Groundwater recharge in Pleistocene sediments overlying basalt aquifers in the Palouse Basin, USA: modeling of distributed recharge potential and identification of water pathways

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Abstract Groundwater levels in basalt aquifers around the world have been declining for many years. Understanding water pathways is needed for solutions like artificial drainage. Water supply in the Palouse Basin, Washington and Idaho, USA, primarily relies on basalt aquifers. This study presents a combination of modeling and field observations to understand the spatial distribution of recharge pathways in the overlying Pleistocene sediments. A spatially distributed model was used to quantify potential recharge rates. The model shows clearly that recharge predominantly occurs through non-argilic soils and soils that are not underlain by fine-grained sediments, i.e. the upper area of the watershed. A field survey was conducted to determine recharge pathways from this area. It revealed 83 perennial springs. Drillings near springs showed connection of coarse-grained layers within the fine-grained Sediments of Bovill to these springs. Such layers, with streambed-like features, act as paleo-channels. Water from one of these coarse-grained layers had a similar electrical conductivity (200 μS cm^{-1}) to water from a downstream perennial spring, also suggesting the existence of a lateral conduit for deep percolation water.

Keywords Groundwater exploration · Basalt aquifers · Numerical modeling · Sustainable water use · USA

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Introduction

Many urban and agricultural water users in the world rely on groundwater as their water source. In recent decades, a large number of aquifer systems worldwide have been experiencing severe water-table declines, impacting present and future socio-economic development (UNESCO 2009). Uncertainties in groundwater volumes and recharge rates as well as the effects of climate change and population growth surround the future of groundwater supplies.

For groundwater abstraction, alluvial aquifers in general are the most economically viable. However, in many locations such aquifers are not available. Igneous and other crystalline rocks typically are low-water yielding aquifers, depending on interconnected fracture networks. Because they are pervasively fractured, extrusive basalts are one of few igneous rocks that may provide significant quantities of water. Areas underlain by extensive basalt formations, therefore, can be used for drinking-water supply. Examples of such basalt formations are the Deccan Trap Aquifer in Peninsular India (Das and Ars 1971; Kulkarni et al. 2000), the Columbia River Basalt Group in USA (Miller 1999), and the Golan Heights (Dafny et al. 2006) and Azraq Basin in the Middle East (El-Naqa et al. 2007). When such aquifers suffer depleting groundwater levels, it means that pumping rates exceed recharge rates. Das and Ars (1971) showed how groundwater recharge to the Deccan Trap Aquifer formation can be enhanced by creating small recharge basins. Recharge processes, however, are often poorly understood (De Vries and Simmers 2002).

Declining water levels are a major concern in the Palouse Basin, northwestern USA (see Fig. 1). Palouse Basin (2,050 km^2) is one of the eastern reaches of the Columbia River Basalt Group. Water supply in the Basin primarily relies on the deeper Grande Ronde basalt aquifer, and secondarily on the shallower Wanapum basalt aquifer in the eastern part of the Basin. Basalt flows in the Palouse Basin ended at the bottom of crystalline rock outcrops, choking south-westerly drainage patterns. The Wanapum basalts are overlain by the Sediments of Bovill, a Quaternary formation consisting of a mixture of alluvial sediments, which, in turn, are covered by wind-blown loess (Palouse Formation). Since 1890, a network of

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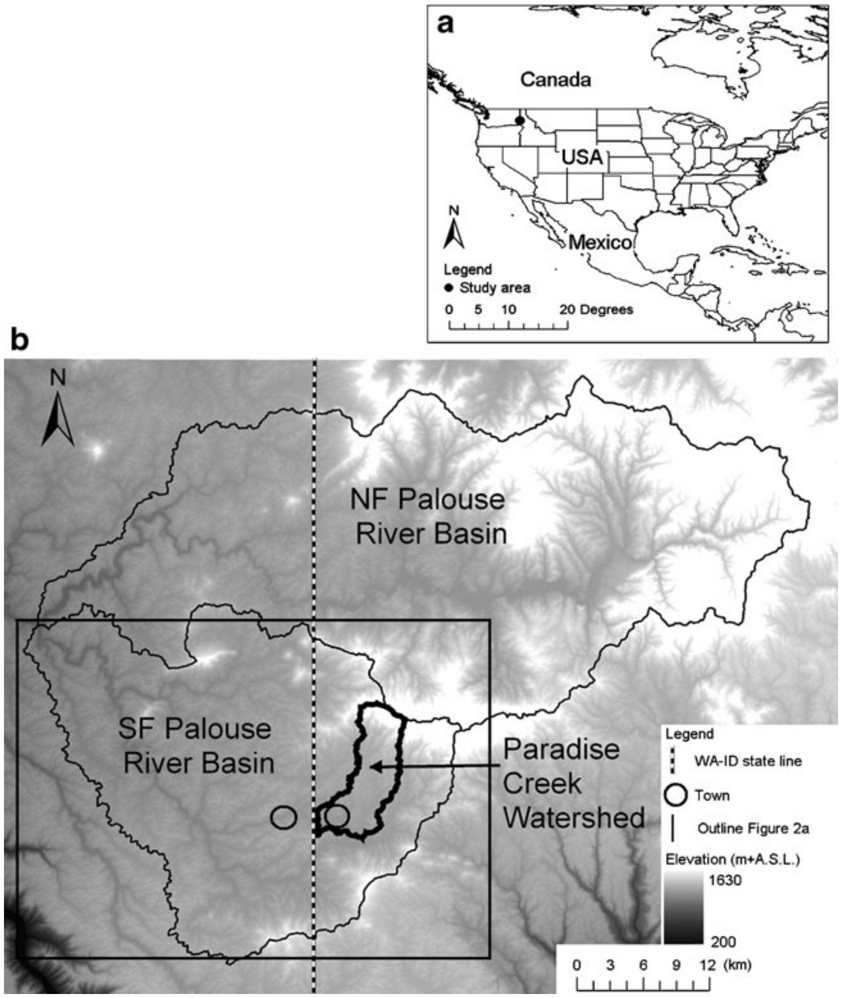

Fig. 1 Paradise Creek watershed in the Palouse Basin, Idaho (*ID*), USA. **a** location of the watershed in USA, and **b** site map indicating elevation. *NF* North Fork; *SF* South Fork; *WA* Washington

pumping wells has been used for the drinking-water supply of two urban communities and two universities. As early as 1897, there were warnings that free-flowing artesian wells were wasting groundwater, ultimately leading to declining groundwater levels (Barker 1979). Robischon (2006, 2008) reported that water levels have been declining by 40 to 60 cm yr^{-1} for decades.

