Journal of Hydrology 448–449 (2012) 161–173

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

Hyporheic flow patterns in relation to large river floodplain attributes

Barton R. Faulkner [a,*], J. Renée Brooks [b], Kenneth J. Forshay [a], Steven P. Cline [b]

[a] US Environmental Protection Agency, National Risk Management Research Laboratory, Ada, OK 74820, United States
[b] US Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Corvallis, OR 97333, United States

ARTICLE INFO

Article history:
Received 9 August 2011
Received in revised form 5 March 2012
Accepted 24 April 2012
Available online 5 May 2012
This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Ercan Kahya, Associate Editor

Keywords:
Hyporheic flow
Geomorphology
Floodplain age
MODFLOW
Willamette River
LiDAR

SUMMARY

Field-calibrated models of hyporheic flow have emphasized low-order headwater systems. In many cases, however, hyporheic flow in large lowland river floodplains may be an important contributor to ecosystem services such as maintenance of water quality and habitat. In this study, we used a network of shallow monitoring wells, Light Detection and Ranging (LiDAR), and continuous monitoring to parameterize and calibrate stochastic three-dimensional ground water models for a 9.7 km^2 (2400 acres) area along a naturally-meandering section of the Willamette River floodplain in Oregon. This large river floodplain is representative of other similar systems. Steady-state simulations were done representing the wet winter and dry summer seasons. During the dry season, hyporheic flow was oriented along the floodplain elevation gradient and median steady-state residence times in small islands and bars were on the order of months. In the larger islands steady-state residence times were on the order of years. In the wet season, flow was oriented laterally away from the river and quickly intercepted and returned to the surface water system in alcoves and cutoffs connected to the river, and recharge due to infiltration of precipitation prevented hyporheic flow through older island areas. In the younger islands, median steady-state residence times ranged from about 6.1×10^1 to 1.6×10^2 days. In the model domain overall, the steady-state dry season median pathline length was about 8.2×10^2 with a maximum length of about 5.7×10^3 m. For the wet season, the median was about 2.0×10^2 m with a maximum length of about 3.5×10^3 m. Wet season hyporheic water penetrated deeper into the lower permeability geologic units by an order of magnitude, as compared to the dry season. This was likely due to the absence of precipitation infiltration during the dry season. We used particle tracking in order to characterize residence time distributions for hyporheic water. We found two behaviors: lognormal decay with shorter distributions of residence times, and heavy tailing, following power-law behavior. Interestingly, we found the heavy tailing behavior more during the wet season when mean residence times were short. This result implies that even though some rates of hyporheic flow were relatively fast, there were also zones of relatively stagnant water causing this large variation in residence time. Observed slopes for log–log plots of the histograms fell in the range of 2.3–5.6. This behavior appeared to be restricted to regions affected by natural river meandering, where avulsions create isolated islands. In some areas, land managers may consider revetment removal as a means to convert channelized systems to more natural systems with shallower depths in the main channel, meander scrolls, and alcoves that can enhance hyporheic flow. The results of this study provide information on how such decisions may affect the extent of hyporheic flow that may occur as a large river returns to its natural geomorphological dynamics.

Published by Elsevier B.V.

1. Introduction

Studies focused on the hyporheic zone are frequently conducted in headwater and low-order streams, however, the hyporheic zone of large river floodplains may also play a very substantial role in maintaining water quality and habitat (e.g., see Stanford and Ward, 1993; Hinkle et al., 2001; Fischer et al., 2005; Fernald et al., 2006). While the hyporheic zone is usually defined as the region of ground water flow with water that has originated in an adjacent stream, and will soon return to it, its maximum spatial or temporal extent has not been clearly defined. In other words, the demarcation between hyporheic flow and local ground water flow in the sense conceptualized by Tóth (1963) is somewhat indistinct. In a large anastomosing river corridor, the distance between cutoff portions and branches may be quite large, and hyporheic residence times very long. Nevertheless we expect that the water quality benefits of large-scale hyporheic flow (e.g., denitrification enhancement, temperature buffering, and riverbank filtration) will occur.

* Corresponding author. Tel.: +1 580 436 8530; fax: +1 580 436 8703.
E-mail addresses: faulkner.bart@epa.gov (B.R. Faulkner), brooks.reneej@epa.gov (J. Renée Brooks), forshay.ken@epa.gov (K.J. Forshay), cline.steve@epa.gov (S.P. Cline).

0022-1694/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jhydrol.2012.04.039

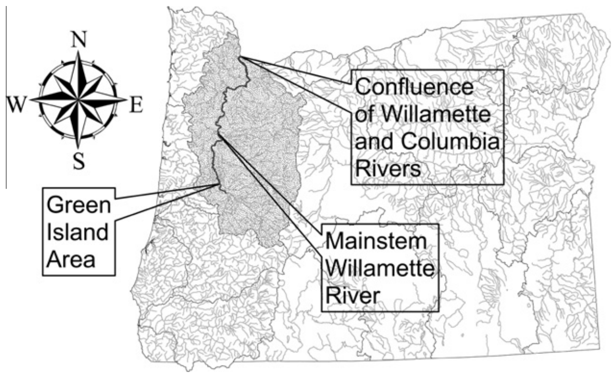

Fig. 1. Map of the State of Oregon showing major watersheds and the location of the Green Island study site. The mainstem Willamette River and its watershed are highlighted.

