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The role of perched aquifers in hydrological connectivity and biogeochemical processes in vernal pool landscapes, Central Valley, California

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Abstract:

Relatively little is known about the role of perched aquifers in hydrological, biogeochemical, and biological processes of vernal pool landscapes. The objectives of this study are to introduce a perched aquifer concept for vernal pool formation and maintenance and to examine the resulting hydrological and biogeochemical phenomena in a representative catchment with three vernal pools connected to one another and to a seasonal stream by swales. A combined hydrometric and geochemical approach was used. Annual rainfall infiltrated but perched on a claypan/duripan, and this perched groundwater flowed downgradient toward the seasonal stream. The upper layer of soil above the claypan/duripan is ~0·6 m in thickness in the uplands and ~0·1 m in thickness in the vernal pools. Some groundwater flowed through the vernal pools when heads in the perched aquifer exceeded ~0·1 m above the claypan/duripan. Perched groundwater discharge accounted for 30–60% of the inflow to the vernal pools during and immediately following storm events. However, most perched groundwater flowed under or around the vernal pools or was recharged by annual rainfall downgradient of the vernal pools. Most of the perched groundwater was discharged to the outlet swale immediately upgradient of the seasonal stream, and most water discharging from the outlet swale to the seasonal stream was perched groundwater that had not flowed through the vernal pools. Therefore, nitrate-nitrogen concentrations were lower (e.g. 0·17 to 0·39 mg l^{-1}) and dissolved organic carbon concentrations were higher (e.g. 5·97 to 3·24 mg l^{-1}) in vernal pool water than in outlet swale water discharging to the seasonal stream. Though the uplands, vernal pools, and seasonal stream are part of a single surface-water and perched groundwater system, the vernal pools apparently play a limited role in controlling landscape-scale water quality.

KEY WORDS wetlands; vernal pools; perched aquifers; claypans; duripans; connectivity

INTRODUCTION

Perched aquifers have long been recognized, but have infrequently been studied (Fetter, 2001). Perching layers reduce rates of recharge to underlying regional aquifers (Bagtzoglou *et al.*, 2000) and redirect subsurface water flow along horizontal flowpaths (Driese *et al.*, 2001). Where perching layers outcrop or intersect the ground surface, perched aquifers can discharge water to springs (Rabbo, 2000; Amit *et al.*, 2002), streams (von der Heyden and New, 2003), and wetlands (O'Driscoll and Parizek, 2003; von der Heyden and New, 2003). Where perching layers completely underlie wetlands and lakes, surface-water levels can remain relatively stable even as regional water tables decline (Pirkle and Brooks, 1959; Auler, 1995). Still, relatively little is known about how perched aquifers regulate hydrological, biogeochemical, and biological processes in wetland ecosystems in general and vernal pool landscapes in particular.

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Vernal pools are small depressional wetlands that pond for portions of the wet season, then drain and dry in the late wet and early dry seasons (Stebbins, 1976). Vernal pools occur in southern Oregon, California, northern Baja California, and in other seasonal climates of the world (Riefner and Pryor, 1996). Vernal pools typically range from 50 to 5000 m^2 in area (Mitsch and Gosselink, 2000) and from 0·1 to 1 m in depth (Hanes and Stromberg, 1998; Brooks and Hayashi, 2002).

Vernal pools occur on many geological surfaces. However, in all cases vernal pools are underlain by low-permeability layers such as claypans or hardpans (e.g. silica-cemented duripans; Nikiforoff, 1941; Hobson and Dahlgren, 1998; Smith and Verrill, 1998), clay-rich soils (Smith and Verrill, 1998), mudflows or lahars (Jokerst, 1990; Smith and Verrill, 1998), or bedrock (Weitkamp *et al.*, 1996). In all cases, vernal pool surface water and/or groundwater are perched above regional water tables.

Vernal pools are associated with specific types of geological formations, landforms, and soils (Smith and Verrill, 1998). Therefore, vernal pools tend to be clustered at the landscape scale. Currently, these vernal pool landscapes cover more than 4100 km^2, or $\sim$5% of the total land surface of the Central Valley, California (Holland, 1998). In these vernal pool landscapes, vernal pools that are potentially jurisdictional wetlands typically comprise less than 10% of the total land surface. In many of these vernal pool landscapes, surface water flows through ephemeral or seasonal swales to other vernal pools and ultimately to seasonal streams. Therefore, vernal pool landscapes comprise the upper watershed position of many stream systems that originate in the Central Valley, California.

Vernal pools are best known for the biological functions that they perform. Vernal pools are among the last remaining California ecosystems still typically dominated by native flora (Barbour *et al.*, 1993). Many vernal pool floral and macroinvertebrate species are endemic, and some vernal pool floral and macroinvertebrate species are rare (Holland and Jain, 1988; Keeley and Zedler, 1998). Therefore, vernal pools are critical components of regional biological conservation efforts. Vernal pool flora are sensitive to variations in inundation duration (Holland and Jain, 1984; Bauder, 2000), and vernal pool macroinvertebrates are sensitive to variations in inundation duration (Gallagher, 1996), salinity (Gonzales *et al.*, 1996), and possibly several other water chemistry constituents (e.g. pH, dissolved oxygen, and nutrients). It is therefore surprising that few studies of vernal pool hydrogeology and biogeochemistry have been conducted (Hanes and Stromberg, 1998; Brooks and Hayashi, 2002).

This project is part of a larger interdisciplinary project, the overall objective of which is to provide public and private sector land managers with information to be used in making informed land-use decisions in vernal pool landscapes. Vernal pools typically are treated as isolated depressions that pond largely due to direct precipitation and drain and dry largely due to evapotranspiration. The specific objective of this study is to show that this conceptual model may be largely incorrect for vernal pools underlain by a claypan or duripan, perhaps the most common type of vernal pool in the Central Valley, California (Smith and Verrill, 1998). Rather, many or most of these vernal pools appear to be supported by perched aquifers, wherein seasonal surface water and perched groundwater hydrologically and biogeochemically connect uplands, vernal pools, and streams at the catchment scale. To our knowledge, this is the first study to document the importance of perched aquifers as hydrological and biogeochemical pathways in vernal pool landscapes.