Several studies have reported a range of recharge rates to the shallower Wanapum aquifer starting as early as in the 1960s. Stevens (1960) used a water-budget method to estimate a recharge rate of 3 cm yr^{-1} and emphasized that this estimate is within the accuracy of calculations of evapotranspiration. Similar estimates were reported by Foxworthy and Washburn (1963) and Barker (1979). Bauer and Vaccaro (1990) estimated recharge in the range of 7–10 cm yr^{-1}. Isotope tracer studies (O'Geen et al. 2004), and vadose sampling and modeling with LEACHM (Muniz 1991) estimated recharge at different hillslope positions in the range of 0.4–10.5 cm yr^{-1}, respectively. Based on the set of recharge estimates, Reeves (2009) used expert elicitation and Bayesian Model Averaging to estimate areal average recharge to be 5.1 cm yr^{-1} with an uncertainty of +/– 4.6 cm yr^{-1}.

Recharge studies indicate that recharge pathways to the aquifer systems are unknown. These pathways are important for recharge enhancement plans. Three recharge pathways to the Wanapum aquifer are believed to exist: (1) water infiltrating through sediments overlying crystalline rock (Lin 1967); (2) water infiltrating through the loess (Larson et al. 2000); and (3) water loss from streams in close contact with basalt (Provant 1995). Hosterman et al. (1960) postulated paleo-channels as a fourth pathway, where water flows in coarse materials below the loess through the Sediments of Bovill, possibly finding a connection to the basalt. Thus, while an accurate recharge rate is not available, more importantly, it is still not clear where and how recharge to the basalt formation occurs and which role Quaternary formations play. The hypothesis is that recharge rates, and in turn pathways, are variable throughout the landscape due to differing surficial deposits overlying the Quaternary formation. The objective of this study was to combine distributed hydrological modeling, field observations and literature review to determine pathways for groundwater recharge to the Wanapum Formation. A particular focus was placed on distributed modeling using a water-balance approach, field

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evidence of paleo-channel activity, and observations of water flow towards a characteristic spring.

Site description

The study area is the Paradise Creek (PC) watershed located in the Palouse Basin in eastern Washington and northern Idaho, USA (46°38′–46°56′N and 116°31′–117°11′W). The PC watershed constitutes a 49 km^2 area ranging in elevation from 800 meters above sea level (m + A.S.L.) around the city of Moscow to 1,100 m + A.S.L. on Moscow Mountain (north of Moscow). Figure 1 shows the location and elevation of the study area.

Several Tertiary basalt flows overlie Precambrian quartzite, gneiss and Cretaceous granitic rock, which in turn are covered with relatively young sedimentary formations (Fig. 2; Barker 1979). The Colombia River Basalt Group consists of several formations. The oldest formation, the Imnaha Formation, dates back to 17.4–17 million years (MA) ago. This formation can only be found in the western part of the study area. The total thickness of the more important overlying basalt formation, i.e. Grande Ronde Formation, is about 150 m. The thickness of the two or three individual flows of the younger Wanapum Formation ranges from 15 to 60 m each (Bush et al. 1998).

Sedimentary deposits within and overlying the Wanapum Formation, called the Latah Formation, consist of a mixture of lacustrine and fluvial sediments including clay, silt, sand and gravel. The sediments interbedding the Wanapum Formation are called Vantage Member, the sediments overlying the Wanapum Basalts are called Sediments of Bovill. These Sediments of Bovill have several origins, ranging from weathered granite to shallow lacustrine deposits. The Wanapum Formation basalt flows covered the existing drainage pattern (14.5 Ma ago).

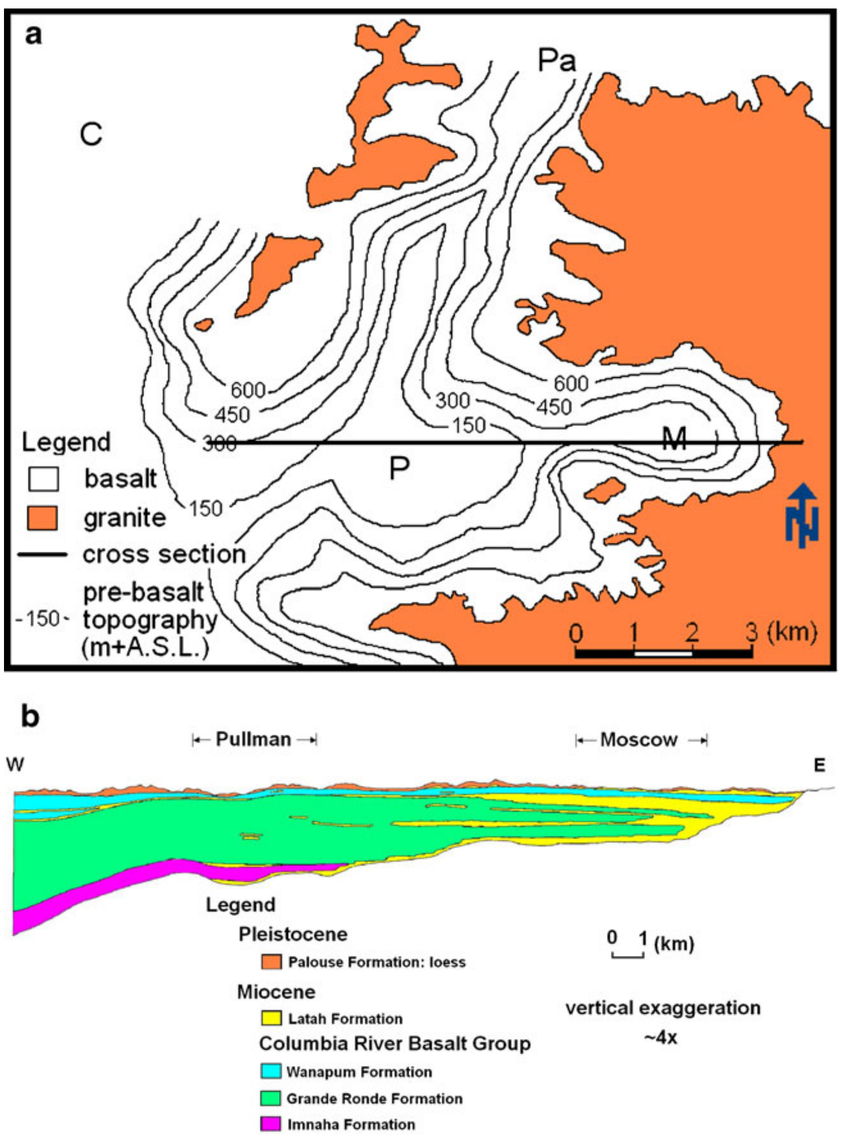

Fig. 2 **a** Pre-basalt topography of the Pullman/Moscow basin (after Ralston 2002) and **b** geological cross-section of Moscow-Pullman basin (after Bush and Garwood 2004). (*M* Moscow; *P* Pullman; *C* Colfax; *Pa* Palouse

