Journal of Hydrology (2006) **330**, 235–248

available at www.sciencedirect.com

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

Differential gauging and tracer tests resolve seepage fluxes in a strongly-losing stream

C. Ruehl [a,*], A.T. Fisher [a,b], C. Hatch [a], M. Los Huertos [c,d], G. Stemler [a], C. Shennan [c,d]

[a] *Earth Sciences Department, University of California, E&MS rm A232, 1156 High Street, Santa Cruz, CA 95064, USA*
[b] *Institute for Geophysics and Planetary Physics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA*
[c] *Environmental Studies Department, University of California, 1156 High Street, Santa Cruz, CA 95064, USA*
[d] *Center for Agroecology and Sustainable Food Systems, University of California, 1156 High Street, Santa Cruz, CA 95064, USA*

Received 28 July 2005; received in revised form 24 March 2006; accepted 27 March 2006

KEYWORDS
Seepage;
Recharge;
Stream transport;
Tracers;
Water balance

Summary The Pajaro River, central coastal California, consistently loses 0.2–0.4 m^3/s of discharge along an 11.42-km experimental reach late in the water year, when discharge is $\leqslant$4.5 m^3/s. Channel loss occurs throughout this reach, but is greatest in magnitude near the bottom of the reach. Water isotopic data and other observations suggest that channel loss results mainly from streambed seepage, as opposed to evapotranspiration. If it occurs throughout the year, the channel loss along this short stream reach could contribute 6–13 × 10^6 m^3 of annual aquifer recharge, or ~20–40% of current sustainable basin yield. We performed a series of tracer injections along this reach to determine if hydrologic exchange occurs within this strongly-losing stream. We found that during periods of high channel loss, there were also comparable storage exchange fluxes and lateral inflow of tracer-free water. Within upper and lower parts of the experimental reach, storage exchange fluxes are about 10 times greater than lateral inflow. The former are associated with the movement of water between the main channel and surface or subsurface storage zones. In this system, it is likely that the latter are primarily associated with spatially- or temporally-long subsurface flow paths within the shallow streambed, as opposed to inflow of ground water from deeper in the basin. Along both upper and lower parts of the experimental reach, lateral inflow tends to increase as channel discharge decreases. In contrast, storage exchange fluxes increase with decreasing discharge along the upper parts of the reach, but decrease with decreasing discharge along the lower parts. Gauging and tracer test results suggest that subsurface storage exchange and loss may occur

* Corresponding author. Tel.: +1 831 459 1724.
E-mail address: cruehl@ucsc.edu (C. Ruehl).

doi:10.1016/j.jhydrol.2006.03.025

simultaneously, and that the lateral inflow of tracer-free water can be caused by long-scale subsurface flow as well as ground water making its first appearance in the channel.

Introduction

Surface water and ground water are increasingly viewed as a single resource within linked reservoirs (Jones and Mulholland, 2000; Winter et al., 1998). The movement of water from streams to aquifers and from aquifers to streams influences both the quantity and quality of available water within both reservoirs, depending on the magnitudes of fluxes, the initial chemistry of water moving through the stream bed, and transformations that occur during transport. These fluxes are driven by differences between stream water levels and hydraulic heads in the stream bed and aquifers adjacent to the stream channel. They occur over a range of time and length scales, and are influenced by channel geomorphology, lithologic variability, and hydrogeologic properties of the streambed and near-stream formations.

We use the term ''streambed seepage'' in this paper to refer to the movement of water across the streambed, both into and out of the stream channel. Where there is net loss in stream channel discharge due to streambed seepage, aquifer recharge may occur if the infiltrating water reaches the water table, or water may be used by riparian plants or remain in the vadose zone above the water table. Similarly there may be a net gain in channel discharge under baseflow conditions, when ground water moves into the stream. Alternatively, seepage may contribute to hyporheic flow, the movement of stream channel water into the shallow subsurface with subsequent return to the channel and no net change in channel discharge (Fig. 1). This definition of hyporheic flow, essentially process based, is a compromise of usage applied by ecologists, biologists, and hydrologists (Bencala et al., 1984; Bencala and Walters, 1983; Grimm and Fisher, 1984; Malard et al., 2002; Triska et al., 1989; Williams and Haynes, 1974).