SITE DESCRIPTION

Location and setting

This study was conducted at Mather Regional Park in the southern Sacramento Valley near Sacramento, California (Figure 1). The study site is a 0·1 km^2 catchment with three vernal pools connected to one another and to a seasonal stream by ephemeral or seasonal swales. The three vernal pools cover $\sim$2% of the catchment area. Elevations of the upper catchment divide, the vernal pools, and the outlet swale just upgradient of the seasonal stream are $\sim$47 m, 43 m, and 39 m above mean sea level respectively. Slope, though locally variable, is $\sim$0·02. The site was grazed during the late 19th and early 20th centuries, but it has been used largely as

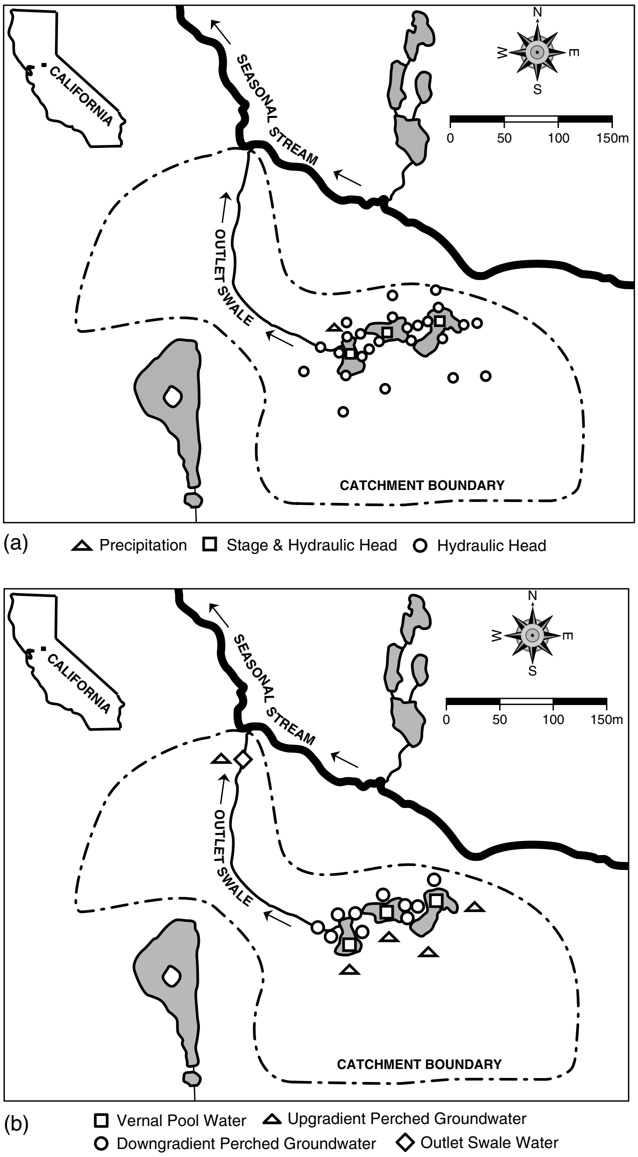

Figure 1. Local setting showing (a) the hydrometric instrumentation locations and (b) the surface water and perched groundwater sample collection locations. The study site is the delineated catchment with the three vernal pools connected to one another and to the seasonal stream by swales. Elevations of the upper catchment divide, the vernal pools, and the confluence of the outlet swale and the seasonal stream are ~47 m, 43 m, and 39 m respectively above mean sea level

open space since being annexed for military use in 1918 and becoming part of Mather Regional Park in 1995. The study site is generally representative of regional vernal pool landscapes.

Climate

The climate is Mediterranean, with mild, wet winters and hot, dry summers (Western Regional Climate Center data for Sacramento Executive Airport for the years 1971–2000). Mean maximum, minimum, and daily temperatures are 23·0 °C, 9·0 °C, and 16·0 °C respectively. Mean annual precipitation is 455 mm, with

~96% falling during the months of October–May. However, annual precipitation is variable, with the standard deviation around the mean annual precipitation being 174 mm. Annual precipitation during the 2003 water year (October 2002–September 2003), in which the study took place, was 388 mm, with 100% falling during the months of October–May. These are within normal ranges, so the 2003 water year in which the study took place was a typical water year.

Geology and soils

The study site is located on the Fair Oaks Formation, an alluvial deposit composed primarily of quartzite and amphibole cobbles and boulders in a granitic sand matrix (Shlemon, 1972). The absolute age of the Fair Oaks Formation is unknown, though younger deposits occur in the same stratigraphic interval as sediments in the San Joaquin Valley that have been radiometrically dated at about 600 000 years old (Shlemon, 1972).

The Fair Oaks Formation is capped with well-developed soils of the Red Bluff and Redding series (Shlemon, 1972; Tugel, 1993). Red Bluff soils (Ultic Palexeralfs) occur on summit positions, and Redding soils (Abruptic Durixeralfs) occur on shoulder, backslope, footslope, and toeslope positions (Tugel, 1993). Field investigations indicate that soils at the study site are predominantly of the Redding series. The upper layer of the soil has a gravelly loam texture. The upper layer is underlain by a claypan composed of ~50% clay and is immediately underlain by a duripan composed of gravel and cobbles in a granitic sand matrix cemented by silica and iron (Tugel, 1993). Redding soils typically have hydraulic conductivities of $10^{-1} - 10^{0}$ m day^{-1} in the upper layer of the soil and $<10^{-2}$ m day^{-1} in the claypan/duripan (Tugel, 1993). Values for the upper layer of soil on the study site were not confirmed, though slug tests indicated that hydraulic conductivities of the claypan/duripan on the study site are $\leq 10^{-2}$ m day^{-1}. The claypan/duripan is laterally extensive throughout the catchment. The vernal pools appear to be deflation basins, ~0·5 m in depth. Multiple hand-augered holes and tile probe penetrations indicate that the upper layer of soil above the claypan/duripan is ~0·6 m in thickness in the uplands and ~0·1m in thickness in the vernal pools (Figure 2).