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Temporary lakes and streams developed, which resulted in a highly variable sediment profile. Most of the sediments are believed to have formed in a fluvial environment (Bush et al. 1998). The fine-grained lacustrine and back swamp deposits act as aquitards, but the sandy stream bed deposits can act as narrow but long-stretched aquifers. The Palouse Formation loess overlies the Sediments of Bovill (Busacca and McDonald 1994). Poorly permeable or impermeable argillic layers or fragipans exist within the loess (McDaniel et al. 2001), and elevation ranges from 767 to 1,327 m + A.S.L. Average annual precipitation (P) varies directly with elevation, ranging from 653 mm yr^{-1} at the lowest to 1,020 mm yr^{-1} at the highest elevation according to 800-m resolution PRISM (parameter-elevation regressions on independent slopes model) maps (PRISM 2009). Excess precipitation (P_{excess}) for the region calculated as average total P provided by the Western Regional Climate Center (2009) minus average total actual evapotranspiration (ET_{act}), is shown in Fig. 3. During summer, ET_{act} exceeds P, resulting in a negative P_{excess}.

The high elevation headwater region is forested, the middle elevation region is composed mostly of dryland grain production with a smaller portion of perennial grasslands, and the lower elevation region near the outlet of the watershed is composed of impervious urban and residential areas (see Fig. 4).

In 2001, a nested monitoring network was established in PC watershed providing 7 years (2002–2008) of continuous streamflow data. Monitoring station S_a measured flow from a 160-ha forested headwater-drainage catchment, S_b recorded flow from a 2,770-ha drainage catchment including the entire forested region and the majority of the rural areas, and S_c recorded flow from the entire 4,900 ha watershed integrating the response of the urban, rural, and forested regions. The forested region is composed of highly permeable Andisols and the rural region is composed entirely of Mollisols. Of particular importance is the presence of argillic soil horizons within the Mollisols. Southwick and Taney soil types have the most well-developed argillic soil layers with very low permeability resulting in extensive seasonal perched water tables.

Methods

Modeling of distributed recharge potential

The soil moisture routing (SMR) model, a geographic information system (GIS)-based distributed hydrology model adapted and validated for the Palouse region (Brooks et al. 2007; Brooks and Boll 2002) was used to identify the relative potential for groundwater recharge throughout the PC watershed. Simulations were run for the PC watershed over a 7-year period (2002–2008).

The SMR model is a grid-based water-balance model which simulates snow accumulation and melt (Brooks and Boll 2005), interception, evapotranspiration (ET), subsurface lateral flow, deep vertical percolation and saturation-excess surface runoff. Deep percolation below the root zone is accumulated into a single reservoir which either returns water to the stream as baseflow or passes water to a deep aquifer system, defined here as potential recharge, using linear reservoir coefficients. The baseflow reservoir coefficient is determined directly from recession analysis of observed streamflow data (Barnes 1939; Brutsaert and Nieber 1977). The deep aquifer coefficient is determined by matching simulated and observed annual water yields. Despite minimal input requirements, agreements with observed streamflow and distributed moisture data are often as good as, or better than, more complex hydrology models (Johnson et al. 2003; Mehta et al. 2004). The model is written as a set of batch programs written in the PERL programming language that can be implemented into most grid-based GIS programs. A daily, two-soil layer version of the SMR model was used to simulate the hydrology of the PC watershed. Further details on the SMR model are available in Brooks et al. (2007).

Daily temperature and precipitation maps were calculated assuming linear lapse rates with elevation using climate data from Moscow (elevation 811 m + A.S.L.) and the Moscow Mountain SNOTEL site (SNOTEL being the national snow survey and water-supply forecasting service, elevation 1,433 m + A.S.L.). Average annual precipitation at the upper gauging station S_a (1,066 mm) for 2002–2008 was 59% greater than average annual precipitation at the lower station (681 mm), which is typical for the region. Potential ET was calculated from minimum and

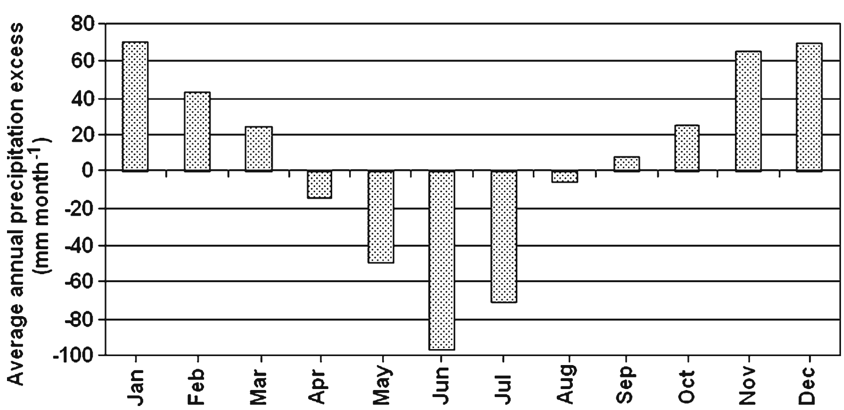

Fig. 3 Average actual precipitation excess (P-ET_{act} (mm per month)) for period 1893–2004 at Moscow, Idaho, derived from total precipitation recorded by the Western Regional Climate Center using 90 m × 90 m grids (Western Regional Climate Center 2009)

