Journal of Hydrology 511 (2014) 518–529

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review Paper

Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods

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ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form 24 January 2014
Accepted 28 January 2014
Available online 10 February 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Ty Ferre, Associate Editor

Keywords:
Surface water groundwater interactions
Streambed dynamics
Tracers
Dating
Floodwave infiltration

SUMMARY

Aquifer recharge through ephemeral streambeds is believed to be a major source of groundwater recharge in arid areas; however, comparatively few studies quantify this streamflow recharge. This review synthesizes the available field-based aquifer recharge literature from arid regions around the world. Seven methods for quantifying ephemeral and intermittent stream infiltration and aquifer recharge are reviewed; controlled infiltration experiments, monitoring changes in water content, heat as a tracer of infiltration, reach length water balances, floodwave front tracking, groundwater mounding, and groundwater dating. The pertinent temporal and spatial scales, as well as the advantages and limitations of each method are illustrated with examples from the literature. Comparisons between the methods are used to highlight appropriate uses of each field method, with emphasis on the advantages of using multiple methods within a study in order to avoid the potential drawbacks inherent in any single method. Research needs are identified, including: quantitative uncertainty analysis, long-term data collection and analysis, understanding of the role of riparian vegetation, and reconciliation of transmission losses and infiltration estimates with actual aquifer recharge.

Contents

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http://dx.doi.org/10.1016/j.jhydrol.2014.01.068
0022-1694/

1. Introduction

As the global population increases, humans are increasingly putting pressure on the resources of arid regions, where water scarcity is a major issue (Seely et al., 2003). In these regions, aquifers are often the principal water supply, because surface water is unreliable and usually only present during or after flood events; however, the development of groundwater resources often proceeds without a thorough understanding of the recharge processes (Edmunds, 1998). It is frequently asserted that infiltration through streambeds during flood events is the main form of recharge (Sorman and Abdulrazzak, 1993; Abdulrazzak, 1995; Shentsis and Rosenthal, 2003; Subyani, 2004; Niswonger et al., 2005), though there have only been a relatively small number of studies that have quantified this rate. In many areas, groundwater resources may be fossil resources, and rates of extraction may greatly exceed rates of recharge. Because precipitation varies both spatially and on temporal scales of years to decades, extraction rates need to take into account long-term aquifer recharge, which is only complicated further by the sporadic nature of the recharge events themselves (Besbes et al., 1978). Although the actual amount of streamflow that reaches the underlying aquifer (i.e. recharge) is typically the quantity of interest, several factors make it difficult to measure this recharge. These factors include the often large depth to groundwater (potentially causing a long delay from infiltration to recharge and complicating efforts to collect data), spatial variability in recharge due to geologic heterogeneity beneath streams, and potential difficulties in linking a specific streamflow event to a change in aquifer level. Therefore, it is common to use methods that estimate transmission loss or infiltration as a proxy for measuring groundwater recharge. Transmission loss quantifies streamflow reductions including infiltration through the sediments, evapotranspiration back to the atmosphere, and loss to stream banks or floodplains as the water travels downstream. Infiltration rates are typically measured at or just below the streambed surface, which is easier to access than a deep water table. However, several other factors complicate infiltration measurements, specifically in ephemeral and intermittent streams. For example, precipitation is spatially variable, making it difficult to arrive on-site in time to collect data in typically remote areas, frequent scouring and deposition of the streambed during flood events makes it difficult to estimate streambed geometry, and flood events themselves are unpredictable and transient in nature (Pilgrim et al., 1988; Shannon et al., 2002). Partly because of these challenges, there is a wide body of literature characterizing infiltration through unsaturated soils or diffuse recharge, but fewer studies describe field results from the ephemeral streambeds themselves.

Review papers exist for groundwater recharge in general (De Vries and Simmers, 2002; Scanlon et al., 2002), but not specifically for the ephemeral and intermittent streams characteristic of arid systems. In this paper, we therefore synthesize the field-based studies that quantify transmission losses, infiltration, or aquifer recharge from ephemeral and intermittent stream systems. Much of the available literature describes the arid regions of western USA, with the findings of that research summarized in Hogan et al. (2004) and Stonestrom et al. (2007). Some of the arid systems of southwest Africa have also been studied extensively (Lange, 2005; Bauer et al., 2006; Dahan et al., 2008; Morin et al., 2009). A further area of concentrated research is in the wadis of Saudi Arabia (Abdulrazzak et al., 1989; Sorman et al., 1997; El-Hames and Richards, 1998; Wheater and Al-Weshah, 2002). In this summary, we aim to review the pertinent methods using examples from all of these areas. Although many more studies have examined the processes involved in ephemeral stream recharge using theoretical or laboratory studies, we focus here on field-based studies. Further, although diffuse recharge throughout the catchment can also play a role in aquifer recharge during precipitation in arid zone catchments, for simplicity we focus on the methods and examples related specifically to streambed infiltration or recharge. Each of the appropriate methods is presented in terms of what is being measured (i.e. infiltration, transmission loss, or recharge), spatial and temporal ranges, and advantages and limitations. To illustrate cases where each of these techniques is relevant, we review the pertinent studies describing field applications of each method. The methods are then compared, and considerations common to all of the methods are illustrated with further examples. Finally, potential research gaps and future directions are suggested.

2. Methods

Several methods have been used for quantifying loss rates from losing streams, and some of these have recently been reviewed by Kalbus et al. (2006). However, not all of the methods that can be used in perennial streams are appropriate for ephemeral or intermittent streams. The techniques that are generally available to study ephemeral systems can be divided into three groups. The first group of methods monitors infiltration through the streambed. These methods typically provide point estimates of infiltration. They include:

(1) Controlled infiltration experiments.
(2) Monitoring changes in water content.
(3) Heat as a tracer of infiltration.

The second group of methods is based on measurements of streamflow during flow events. These methods provide estimates of either transmission losses or streambed infiltration over much larger spatial scales, sometimes up to several tens of kilometers of river distance. The methods include:

(4) Reach length water balance.
(5) Floodwave front tracking.

The third group of methods is based on measurements within the groundwater underlying the ephemeral stream. These methods therefore provide estimates of actual groundwater recharge, rather than streambed infiltration. These estimates will usually represent spatial and temporal averages. The methods include:

(6) Groundwater mounding.
(7) Groundwater dating.

The broad principles of each method are described in the following sections, together with their advantages and challenges. The reader is referred to the cited literature for detailed technical descriptions of each method, as these are described elsewhere and because the equations and methods can vary widely even within one category.

2.1. Controlled infiltration experiments

Controlled experiments in dry channels can be used to estimate infiltration rates during flood events. These experiments typically involve creating a column of constant head above the streambed and directly measuring the rate of infiltration, from which soil properties such as sorptivity and field saturated hydraulic conductivity can be calculated. This can be achieved using an infiltrometer or permeameter for measurement at a certain location within the streambed, or by isolating and filling a relatively short reach of the