infiltration capacity to represent the surface flux under any set of conditions, whatever the rate or pressure at which the water is supplied to the soil (Hillel 2004).