Vegetation

Vegetation is typical of vernal pools in the Central Valley, California, with primarily native annual grasses and forbs and a ~1 cm layer of pool-bed algae. Species composition is typical of Northern Hardpan Vernal

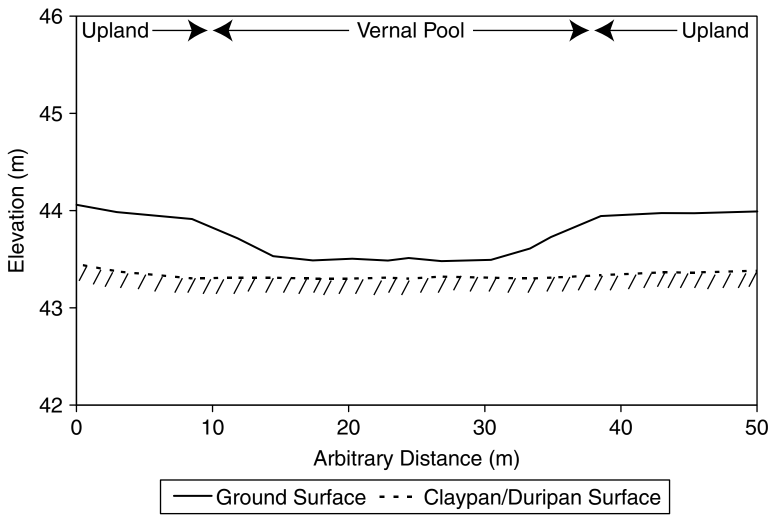

Figure 2. Cross-section running east–west across the middle pool showing the elevation of the ground surface and the underlying claypan/duripan in metres above mean sea level. Vertical exaggeration is ~7×

Pool series (Sawyer and Keeler-Wolf, 1995). Typical species include the native species pale spikerush (*Eleocharis macrostachya*), wooly marbles (*Psilocarphus brevissimus* var. *brevissimus*), and Vasey's coyote-thistle (*Eryngium vaseyi*). The surrounding uplands are characterized by moderate coverage with primarily non-native annual grasses. Species composition is typical of California Annual Grassland series (Sawyer and Keeler-Wolf, 1995). Species commonly include the non-native species soft chess (*Bromus hordeaceous*), ripgut brome (*Bromus diandrus*), and wild oat (*Avena fatua*).

METHODS

A combined hydrometric and geochemical approach was used in this study. Hydrometric data included precipitation depths, vernal pool stages, and groundwater hydraulic heads, and geochemical data included dissolved constituent concentrations and stable isotope ratios.

Field measurements

Precipitation was measured in the catchment, stages were measured in the three vernal pools, and hydraulic heads were measured at 28 piezometer nests (Figure 1). Precipitation was measured continuously with a tipping-bucket rain gauge, and stages in the three vernal pools were measured hourly with pressure transducers and dataloggers. Each piezometer nest had three piezometers with 2·5 cm inside diameters and with open ends $\sim$0·6, 1·2, and 1·8 m below the ground surface. The shallow piezometers (0·6 m) were either above or in the upper part of the claypan/duripan. The middle piezometers (1·2 m) and deep piezometers (1·8 m) were either below or in the lower part of the claypan/duripan. Piezometers were installed using a Geoprobe hydraulic-powered direct push system by removing cores and pushing the piezometers into the open boreholes. The inside diameters of the boreholes were slightly smaller than the outside diameters of the piezometers, which ensured a tight fit. Bentonite surface seals were emplaced around the outside of the piezometers. Hydraulic heads at the 28 piezometer nests were measured at least weekly with a manually operated water-level meter. Time-lag errors can arise in piezometers screened in low-conductivity formations (Hanschke and Baird, 2001). The potential for time-lag errors was minimized during data collection by using small-diameter standpipes so that the volumes of water required to flow between the formations and the standpipes were minimal. The potential for time-lag errors was further minimized during data interpretation by interpreting time-series data over the course of days and weeks, which eliminated time-lag errors that occurred over the course of hours.

Water sample collection

Surface water samples were collected at four locations, while perched groundwater samples were collected at 15 locations (Figure 1). Vernal pool water samples were collected from each of the vernal pools, while outlet swale water samples were collected just upgradient of the seasonal stream. Perched groundwater samples were collected from above the claypan/duripan throughout the catchment. Perched groundwater samples collected upgradient of the vernal pools and upgradient of the outlet swale are hereafter referred to as upgradient perched groundwater, while perched groundwater samples collected downgradient of at least one vernal pool are hereafter referred to as downgradient perched groundwater (Figure 1).

Surface water samples were collected during and immediately following storms in December 2002 and March 2003, and surface water and perched groundwater samples were collected once between storms in early March 2003. Each surface water sample was a composite of two surface water subsamples. Piezometers were not available at every groundwater sampling location, and the small-diameter piezometers did not always contain enough water to comprise meaningful samples, so perched groundwater samples were collected from uncased boreholes. Boreholes were hand-augered, perched groundwater was purged until electrical conductivity stabilized, perched groundwater samples were collected, and boreholes were refilled with native materials. A total of 50 surface water and 15 perched groundwater samples were collected.