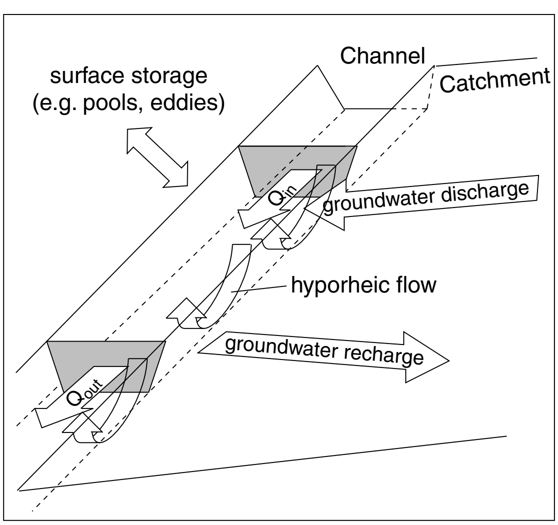

Figure 1 Cartoon showing surface—subsurface (seepage) exchange concepts (Harvey et al., 1996; Woessner, 2000). Channel discharge occurs at the upper and lower ends of an experimental reach. Tracer is injected at the upper end of the reach and monitored as the lower end of the reach. During transport down the reach, water exchanges with storage areas in and off the channel, above and below the stream bottom.

Thus streambed seepage comprises both lateral inflow and outflow of ground water and hyporheic exchange, including all subsurface flow paths that start and end at the streambed (Fig. 1). One of the major goals of this study was to estimate the magnitude of the seepage flux within a specific stream system, as well as the contributions of its components (the hyporheic flux, inflow of ground water, and outflow of ground water). The extent of seepage across streambeds has been linked to various characteristics of previously studied stream systems, including parent lithology (Valett et al., 1996), variations in stream gradient (Harvey and Bencala, 1993; Hill et al., 1998; Wondzell and Swanson, 1996), and formation and migration of sediment bedforms (Packman and Brooks, 2001). Several recent studies have documented aquifer recharge contributions made by streams using field observations, geochemical data, and modeling (Criss and Davidson, 1996; Izbicki et al., 2004; Rains and Mount, 2002). Water management goals towards sustainable ground water extraction often include maintenance of stream discharges sufficient to support aquatic ecologic systems, which requires knowledge of seepage rates both into and out of the streambed.

The most commonly used method for evaluating subsurface—surface exchange at long spatial scales (i.e., greater than ~100 m) is use of transient storage models (TSMs) (Harvey and Wagner, 2000). One important limitation of the TSM approach is that multiple (complex) surface and subsurface storage zones are combined into a single (highly idealized) storage zone (Choi et al., 2000). In addition, many applications of TSMs assume that the frequency distribution of storage zone residence times is exponential, whereas non-exponential residence time distributions are more consistent with experiment in some systems (Gooseff et al., 2003b; Haggerty et al., 2002; Worman et al., 2002). Also, storage exchange that occurs over time or length scales longer than that of the tracer test may not be properly represented (Harvey et al., 1996; Zaramella et al., 2003); most stream tracer studies last several hours to a few days, but longer-scale (temporal, spatial) exchange is important in some systems (Gooseff et al., 2003a; Haggerty et al., 2002; Kasahara and Wondzell, 2003; Storey et al., 2003). Nevertheless, the TSM approach remains useful for quantitative (albeit highly idealized) characterization and comparison of stream systems (Gooseff et al., 2005; Harvey et al., 1996; Wagner and Harvey, 1997). In this study, we apply a TSM approach in combination with a detailed water budget in an attempt to estimate both short and long-scale hyporheic flow. Although subsurface—surface exchange at a wide range of time and length scales has been observed in many streams, few studies compared inflow and