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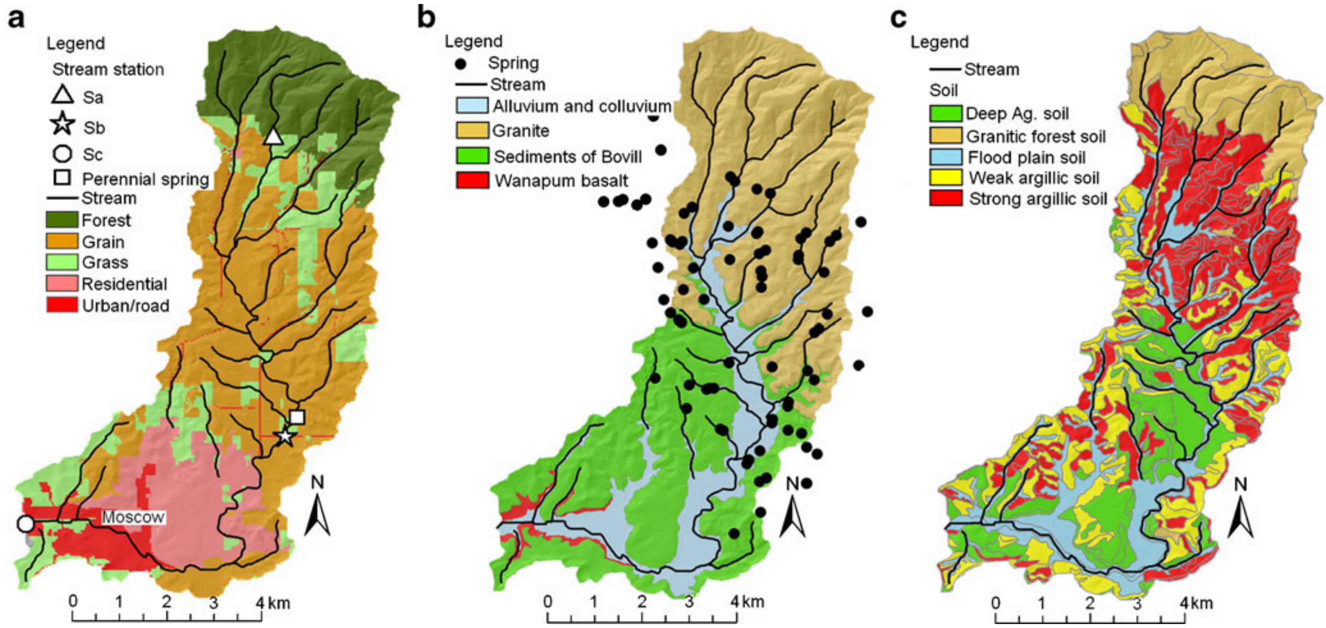

Fig. 4 **a** Land use streams and three gauging stations (S_a, S_b, S_c), **b** geology and spring locations and **c** soils within the Paradise Creek watershed. *Ag.* agriculture

maximum air temperature using the 1985 Hargreaves equation (Hargreaves et al. 1985). Soil, topography, and land use maps were imported as 30×30 m grid maps. Soil properties of surficial deposits, including bulk density, field capacity, and wilting point were taken directly from the soil survey (Barker 1981). The thickness of the upper soil layer was defined by the depth to an argillic soil layer. Although the argillic layers in the region have a low-saturated hydraulic conductivity, they do not fully impede root growth. Therefore the thickness of the second soil layer was defined by either the minimum of the rooting depth of the vegetation or the depth to bedrock (i.e. granite or basalt). The vertical saturated hydraulic conductivity of the argillic layer was set equal to the representative rate listed in the county soil survey. Lateral saturated hydraulic conductivity of the upper soil layer was assumed to be ten times greater than the vertical saturated hydraulic conductivity listed in the soil survey because of the influence of macropores (Brooks et al. 2004). The ratio between lateral and vertical-saturated hydraulic conductivity was reduced with depth following Brooks et al. (2004). The vertical percolation rate through the Sediments of Bovill was set at 0.24 mm d^{-1}, which is equivalent to the rate reported for argillic horizons within Southwick and Taney soils.

Sensitivity and SMR model error was previously assessed by Brooks et al. (2007) using detailed integrated and distributed hydrometric data. Brooks et al. (2007) compared simulated and observed perched water-table depths recorded every 12 h over a 3-year period at over 100 shallow well locations in a 2-ha catchment. Model agreement with perched water-table depths was very good with average root mean square error (RMSE) values less than 18 cm which equated to less than 1-cm error in total depth of water stored in the soil profile (Brooks et al. 2007). In this study, assessment of the ability of the model to predict streamflow was based on the Nash-Sutcliffe efficiency (NSE) statistic (Nash and Suthcliffe 1970) and the RMSE statistics. Perfect agreement between model simulations and observations yields a NSE of unity and a RMSE of zero. A negative NSE value result is possible with poor agreement between simulated and observed values. A NSE value of zero means that the model is able to capture the long-term mean average flows. In this study, the qualitative assessment of NSE by Foglia et al. (2009) was adopted, that a NSE below 0.2 is insufficient, 0.2–0.4 is sufficient, 0.4–0.6 is good, 0.6–0.8 is very good, and greater than 0.8 is excellent.

Paleo-channels

An extensive field survey was conducted to locate springs and wet spots throughout the PC watershed. Springs were defined as locations where subsurface water visibly and consistently becomes surface flow. Wet spots were defined as areas where subsurface water created near saturated soil surrounded by surface soils at ambient moisture conditions. At the time of the survey, the surface soil was relatively dry (April 2010, after a dry winter) so that wet spots could easily be identified. Local landowners were consulted on location of springs and wet spots followed by field checks by using a soil auger up to depths of 6 m on a subset of them.

Twelve phreatic piezometers were installed to a maximum depth of 3 m in a 20×30 m area above a perennial spring in the PC watershed (46°45′05.79″N and 116°57′35.92″W). The location of this spring is approximately 1 km downslope of the forested area in PC watershed, approximately 150 m upstream of gauging station S_b (see Fig. 4). Spring discharge was measured and spring water and groundwater were tested for electrical conductivity (EC, in μS cm^{-1}).

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Stream recharge

To estimate the order of magnitude of recharge from losing streams in the basin (Fairley et al. 2006), five seepage meters (Rosenberry 2008) were installed in the Paradise Creek streambed, with minimal disturbance of the bed profile. All seepage meters were installed within a distance of 30 m approximately 500 m upstream of gauging station S_c (see Fig. 4). The water reservoir was weighed and refilled several times in October 2008. Seepage (mm d^{-1}) was calculated by dividing the change in water volume by the surface area of the seepage meter.

Results and discussion

Modeling results

Comparison of simulated and observed streamflow over the 7-year time period at each of the monitoring locations showed sufficient to good agreement based on the overall NSE, with some individual years showing insufficient agreement and some showing excellent agreement (see Table 1). Simulated and observed streamflow at the outlet of PC watershed is shown in Fig. 5. Overall NSE was greatest for the entire PC watershed, at 0.57. The overall NSE for the two sub-watersheds was greater than 0.3 and therefore was sufficient or better. Interestingly, the NSE for 2006 simulation results, which is sensitive to the disagreement between the simulated and observed magnitude of peak flow events, were greatly affected by mismatch of a single 2-day event in January. Neglecting streamflow on 1/10/2006–1/11/2006 raises the NSE value from –0.18 to 0.76 for the PC watershed and raises the NSE value from –0.33 to 0.79 for the “Rural + Forest” sub-watershed for the 2006 water year. Likewise, this improves the overall NSE for the entire simulation to 0.66 and 0.53 for the PC watershed and “Rural + Forest” subwatershed, respectively. The model predicted an extreme rain-on-snow event with nearly 5 cm of rain falling on 0.3 cm of melting snow on 1/10/2006. However, rainfall totals from nearby weather stations reported less than 4 cm of rainfall with much of the precipitation falling at night during near freezing temperatures. Daily total precipitation at the top of the watershed at the Moscow Mtn. SNOTEL was less than the low elevation station at the Moscow weather station. It is likely that the storm was more localized than the model predicted leading to a large over-prediction in runoff. Simulations for a drought year (hydrological year 2005) were insufficient regarding the NSE, but still were able to capture the much lower flow during this year. Other than the isolated event in 2006 and the drought period in 2005, the agreement between simulated and observed streamflow is very good. Figure 5 shows a detailed comparison of simulated and observed streamflow for WY 2007; Table 1 shows the NSE and the RMSE between daily simulated and observed streamflow. Table 2 provides the total observed and simulated streamflow for the 2002–2008 water years. Overall the SMR model adequately captured the integrated response of the PC watershed based on the nested watershed comparison.