Analytical procedures

Electrical conductivity on each surface water and perched groundwater sample was measured in the field at least weekly while conducting regular hydrometric monitoring (Thermo Orion Model 116). All samples, except samples used for deuterium (D) and oxygen-18 (^{18}O) analyses, were filtered through 0·2 μm polycarbonate membranes prior to analysis. Samples were stored at 4 °C through completion of analyses. Total alkalinity, as an estimate of carbonate alkalinity, was measured in the laboratory by titration of samples with 0·25 M H_2SO_4 (Rhoades, 1982). Major cations (i.e. sodium, potassium, calcium, magnesium, and ammonium) and anions (i.e. chloride, sulphate, nitrate, and phosphate) were measured on a Dionex 500x ion chromatograph. Silica was measured by the molybdosilicate method on a Lachat Quik-Chem 8000 autoanalyser (Clesceri *et al.*, 1998). Dissolved organic carbon (DOC) was measured by the UV–persulphate oxidation/IR detection using a Tekmar-Dohrmann Phoenix 8000 TOC analyser (Clesceri *et al.*, 1998). Analytical precisions were typically better than ±5% for all analyses.

Surface water and perched groundwater samples that were collected between storms in early March 2003 were also analysed for D and ^{18}O, which were measured on a Finnigan 251 isotope ratio mass spectrometer using a constant-temperature water bath for equilibration of aqueous samples. For D analyses, 5 ml samples were equilibrated with H_2 in the presence of a platinum catalyst (Coplen *et al.*, 1991). For ^{18}O analyses, 5 ml samples were equilibrated with CO_2 (Epstein and Mayeda, 1953). Equilibration temperature was 18·1 °C, and equilibration times were 120 min and 600 min for D and ^{18}O respectively. Analytical precisions were ±1·0‰ and ±0·05‰ for D and ^{18}O analyses respectively.

D and ^{18}O are reported in the conventional δ notation:

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 10^3$$

where R is the D/H ratio or $^{18}O/^{16}O$ for D or ^{18}O respectively (Craig, 1961). The resulting sample values of δD and $\delta^{18}O$ are reported in per mil deviation relative to Vienna Standard Mean Ocean Water (VSMOW) and, by convention, the δD and $\delta^{18}O$ of VSMOW are set at 0‰ VSMOW (Gonfiantini, 1978).

Mass-balance mixing modelling

The relative contributions of direct precipitation and upgradient perched groundwater to vernal pool water during and immediately following storms in December 2002 and March 2003 were estimated using three-end, mass-balance mixing models with silica as a conservative natural tracer. Silica in natural water originates primarily from contact between natural water and silicate and clay minerals or decomposed plant materials (Iler, 1979). Therefore, silica was used as a conservative, natural tracer to distinguish between direct precipitation and upgradient perched groundwater. The mass balance mixing model was

$$[SiO_2]_s = f_{vp}[SiO_2]_{vp} + f_p[SiO_2]_p + f_{gw}[SiO_2]_{gw}$$

$$f_{pvp} + f_p + f_{gw} = 1$$

where $[SiO_2]$ and f are the silica concentrations and proportions that sum to one respectively, and where the subscripts 's', 'vp', 'p', and 'gw' refer to a given sample of vernal pool water during or immediately following a storm event, vernal pool water immediately prior to a storm event, direct precipitation, and upgradient perched groundwater respectively. This is a mathematically indeterminate system of two equations in three unknowns for which there is no unique solution. However, mass-balance conservation can still be used to find multiple combinations of end-member proportions that are feasible solutions to the system of equations (Phillips and Gregg, 2003). The primary assumptions of the three-end, mass-balance mixing model were that a given sample was an instantaneous mix of the three end members and that silica was conservative in the vernal pool water column over short time periods.

Results of the three-end, mass-balance mixing models were corroborated by water budgets for one vernal pool during and immediately following the storms in December 2002 and March 2003. In both cases, surface water flux was negligible and the simplified water budget was

$$P - ET + \Delta GW = \Delta S$$

where P is direct precipitation, ET is evapotranspiration, ΔGW is the net groundwater flux into the vernal pool (i.e. groundwater inflow minus groundwater outflow), and ΔS is the change in storage (i.e. change in vernal pool stage). Evapotranspiration estimates were computed by a modified Penman equation (Pruitt and Doorenbos, 1977) using data from a station located ~10 km from the study site in an environment with similar characteristics, e.g. same landform, soils, vegetation, and fetch (California Irrigation Management System Station No. 131). The simplified water budget was solved for groundwater flux, and groundwater flux was expressed as the proportion of the change in storage during and immediately following the December 2002 and March 2003 storms.

The relative contributions of vernal pool water and upgradient perched groundwater to downgradient perched groundwater and outlet swale water between storms in early March 2003 were estimated using a two-end, mass-balance mixing model with $\delta^{18}O$ as a conservative natural tracer. The mass-balance mixing model was run for a typical day in early March 2003 when vernal pool stages were moderately high and surface water was flowing out of the middle and lower vernal pools and discharging to the seasonal stream. $\delta^{18}O$ in natural water varies as a function of conservative mixing, evaporation, or high-temperature and/or long-term water–rock interaction and does not vary as a function of uptake by vegetation (Gat, 1996; Clark and Fritz, 1997). Therefore, $\delta^{18}O$ was used as a conservative, natural tracer to distinguish between vernal pool water and upgradient perched groundwater. The mass-balance mixing model was

$$\delta^{18}O_s = f_{vp}\delta^{18}O_{vp} + f_{gw}\delta^{18}O_{gw}$$

$$f_{vp} + f_{gw} = 1$$

where $\delta^{18}O$ and f are the ^{18}O signatures and proportions that sum to one respectively, and where the subscripts 's', 'vp', and 'gw' refer to a given sample of downgradient perched groundwater or outlet swale water, vernal pool water, and upgradient perched groundwater respectively. The primary assumptions of the two-end, mass-balance mixing model were that a given sample was an instantaneous mix of the two end members and that fractionation during mixing was negligible.

