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Introduction

'Tracers in Hydrology' defines the scientific field that aims at *understanding the hydrologic system* by making use of environmental and artificial tracers and modelling. Tracing of water provides unique methods for a direct insight into the dynamics of surface and subsurface water bodies. The relevance of tracer techniques in hydrological investigations and in applied hydrology ensues from the astounding complexity of water flow in natural systems. How much runoff in rivers really stems from rainstorms? How does water flow through a hill-slope or a glacier? How large is the storage of water resources in aquifers? Where, how and when was the water found in an aquifer formed? Tracer techniques are a useful tool in understanding the transport processes and quantifying their parameters. Tracers help to identify and quantify the phase changes (evaporation, condensation, sublimation), shed light on the origin of pollution and assist in the respective remediation processes. The natural tracers constitute a tool of prime importance in the reconstruction of the climate during the Holocene period when studying ice cores, old groundwater and the unsaturated zone in arid and semiarid regions. Tracer methods are also a major tool for calibration and validation both of strategies in modelling catchment hydrology and hydrological models of groundwater systems. Furthermore, tracer approaches are commonly used to address issues like surface water–groundwater interactions, paleohydrology, water movement in very low permeable rocks, calibrating and validating numerical flow and transport models and evaluating vulnerability of water resources. Finally for Integrated Water Resource Management, tracer techniques have great potential as tracers that provide integrated information and can be very efficient in characterising complex systems in remote areas.

The empirical observation of flow and transport processes with tracers and the theoretical formulation of flow and transport processes depend on each other and have resulted in a beneficial coevolution of both approaches if adequately combined. Tracers provide empirical data of real and often unexpected flow patterns – models provide tools for flow and transport predictions.

The term '*Tracerhydrology*' is used as a short expression for the use of tracers in hydrology understood as an advanced method that allows for an integrative investigation

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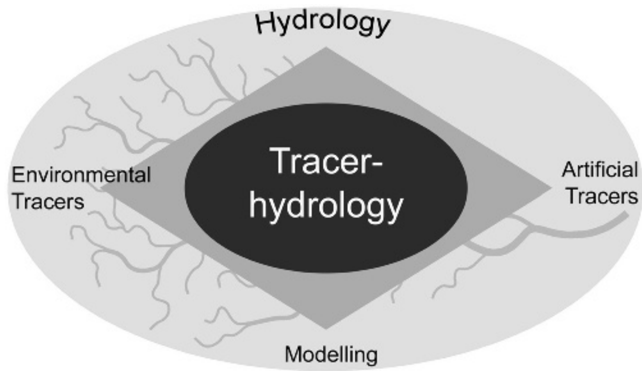

Figure 1.1 Tracerhydrology as a method of application tracers in water sciences understood as a holistic approach of hydrology and water research.

of the hydrologic system. It is not regarded merely as an isolated technique for solving particular problems of applied hydrology, although it certainly can be useful in those fields.

This book originated from the idea of interweaving knowledge from the fields of artificial and environmental tracers and of modelling, in order to present the options, opportunities and limits of tracers in hydrology to students, scientists, engineers and other users. In the following chapters the explanation of tracer and modelling basics builds a foundation for students and users to be able to understand the techniques, which are then applied to case studies of both specific applications and integrated studies. Herein, tracer techniques are described with regard to their relevance for advancing hydrological science and to their role in solving problems in applied hydrology. Students, scientists and consultants will find a wealth of information on tracers and modelling in order to introduce them to the field of tracerhydrology. A methodological chapter provides specific techniques such as the calculation of injection mass and the chloride method and also case studies dealing with the different approaches and problems of applied tracerhydrology (groundwater recharge).

Scientists can see the range of opportunities that tracer techniques offer through the variety of comprehensive case studies that are presented. Engineers and other users will find a large collection of work examples and may apply the methods described, for example tasks in integrated water resources management or the allocation of water supply protection zones, as well as many others. In this book the application of tracers in hydrology is understood basically as the integrated use of tracers in hydrology and therefore as a part of an integrated hydrological approach (Figure 1.1).

In Chapter 2 a detailed concept of tracerhydrology will be presented. The role of modelling in integrated tracerhydrology will be defined in a separate chapter. The combined application of tracerhydrology and modelling is presented by means of selected examples of applications in various hydrological compartments (glaciers, rivers, lakes, groundwater). The authors wish to present a textbook that starts from a simple and general overview and moves on to the more complex topics of tracerhydrology in

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order to facilitate an easy understanding by the readers, be they students, water research scientists, engineers or applied hydrologists.

The application of tracers in hydrology has a long tradition among the geo- and water sciences. After what were at first somewhat 'trial and error' – based experiments about 150 years ago a fascinating development began. Artificial salt and fluorescence tracers have been used for decades. In the 1950s a wide variety of new artificial tracers were included in tests designed to trace water, mainly in karst aquifers. At the same time a compelling new direction in tracerhydrology based on the use of natural, mainly isotopic tracers began to develop. Most of the fundamental principles had been developed during this phase. Stable isotopes have provided a major input into the study of hydrological processes such as runoff generation and runoff component separation as well as recharge and groundwater flow and are still at the centre of defining the conceptual models of hydrological processes. The role of isotopes in the validation of circulation models and response of ecosystems to climate change is not yet fully explored.

In addition to an increasing number of papers on tracerhydrology published in international hydrological journals, there are many publications on the use of tracers for water research issued by international organizations, such as (i) the IAHS (International Association on Hydrological Sciences), (ii) the symposia proceedings of the IAEA (International Atomic Energy Agency), and (iii) the proceedings and project volumes of the ATH (International Association of Tracers). These publications are an excellent resource for all matters concerning the methodological aspects and application of tracers.

Comprehensive presentations of large combined tracerhydrological studies are given in the reports of the ATH (International Association of Tracers). The focus of these investigations was on groundwater systems but the approach was holistic within the respective river basins. Increasingly, investigations on runoff generation and catchment modelling have adopted an integrated tracerhydrological approach.

Innovations in analytical techniques will provide new tools for tracerhydrology. There are trends towards reducing sample volumes, increasing the number of samples analysed, reducing detection limits and identifying new natural and industrial substances that can be used for tracer studies. Certainly, natural remediation and reactive transport processes will be explored increasingly with tracers. For the advance of hydrological science, empirical data provided by tracer methods have and will continue to play an important role. Further integration of experimental and theoretical approaches leading to an integration of tracers into soil water atmosphere transfer schemes and catchment and groundwater models, will provide additional means of validating the hydrological concepts.