Table 1 Nash-Sutcliffe Efficiency values for Paradise Creek watershed (PC watershed) and two sub-watersheds within PC watershed for each year during 2002–2008 and for the entire time period. Root mean square error values between observed and simulated daily streamflow (mm) are provided in parentheses

Year	PC watershed	Rural + Forest	Forest
2002	0.62 (0.75)	0.30 (0.63)	0.20 (0.82)
2003	0.85 (0.35)	0.85 (0.35)	0.53 (0.64)
2004	0.47 (0.63)	0.17 (0.95)	–0.35 (0.56)
2005	–0.28 (0.31)	–2.5 (0.26)	–1.4 (0.13)
2006	–0.18 (0.71)	–0.33 (0.80)	0.23 (0.48)
2007	0.71 (0.34)	0.61 (0.48)	0.70 (0.35)
2008	0.64 (0.45)	0.50 (0.61)	0.32 (0.59)
All years	0.57 (0.54)	0.38 (0.63)	0.39 (0.56)

Although the agreement between simulated and observed streamflow is very good for most years, model predictions of percolation are highly dependent upon the uncertainty in other components of the model. For example, errors in simulated ET and to a lesser extent in recorded total P will directly affect simulated percolation below the root zone. Thus, an over-prediction of ET may result in an under-prediction in percolation. This counter balance between ET, *P*, and percolation implies that close agreement between simulated and observed streamflow does not mean the model accurately predicts percolation. Given the detailed studies of SMR at smaller watersheds near PC watershed discussed in the preceding, which showed very good to excellent agreement with distributed observations of perched water tables (Brooks et al. 2007; Lin et al. 2008), it is unlikely, however, that the relative distribution of simulated percolation is misrepresented by the model. Hence, the distribution of simulated percolation taking into account soil thickness and underlying restrictive soil layers is useful for identifying regions having a relatively high potential for recharge to the Wanapum basalt aquifer formation.

Table 3 provides a breakdown of the major water-balance components for the entire watershed. According to the SMR model, 71% of the average annual *P* in the PC watershed evaporates, 4% enters the streams as surface runoff, and 24% percolates vertically below the root zone. The baseflow component of the total percolated water is on average 14% of average annual *P* in the watershed. The potential recharge component is on average 10% of total *P*. This proportioning of baseflow and recharge was determined by matching simulated and observed streamflow at each of the monitoring stations (Fig. 6).

Percolation pathways

One of the assumptions for earlier recharge estimates is spatially uniform percolation over large areas at a more or less constant rate, plus the assumption that water is uniformly available over crystalline rock and basalt and infiltration is uniform. Often a single recharge value is provided for an entire basin, much like that provided in Table 3, which can be understood to imply spatial

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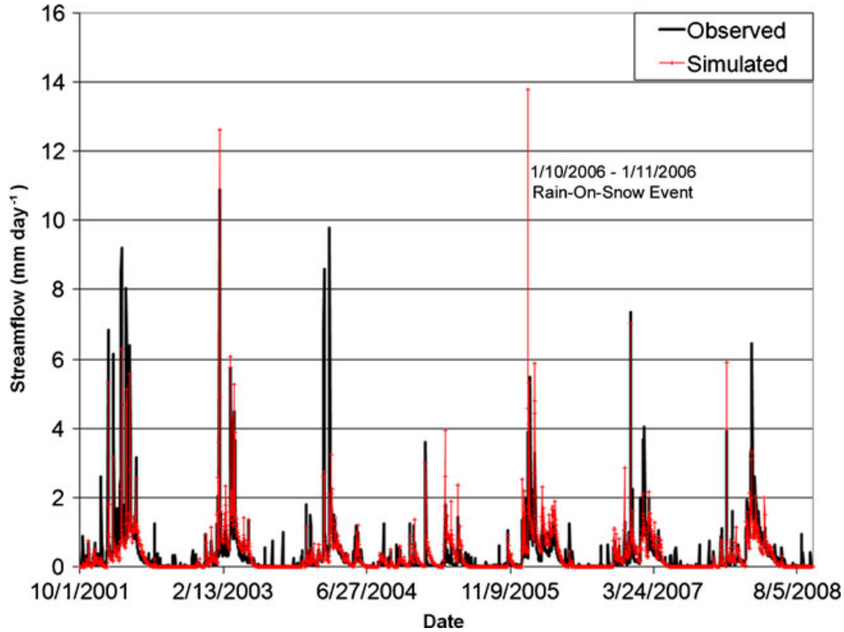

Fig. 5 Simulated and observed daily streamflow (mm) at the outlet of the Paradise Creek watershed at station S_c over the 7–year study period (2002–2008). Date in the format mm/dd/yyyy

uniformity. This study presents evidence that it is highly unlikely in the PC watershed that the dominant flow pathway to the top of Wanapum basalt is one-dimensional vertical flow. The nearly impermeable argillic soils (e.g. Southwick and Taney) and thick clay layers within the Sediments of Bovill act as restrictions to vertical water flow and lead to downslope lateral flow (McDaniel et al. 2001), which redirects water to alluvial soils.