RESULTS

Physical hydrology

Approximately 15 cm of rain fell between November 5 and December 16 prior to the initiation of ponding in the vernal pools, indicating that early wet-season rainfall largely infiltrated and augmented soil moisture (Figure 3). Approximately 75% of the shallow (0·6 m) piezometers had free (i.e. standing) groundwater during or immediately following the early wet-season storm events. Approximately 70% of the middle (1·2 m) piezometers and 95% of the deep (1·8 m) piezometers remained dry for many weeks following the early wet-season storm events, and ~30% of the middle and deep piezometers remained dry for the entire period of record. The regional water table was ~30 m below the ground surface throughout the period of study (California Department of Water Resources data for California State Well Nos. 08N06E17H001 and 08N06E09Q004M). Therefore, shallow groundwater was perched on the claypan/duripan. Throughout the observation period, hydraulic heads measured in the shallow piezometers generally followed the overall gradient of the land surface, with heads being highest in the upper parts of the catchment and lowest in the

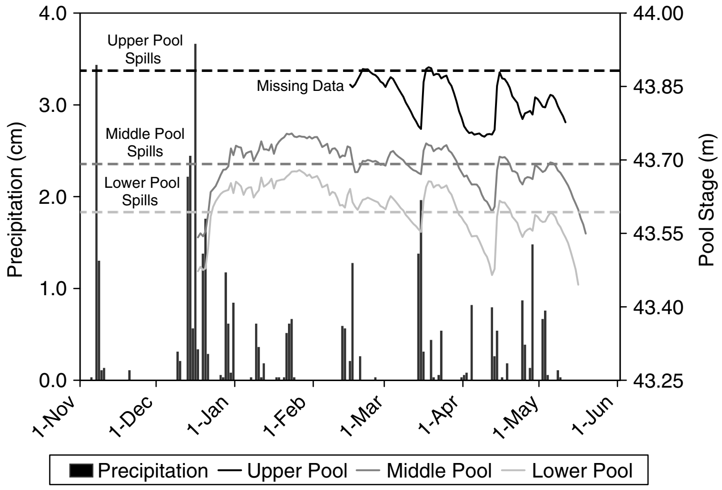

Figure 3. Daily precipitation and vernal pool stages in metres above mean sea level. Horizontal dashed lines indicate the stages at which surface water flows out of each vernal pool via an outlet swale

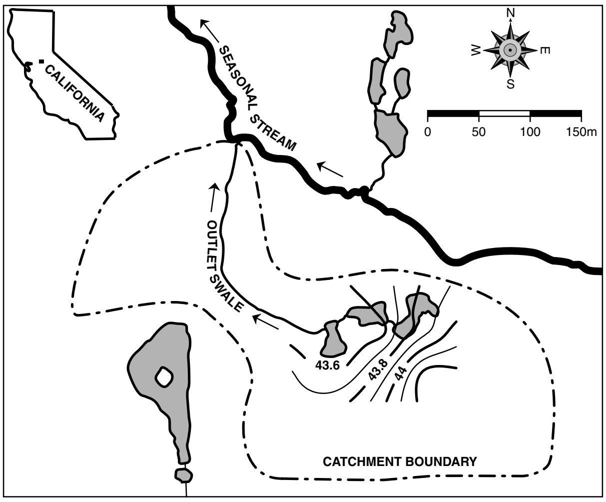

Figure 4. Hydraulic head above the claypan/duripan in the seasonal, perched groundwater system in metres above mean sea level. Stages in the vernal pools were neglected in generating these contours. Data are from late February 2003, and are similar to data from earlier and later in the wet season

lowest parts of the catchment and perched groundwater flowing through, under, or around the vernal pools (Figure 4).

Once the soils above the claypan/duripan were saturated, subsequent rainfall caused the vernal pools to fill, beginning December 17 (Figure 3). A datalogger failure on the upper vernal pool resulted in missing data during the early wet season, but field observations indicated that the upper vernal pool had standing water for slightly less than 150 days. The middle and lower vernal pools had standing water for 154 and 151 days respectively. Surface water outflows from the upper vernal pool were ephemeral, and the surface water connection between the upper and middle vernal pools was maintained for ~10% of the days during which vernal pool water was present. Surface water outflows from the middle and lower vernal pools were seasonal, and the surface water connections between the middle and lower vernal pools and the lower vernal pool and the seasonal stream were maintained for ∼60% of the days during which vernal pool water was present.

During storm events, vernal pool stages began to rise on the same day as the initiation of rainfall and continued to rise until 1 to 2 days after the cessation of rainfall. At no time was overland flow observed delivering water from the uplands to the vernal pools. Therefore, surface water inflows to the upper vernal pool were negligible. The connecting swales are similar in roughness, geometry, and slope, so connecting swale discharge is proportional to vernal pool stage above the outlet. Vernal pool stage above the outlet in the middle vernal pool always equalled or exceeded vernal pool stage above the outlet in the upper vernal pool, with the difference ranging from 0 to 4 cm (Figure 3). Vernal pool stage above the outlet in the lower vernal pool always equalled or exceeded vernal pool stage above the outlet in the middle vernal pool, with the difference ranging from 0 to 2 cm (Figure 3). Therefore, surface water outflows typically equalled or exceeded surface water inflows in each of the vernal pools, indicating that perched groundwater discharge from the uplands to the vernal pools was largely responsible for the observed continued rise in vernal pool stages in the days following the cessation of rainfall.