The Willamette River, Oregon, is a ninth-order tributary of the Columbia River (Fig. 1). In its lowland extent, it occupies a broad populous valley that supports a variety of valuable agricultural services. In many areas the river has been constrained, channelized, and straightened by revetments in order to protect property. Under these conditions, mechanistic models predict that lateral mixing with ground water is minimal (Cardenas, 2009), and therefore the river is functioning mostly as a simple conduit for its discharge. It has been suggested that some areas might be amenable to revetment removal in order to enhance beneficial ecohydrological services (Gregory et al., 2002). The selection of removal locations would rely upon cooperation from farmers and land-owners who may be willing to adapt land use practices near a more dynamic river corridor. Among the potential benefits of revetment removal is enhancement of the extent of hyporheic flow (Gregory et al., 2008). For low-order and headwater streams, largely characterized by riffle and pool sequences, or by natural in-channel flow obstructions, considerable progress has been made in generalizing the types of hyporheic flow that may be expected to occur in relation to these geomorphic features (e.g., see Hester and Doyle, 2008). Kasahara and Hill (2008) used modeling with field measurements to predict the effects of modifying geomorphic environments on low- and intermediate-order streams. In the laboratory, recirculating flumes have been used to develop models for vertical hyporheic exchange induced by bedforms (e.g., see Elliott and Brooks, 1997; Packman and Brooks, 2001). The behavior of hyporheic flow in relation to large river meandering and avulsion has been the subject of model simulations (Boano et al., 2006; Revelli et al., 2008; Cardenas, 2009), but detailed field-calibrated studies in high-order, large river meandering systems have been lacking.

In cooperation with the McKenzie River Trust, the US EPA Office of Research and Development installed and instrumented 50 monitoring wells at Green Island, within the Willamette River floodplain, near its confluence with the McKenzie River. In contrast to portions of the Willamette which are constrained by revetments, the Green Island site is representative of a dynamic anastomosing river with well developed point bars, meander scrolls, and alcoves, more characteristic of the natural geomorphic conditions in the central portion of the Willamette Valley than in areas with revetments (Wallick et al., 2007) and of the natural riparian forest succession (Dykaar and Wigington, 2000). The purpose of this paper is to present the results of a numerical model built upon measurements made at Green Island, and to identify hyporheic flow paths and residence times in relation to large river geomorphic structures. Although this work is focused on a particular geographic location, the system is representative of many alluvial river systems throughout the world.

2. Description of the study site

Green Island is actually comprised of multiple islands (Fig. 2) formed near the historic confluence of the Willamette and McKenzie Rivers. The McKenzie River currently joins the Willamette immediately south of Green Island. During the late 1800s and early 1900s the McKenzie and Willamette Rivers occupied various channels, which now consist of sloughs and alcoves in the Green Island area (Benner and Sedell, 1997). These channels now are active only during relatively high flow events, but the Green Island site is representative of the naturally meandering river, free of revetments. Along the mainstem Willamette River in the area, revetments exist only along the southwestern edge of the southernmost concave bank, to protect homes and property to the southwest. There is an older revetment that separates the south agricultural area and the aggraded zone which no longer functions against the mainstem river. The main river channel ran through the aggraded zone during the 1940s and 1950s, according to aerial photographs.

The surficial geologic unit consists of recently reworked floodplain deposits of the Willamette and McKenzie rivers. These deposits consist of sands, gravels, cobbles, and silts. A detailed description of the deeper Quaternary geology done by the US Geological Survey included an adjacent site to the southwest across the Willamette River (O'Connor et al., 2001). At that site, a deeper Pleistocene layer (mapped as Qg_1) consisting of lower energy deposits was identified at about 8.7 m below ground surface (BGS), and another layer differentiated by moderate cementation (Qg_2) was identified beginning at a depth of about 20 m BGS. At about 22.5 m BGS a strongly cemented sand and gravel unit was identified. This was treated as the bottom no-flow boundary for our model.

All of the 50 monitoring wells installed were completed in the surficial unit (mapped as Qalc). The wells range in depth from 3.8 to 7.8 m BGS. The wells were surveyed using a GPS receiver (Model 4700, micro-centered L1/L2 geodetic ground plane antenna, Trimble Navigation Limited, Sunnyvale, CA, USA). After development of the wells, hydraulic conductivities were successfully measured in 40 of the 50 wells, using pneumatic slug tests, with the Springer and Gelhar (1991) analysis method. Soil samples were collected from the screened zone of two monitoring wells during well construction. A Beckman Coulter LS230™ particle size analyzer was used to measure the distribution of particle diameters in triplicate from each of the two well screen zones. The wells were instrumented with automatic data-logging pressure transducers, recording water level and temperature at 10–15 min intervals.

Based on Light Detection and Ranging (LiDAR) data collected during flights in 2008–2009, a high resolution (0.91 m) Digital Elevation Map (DEM) was developed for the Green Island site. The mean elevation was 111.3 m above mean sea level (AMSL).

At the study site, climate is characteristic of the broader Willamette Valley lowlands, with a cool wet season, beginning about October and lasting until about May, and a warm, dry season during most of the rest of the year. During the years July 1996 to December 2008 the annual average total precipitation in nearby Eugene, Oregon was 992 mm, with 80% of the total falling during the months of November through April, and the average minimum and maximum temperatures were 1.5 °C and 28.6 °C (Western Regional Climate Center, 2011).

The bare earth DEM collected using LiDAR can be used with the reflected water surface to obtain water surface elevations accurate to within about 0.05 m, considering refraction error (English, 2009). These elevations were obtained for the Willamette River thalweg from the September 5, 2008 LiDAR flights. The location of the thalweg along the river was estimated using the flow accumulation algorithm flow paths described in Jenson and Domingue