Recharge pathways in PC watershed are initiated predominantly below non-argillic soils and soils not underlain by the Sediments of Bovill. Thus, while ~10% (7 cm) of the total 72 cm of annual *P* over the PC watershed area is lost to deep percolation (Table 3), the recharge potential is likely much larger within the PC watershed where argillic soils or Sediments of Bovill are absent. For example, in the rural and forested area within PC watershed, SMR model results indicate that the potential recharge is ~13% (9.5 cm) of the total 74 cm of annual *P*. However, potential recharge in the forested area located in the higher elevation area on the crystalline rock formation is much larger, on average ~20% (16.5 cm) of the total 86 cm of annual *P*. It is likely that any water that does percolate through the dense argillic layers and clay layers with the Sediments of Bovill is redirected laterally and returns to the stream as baseflow. Indeed, the mass balance confirms that the total potential recharge for the forested, rural, and urban watersheds can be satisfied by recharge coming only from soils which do not have dense argillic layers and are not underlain by the Sediments of Bovill. A plot of cumulative potential recharge, precipitation and runoff versus cumulative watershed area suggests that potentially all recharge occurs in less than half the watershed area, see Fig. 7. The remaining watershed area is composed of soils with restrictive argillic or clay horizons that have negligible percolation and therefore tend to have greater surface runoff.

A breakdown of potential recharge by land type in Fig. 8 suggests that over half the potential recharge in the entire PC watershed (64%) occurs in land areas underlain by crystalline rock (forested and non-forested areas). The forested areas alone, which occupy only 17.5% of the total watershed area and receive only 20.3% of the total volume of precipitation, provide over 37% of potential recharge in

Table 2 Observed and simulated streamflow related to land use. Observations were made at the three monitoring stations (S_a, S_b and S_c)

Year	Forest (S_a)		Rural (S_b)		Urban (S_c)	
	Observed streamflow (cm yr^{-1})	Simulated streamflow (cm yr^{-1})	Observed streamflow (cm yr^{-1})	Simulated streamflow (cm yr^{-1})	Observed streamflow (cm yr^{-1})	Simulated streamflow (cm yr^{-1})
2002	16.2	11.7	10.6	12.4	19.8	13.9
2003	15.4	6.4	9.7	13.3	13.1	16.5
2004	7.8	5.8	9.4	7.7	12.5	10.0
2005	1.0	1.9	1.1	5.9	3.2	7.7
2006	10.1	10.9	11.4	14.6	12.6	17.8
2007	10.8	9.2	14.7	9.8	11.2	11.9
2008	10.5	10.2	15.0	10.5	14.8	12.0
Avg	10.2	8.0	10.3	10.6	12.5	12.8

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Table 3 Simulated average annual water-balance components for 2002–2008 for the PC watershed.

Water-balance component	Average annual depth (cm yr^{-1})	Percent of average annual precipitation (%)
Precipitation	71.6	100
Simulated evapotranspiration	51.1	71
Simulated runoff	2.9	4
Simulated percolation below the root zone	16.9	24
Simulated baseflow	9.9	14
Simulated potential recharge	6.9	10
Simulated streamflow	12.8	18
Observed streamflow	12.5	17

the entire watershed. Figure 9 shows how average annual potential recharge rates are distributed over the entire PC watershed. The greatest potential recharge rates in the basin occur predominantly through alluvial areas in regions underlain directly by basalt. These alluvial areas, however, are only found in a small portion of PC watershed. In summary, the modeling results point towards two predominant recharge pathways: (1) in forested and non-forested areas above crystalline rock and (2) in alluvial areas above basalt. Both these pathways are examined further in the following based on literature review and field observations.

Paleo-channels

As indicated in the preceding, the (thick) lacustrine clay layers of the Sediments of Bovill (part of Latah Formation) act as restrictions for water flow. However, paleo-channels within the Sediments of Bovill may redistribute water vertically and laterally after deep percolation from areas above crystalline rock (see Fig. 8). Evidence of paleo-channels was found by Fairley et al. (2006), who drilled 47 boreholes into near-surface sediments and six boreholes into the Wanapum Formation along the crystalline rock/basalt contact area within PC watershed. They found a consistent pattern of sediment deposition in which heterogeneous sediments with moderate to high permeability (i.e. intermixed fine and coarse material) overlay crystalline rock and basalt. Many boreholes showed elevated moisture contents in the coarse-grained layers. They also observed a 6–7 m thick layer of fine sediment (silt, clay, and sometimes bog) directly above basalt and many of the cracks in the basalt were filled with smectite (swelling) clays. Since these fine sediments have very low hydraulic conductivity, they concluded that vertical infiltration through the Sediments of Bovill into the basalt was highly unlikely.

As part of this study, a relatively large area near a perennial spring in PC watershed was used to investigate the possible paleo-channel pathway within the Sediments of Bovill. Drill logs around this spring revealed two coarse-grained fluvial layers separated and overlain by fine-grained fluvial material, similar to those recorded by Fairley et al. (2006). The lower coarse-grained layers were continuous and connected to the spring, resembling the final section of a paleo-channel. Figure 10 shows a three-dimensional impression of the drill logs.

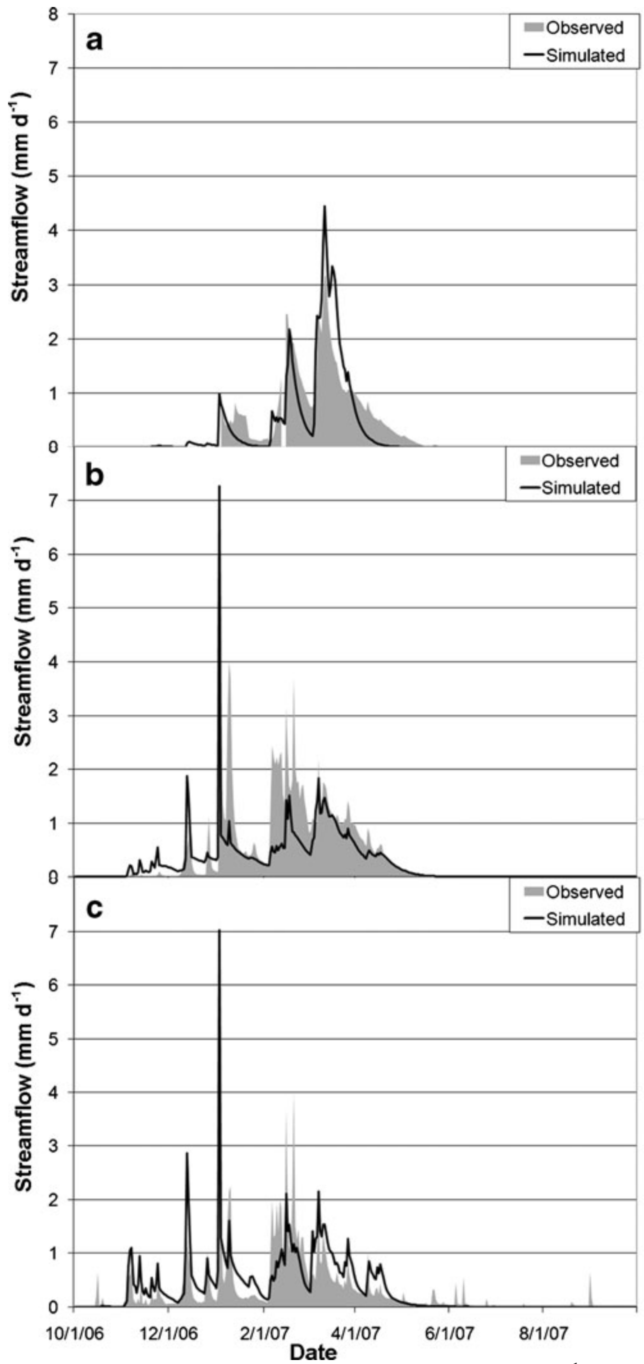

Fig. 6 Simulated and observed daily streamflow (mm d^{-1}) at the three monitoring stations for the 2007 water year, **a** station S_a; **b** station S_b; **c** station S_c