Chemical hydrology and mass-balance mixing models

Silica concentrations in rainfall are typically $<0{\cdot}2$ mg l^{-1} (McCutcheon *et al.*, 1993), and are typically $<0{\cdot}3$ mg l^{-1} in nearby watersheds (Holloway and Dahlgren, 2001). Therefore, silica concentrations of rainfall were assumed to be negligible, whereas silica concentrations of the perched groundwater upgradient of the vernal pools and upgradient of the outlet swale were ∼22 mg l^{-1} (Table I). The silica data can, therefore, be used to elucidate the roles of direct precipitation and perched groundwater discharge during the early- and late-season storm events. Silica concentrations in the vernal pool water began to rise on the same day as the initiation of rainfall and remained level or continued to rise until 1 to 2 days after the cessation of rainfall (Figure 5). Therefore, these data again indicate that perched groundwater was discharging from the uplands to the vernal pools during and immediately following the storm events.

The three-end, mass-balance mixing models indicate that discharge of upgradient perched groundwater to the vernal pools accounted for 35–60% of the inflow to the vernal pools during and immediately following the first rainfall of the early-season storm event and 40–50% of the inflow to the vernal pools during and immediately following the late-season storm event (Table II). Water budget calculations generally corroborate these results. During and immediately following the first rainfall of the early-season rainfall event, direct precipitation was 8·65 cm, evapotranspiration was 0·54 cm, and the change in vernal pool stage was 11·41 cm. Therefore, groundwater flux was 3·30 cm, or approximately 29% of the change in storage. During and immediately following the late-season storm event, direct precipitation was 9·22 cm, evapotranspiration was 1·41 cm, and the change in vernal pool stage was 12·19 cm. Therefore, groundwater flux was 4·38 cm, or approximately 36% of the change in storage.

When plotted in a Piper diagram (Piper, 1944), all surface water and perched groundwater samples plot as Ca–Mg–Na–HCO_3 water types (Figure 6). This is typical of regional rainfall of recent origin that has undergone slight alteration due to short-term contact with soils or sediments (Criss and Davisson, 1996). When plotted on a δD versus $\delta^{18}O$ scatterplot, surface water and perched groundwater samples collected between storms in early March 2003 plot on a line with a slope of 3·8 that intersects the global meteoric water line at −7·5‰ (Figure 7). This is typical of the weighted average of regional rainfall that has undergone varying degrees of fractionation due to evaporation (Criss and Davisson, 1996).

Only surface water and perched groundwater samples collected between storms in early March 2003 were used in the two-end, mass-balance mixing model analysis. These data were collected on a typical day: it was not raining, though there had been moderate amounts of rain in the previous weeks; there was no surface water outflow from the upper vernal pool; and there were moderate surface water outflows from the middle and lower vernal pools. Vernal pool water had mean δD and $\delta^{18}O$ of −32·1‰ and −2·6‰ VSMOW respectively, whereas upgradient perched groundwater had mean δD and $\delta^{18}O$ of −43·3‰ and

Table I. Geochemical and isotopic characteristics of all surface water and perched groundwater samples. Surface water samples were collected prior to, during, and following storms in December 2002 and March 2003, and surface water and perched groundwater samples were collected once between storms in early March 2003. Upgradient perched groundwater samples were collected upgradient of the vernal pools and upgradient of the outlet swale, and downgradient perched groundwater samples were collected downgradient of at least one vernal pool

	Surface water				Perched groundwater			
	Vernal pools ($n = 42$)		Outlet swale ($n = 8$)		Upgradient ($n = 5$)		Downgradient ($n = 10$)	
	$\bar{x}$	s^2	$\bar{x}$	s^2	$\bar{x}$	s^2	$\bar{x}$	s^2
EC (μS cm^{-1})	52	16	41	11	56	11	71	11
Na (mg l^{-1})	3·4	0·5	3·1	0·4	4·4	0·6	5·5	1·4
K (mg l^{-1})	0·9	0·4	0·4	0·2	0·4	0·1	0·6	0·7
Mg (mg l^{-1})	2·2	0·2	2·3	0·3	2·7	0·7	3·3	0·7
Ca (mg l^{-1})	4·8	0·6	4·3	0·6	4·9	1·2	6·1	1·1
Cl (mg l^{-1})	3·0	1·0	2·1	1·2	4·4	1·6	3·9	1·9
SO_4 (mg l^{-1})	2·7	1·3	2·5	0·4	3·4	1·0	4·5	2·1
$HCO_3 + CO_3$(mg l^{-1})	21·5	2·4	19·7	2·5	22·5	6·6	30·6	5·2
SiO_2 (mg l^{-1})	9·8	3·4	14·5	1·3	22·2	5·3	22·9	6·0
NO_3-N (mg l^{-1})[a]	0·17	0·24	0·39	0·54	0·21	0·44	0·01	0·02
NH_4-N (mg l^{-1})[b]	0·03	0·05	0·01	0·01	0·01	0·02	0·02	0·06
PO_4-P (mg l^{-1})	<0·010	<0·010	<0·010	<0·010	<0·010	<0·010	<0·010	<0·010
DOC (mg l^{-1})	5·97	1·57	3·24	1·09	1·24	0·36	2·24	0·66
δD (‰ VSMOW)[c]	−32·1	1·7	−46·9	—[d]	−43·2	2·6	−38·8	2·3
δ^{18}O (‰ VSMOW)[c]	−2·6	0·6	−6·0	—[d]	−5·7	0·3	−4·7	0·5

[a] Below NO_3-N detection limit of 0.006 mg l^{-1} in 20 of 42 vernal pool samples, one of eight outlet swale samples, three of five upgradient perched groundwater samples, and seven of ten downgradient perched groundwater samples.
[b] Below NH_4-N detection limit of 0.010 mg l^{-1} in 28 of 42 vernal pool samples, seven of eight outlet swale samples, four of five upgradient perched groundwater samples, and nine of ten downgradient perched groundwater samples.
[c] δD and δ^{18}O analysed on only 3 of 42 vernal pool and one of eight outlet swale water samples.
[d] Insufficient sample numbers to calculate standard deviation.