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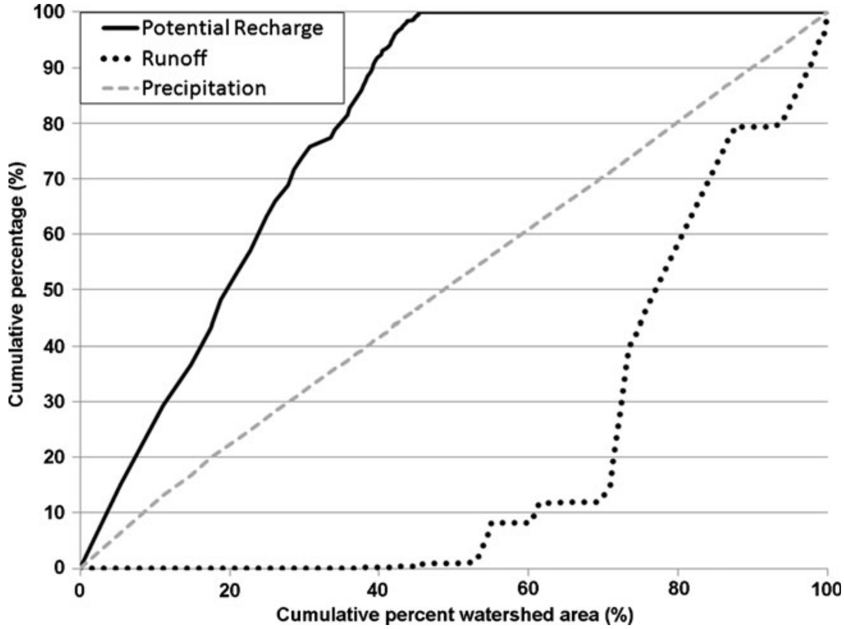

Fig. 7 Simulated cumulative distribution of precipitation, runoff, and potential recharge versus the cumulative percent area

The electrical conductivity (EC) in water samples taken on October 2, 2008 in the lower coarse-grained layer was identical to the EC of the spring water (200±40 μS cm^{-1}). The ECs of groundwater in the surrounding field were much lower (115±18 μS cm^{-1}), and in the upper sandy layer much higher (295±60 μS cm^{-1}). Water from the spring flows at a sustained and rather constant rate of 6 L min^{-1} or 3,000 m^3 yr^{-1}, throughout the year, indicating that the spring may be connected to an upstream water source in the forested part of the PC watershed via a paleo-channel.

During the field survey in 2010, 83 perennial springs and wet spots were located in and around PC watershed (see Fig. 4). Field verification of areas directly upstream of these springs using an auger revealed one to three saturated sand-gravel layers 1–2 m below impermeable argillic layers at a time when no perched water tables were present at shallow depths. Figure 4 shows that the location of these springs and wet spots are located just below the area where the SMR model indicates there is a high potential for recharge (i.e., the forested and non-forested areas above crystalline rock, see Fig. 8), along the interface of crystalline rock/basalt interface.

Further analysis of the 47 borehole data set presented by Fairley et al. (2006) showed that several of the deep saturated coarse layers could connect laterally to the

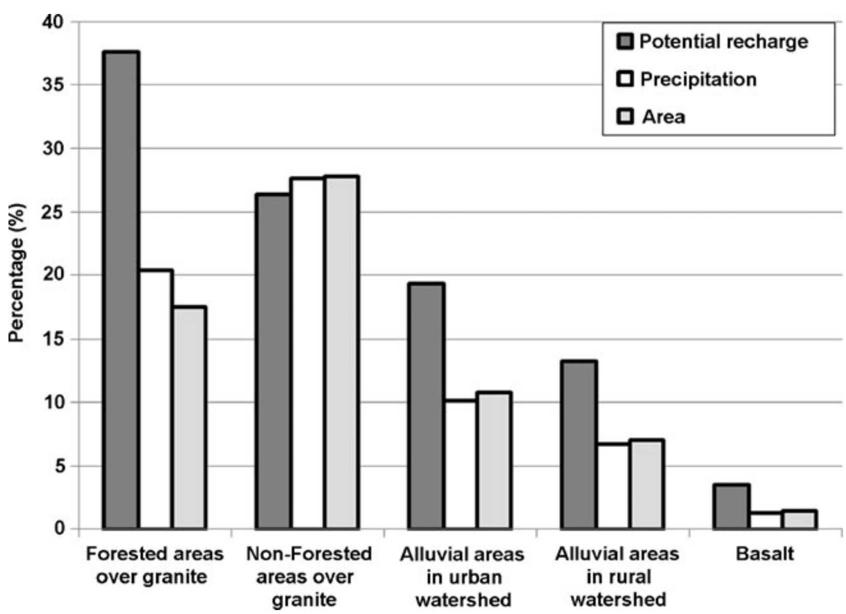

Fig. 8 Spatial distribution of potential recharge and precipitation for major land types in the Paradise creek watershed. Potential recharge percentage is the percentage of total potential recharge in Paradise Creek watershed that occurs in the specific land type. Precipitation percentage is the percentage of total precipitation in Paradise Creek watershed that falls on a specific land type. Area percentage is the percentage of the total watershed composed of a specific land type

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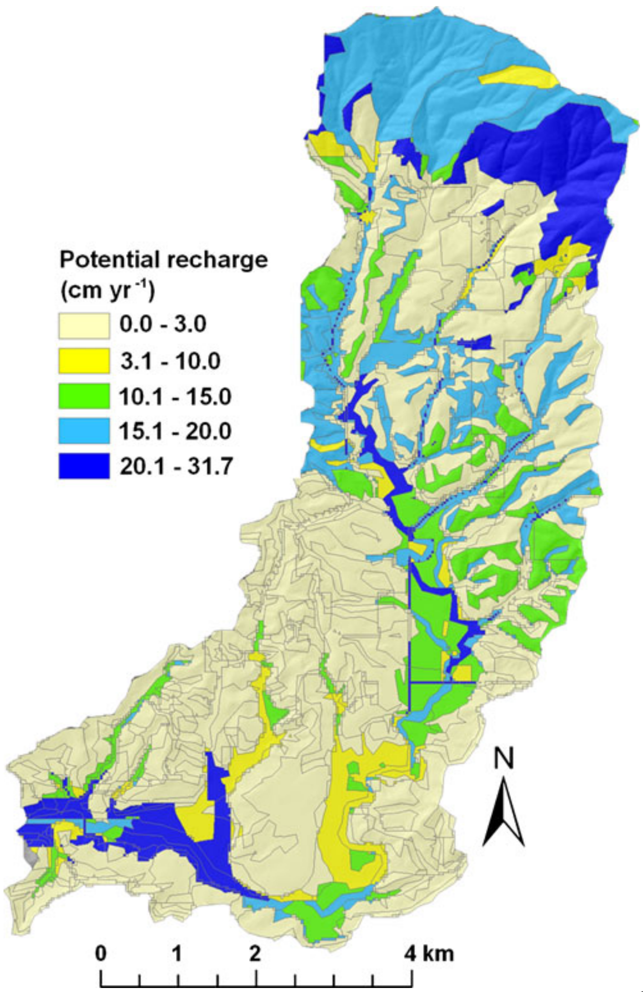

Fig. 9 Simulated average annual net potential recharge in cm yr^{-1} for the 2002–2008 water years throughout the Paradise Creek Watershed

Wanapum basalt formation to the west of the PC watershed. This analysis compared elevations of coarse layers to surface elevations of borehole locations and the surface elevation near the Idaho-Washington border, and assumed that the slope of coarse layers is equal to the land surface slope. Wanapum basalt near the Idaho-Washington border can be found within 1 m of the soil surface (measured at the nearby University of Idaho Groundwater Research Site), and the depth of coarse layers projected from the 47 boreholes to the border ranged from 14 to 25 m below the surface.

Based on the modeling results of this study, the work by Fairley et al. (2006) and this study's own observations, there is a possibility that water enters near-surface sediments above the crystalline rock in the upper areas of the PC watershed, and travels laterally through discontinuous, high permeability sediments. These water pathways are referred to as paleo-channels. Observations (this study) near several springs suggest that some paleo-channels are connected directly to the surface, whereas observations and analysis of saturated coarse-grained sediments in deeper boreholes by Fairley et al. (2006) suggest the possibility that paleo-channels are connected to the basalt interface. The physical process of how paleo-channels connect downslope to where they intersect the land surface as springs, or reach the basalt interface, is a topic for further investigation.

Stream recharge

The findings indicate that recharge pathways in alluvial areas are of small importance. Volume changes in the five seepage meters, installed within a range of 30 m in Paradise Creek near the University of Idaho Groundwater Research Site, measured an average infiltration rate of 6 mm d^{-1}. Maximum and minimum rates measured were 12 and –3 mm d^{-1}, respectively. Given a conservative wetted length of creeks in the basin of 50 km and an average width of 3 m, the annual recharge by the streams will not exceed 330 10^3 m^3 yr^{-1} or 0.3 mm yr^{-1} for the entire Palouse Basin. This amount is very small compared to recharge amounts estimated across the basin.

Spatially, stream recharge can have greater importance in areas where the stream is in closer contact with basalt than where it flows over clays of the Sediments of Bovill. For example, Paradise Creek is in close contact with the underlying basalt near the Groundwater Research Site where the seepage measurements were taken.

Conclusions

A breakdown of the major water-balance components for the entire PC watershed by using the SMR model

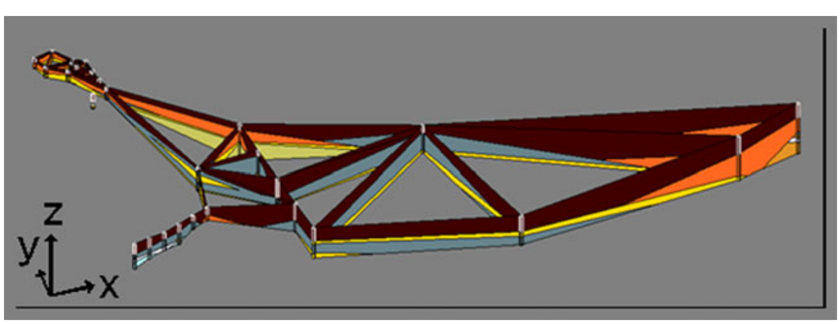

Fig. 10 Transects between drillings near a perennial spring in PC watershed. The spring is at the upper left corner of the figure. *Dark brown* refers to loess; *dark orange* refers to loess with quartz grains; *light orange* is sand (paleo-channel); *yellow* is coarse material (paleo-channel); *blue* clay; *light blue* stands for white sand; *white* is white clay

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indicates that 71% of annual *P* evaporates, about 4% is entering streams as surface runoff, and 24% percolates vertically below the root zone. This study presents evidence that it is highly unlikely that the dominant-flow pathway towards the basalt formations is one-dimensional vertical flow as assumed previously. Nearly impermeable layers within the Sediments of Bovill act as restrictions to vertical infiltration and induce downslope lateral flow. However, these restrictive layers are discontinuous. Soils without these restrictive horizons have very little runoff and consequently high potential recharge.

The SMR model indicated that it is possible that the greatest potential for recharge occurs predominantly through non-argillic soils and soils not underlain by the Sediments of Bovill, pointing to paleo-channels and alluvial sediments as potential recharge pathways. Paleo-channels within the Sediment of Bovill may collect water from the upper forested and non-forested region within PC watershed and transport that water to the lower lying region to feed springs and streams, and possibly recharge the Wanapum aquifer. Field observations around several springs in PC watershed showed strong evidence of paleo-channels that intersect the land surface. Results from seepage meters in Paradise Creek suggest that recharge through alluvial sediments directly to basalt contributes a minor amount to the overall recharge potential in this area.

Findings from this study show the value of incorporating spatially distributed information in water-balance calculations and the spatial distribution of surficial and geologic layers in landscape scale estimation of recharge pathways. These findings are important for the many areas where sediments overlie aquifers. A review of soils in the USA shows that the occurrence of soils with restrictive layers including clay pans and argillic horizons is very common (~82 million ha). Hence, it is expected that the case study presented here will be useful for other cases where groundwater supplies are in jeopardy due to overuse.

Further research is focusing on locating multiple paleo-channels in the region, and identifying chemical signatures between water percolated downward towards the crystalline rock formation and water in springs to determine more conclusively the role of paleo-channels.

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