−5·7‰ VSMOW respectively (Figure 7). These were the two end members from which downgradient perched groundwater and outlet swale water were assumed to have originated. Downgradient perched groundwater had mean δD and δ^{18}O of −38·8‰ and −4·7‰ VSMOW respectively, which was intermediate between the two end members (Figure 7). On average, downgradient perched groundwater was composed of ~30% of the vernal pool water end member and ~70% of the upgradient perched groundwater end member (Table III). Outlet swale water had a δD and δ^{18}O of −46·9‰ and −6·0‰ VSMOW respectively, similar to the upgradient perched groundwater end member (Figure 7). Therefore, contributions from the vernal pool water end member to the outlet swale water were negligible (Table III).

Electrical conductivity of the vernal pool water was relatively low, averaging 44 μS cm^{-1} and ranging from 25 to 66 μS cm^{-1} (Figure 8). Electrical conductivity tended to decline throughout most of the period during which vernal pool water was present, suggesting a progressive flushing of solutes. Electrical conductivity increased sharply only when small volumes of vernal pool water remained, e.g. when the upper vernal pool temporarily dried during a prolonged dry period in late March and when the upper, middle, and lower vernal pools permanently dried at the end of the wet season in late May.

Biogeochemistry

During the early-season storm event, nitrate-nitrogen concentrations in vernal pool water tended to increase immediately in response to the initiation of rainfall and the subsequent increase in perched groundwater

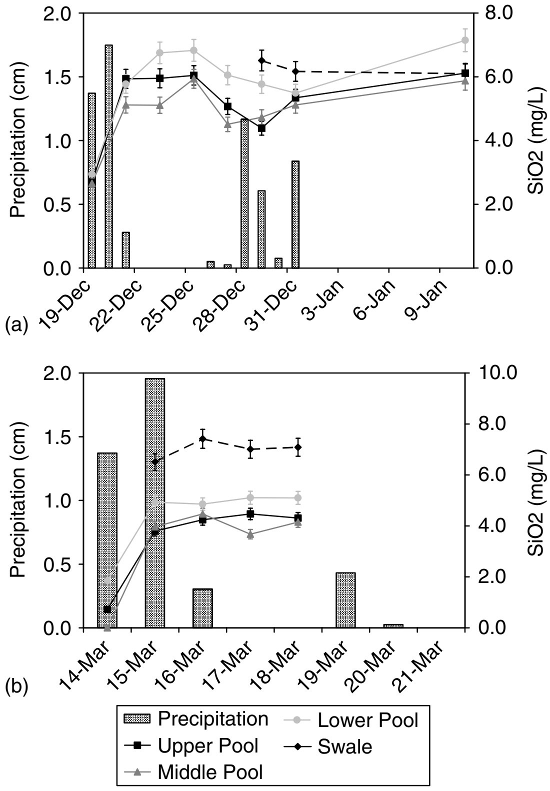

Figure 5. Daily precipitation and silica concentrations in vernal pool water during the (a) early- and (b) late-season storm events

Table II. Three-end, mass-balance mixing model results showing the relative contribution of upgradient perched groundwater to inflow to the vernal pools during and immediately following the December 2002 and March 2003 storms. Three-end, mass-balance mixing models were computed daily. This is a mathematically indeterminate system of two equations in three unknowns for which there is no unique solution, so there were multiple combinations of end member proportions that were feasible solutions to the system of equations. Proportions are presented as the minimum and maximum values computed over the course of the storms

Storm	Upper vernal pool	Middle vernal pool	Lower vernal pool
December 2002	0·35–0·60	0·35–0·50	0·50–0·60
March 2003	0·40	0·40	0·40–0·50

discharge, then decline steadily in response to the cessation of rainfall and the subsequent decrease in perched groundwater discharge (Figure 9). During the late-season storm event, nitrate-nitrogen concentrations in vernal pool water were below detection limits (i.e. [NO_3-N] $<0{\cdot}006$ mg l^{-1}). At all times during the early- and late-season storm events, nitrate-nitrogen concentrations in the outlet swale water were higher than nitrate-nitrogen concentrations in the vernal pools (Figure 9). Overall, nitrate-nitrogen concentrations in the vernal pool water and outlet swale water were 0·17 mg l^{-1} and 0·39 mg l^{-1} respectively (Table I) and were significantly different from one another ($p = 0{\cdot}04$). Ammonium-nitrogen concentrations were always low and typically below detection limits ([NH_4-N] $<0{\cdot}010$ mg l^{-1}) and phosphate-phosphorus concentrations were always below detection limits ([PO_4-P] $<0{\cdot}010$ mg l^{-1}).

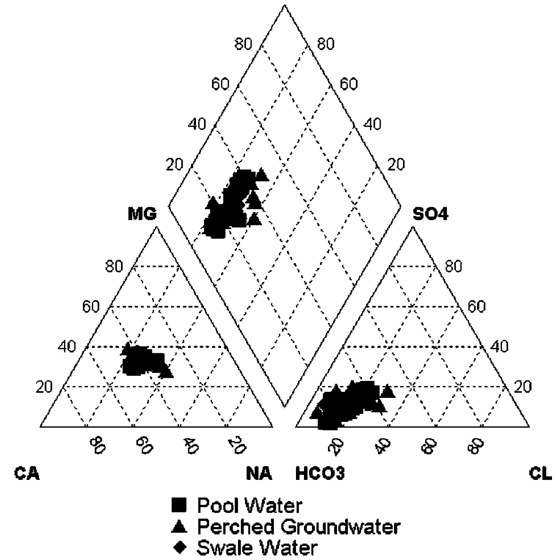

Figure 6. Piper diagrams summarizing the relative concentrations of the major cations and anions in vernal pool water (squares), perched groundwater (triangles), and outlet swale water just upgradient of the seasonal stream (diamonds). All surface water and perched groundwater samples are included. All surface water and perched groundwater samples plot as Ca–Mg–Na–HCO_3, which is typical of regional rainfall that has undergone slight alteration due to short-term contact with sediments

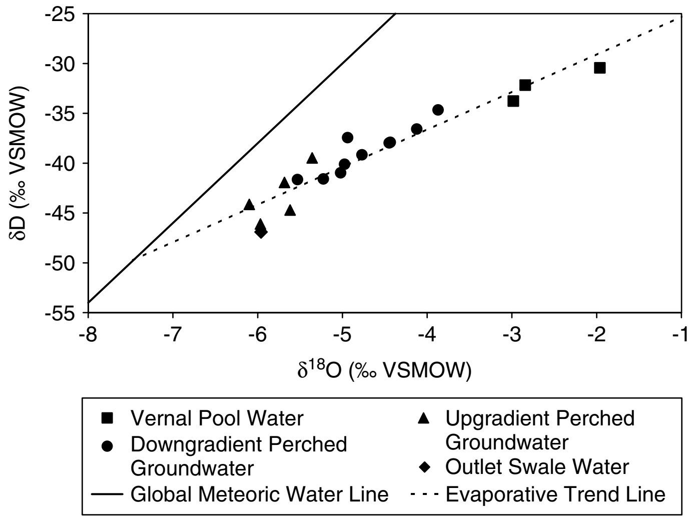

Figure 7. Scatterplot of δD and $\delta^{18}O$ in vernal pool water (squares), upgradient perched groundwater (triangles), downgradient perched groundwater (circles), and outlet swale water (diamonds). The global meteoric water line (Craig, 1961) is the solid line and the evaporative trend line calculated via least-squares regression is the dashed line. Only surface water and perched groundwater samples collected between storms in early March 2003 are included

During the early- and late-season storm events, DOC concentrations in vernal pool water tended to decline immediately in response to the initiation of rainfall and the subsequent increase in perched groundwater discharge, then increase steadily in response to the cessation of rainfall and the subsequent decrease in perched groundwater discharge (Figure 9). With the exception of 1 day at the beginning of the late-season storm event, DOC concentrations in the outlet swale water were lower than DOC concentrations in the vernal pools

Table III. Two-end, mass-balance mixing model results showing the relative contributions of vernal pool water and upgradient perched groundwater to downgradient perched groundwater and outlet swale water between storms in early March 2003

Water	Mean $\delta^{18}O$ (‰ VSMOW)	Standard deviation $\delta^{18}O$ (‰ VSMOW)	Pool water : perched groundwater
Vernal pool water ($n = 3$)	−2·6	0·6	1.0 : 0.0
Upgradient perched groundwater ($n = 5$)	−5·7	0·3	0.0 : 1.0
Downgradient perched groundwater ($n = 10$)	−4·7	0·5	0.3 : 0.7
Outlet swale water ($n = 1$)	−6·0	—[a]	0.0 : 1.0

[a] Insufficient sample numbers to calculate standard deviation.

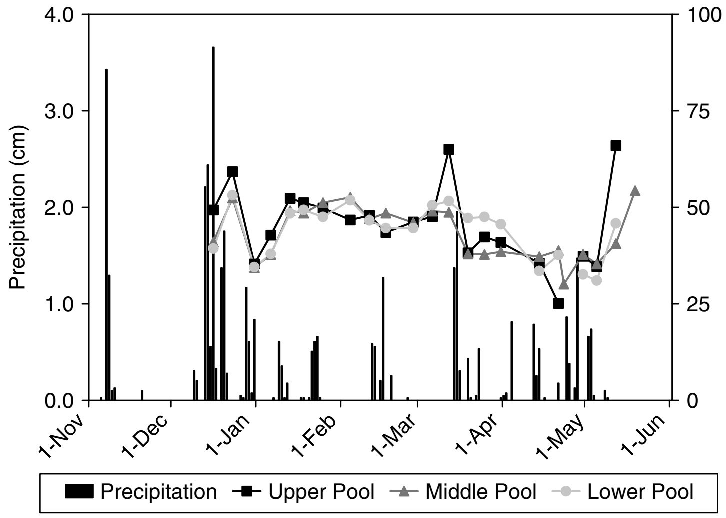

Figure 8. Daily precipitation and weekly vernal pool water electrical conductivities over the study period

(Figure 9). Overall, DOC concentrations in the vernal pool water and outlet swale water were 5·97 mg l^{-1} and 3·24 mg l^{-1} respectively (Table I) and were significantly different from one another ($p < 0{\cdot}01$).

DISCUSSION

Hydrology and hydrological connectivity

The results indicate that vernal pools on soils with relatively coarse-grained surface deposits overlying claypans/duripans are seasonal, surface water components of integrated surface water and perched groundwater systems. Annual rainfall infiltrates but perches on the claypan/duripan, and this perched groundwater flows downgradient toward the seasonal stream. The upper layer of soil above the claypan/duripan is ∼0·6 m in thickness in the uplands and ∼0·1 m in thickness in the vernal pools. When hydraulic heads in the perched aquifer exceed ∼0·1 m above the claypan/duripan, some perched groundwater flows through the vernal pools by discharging primarily at the upgradient end of the vernal pool and recharging primarily at the downgradient end of the vernal pool. The claypan/duripan is laterally extensive throughout the catchment, so all of the perched groundwater must flow through a very small cross-sectional area immediately prior to discharging to the seasonal stream. Accordingly, it appears that perched groundwater discharges to the outlet swale just upgradient of the seasonal stream. However, vernal pools comprise ∼2% of the total catchment area, so most

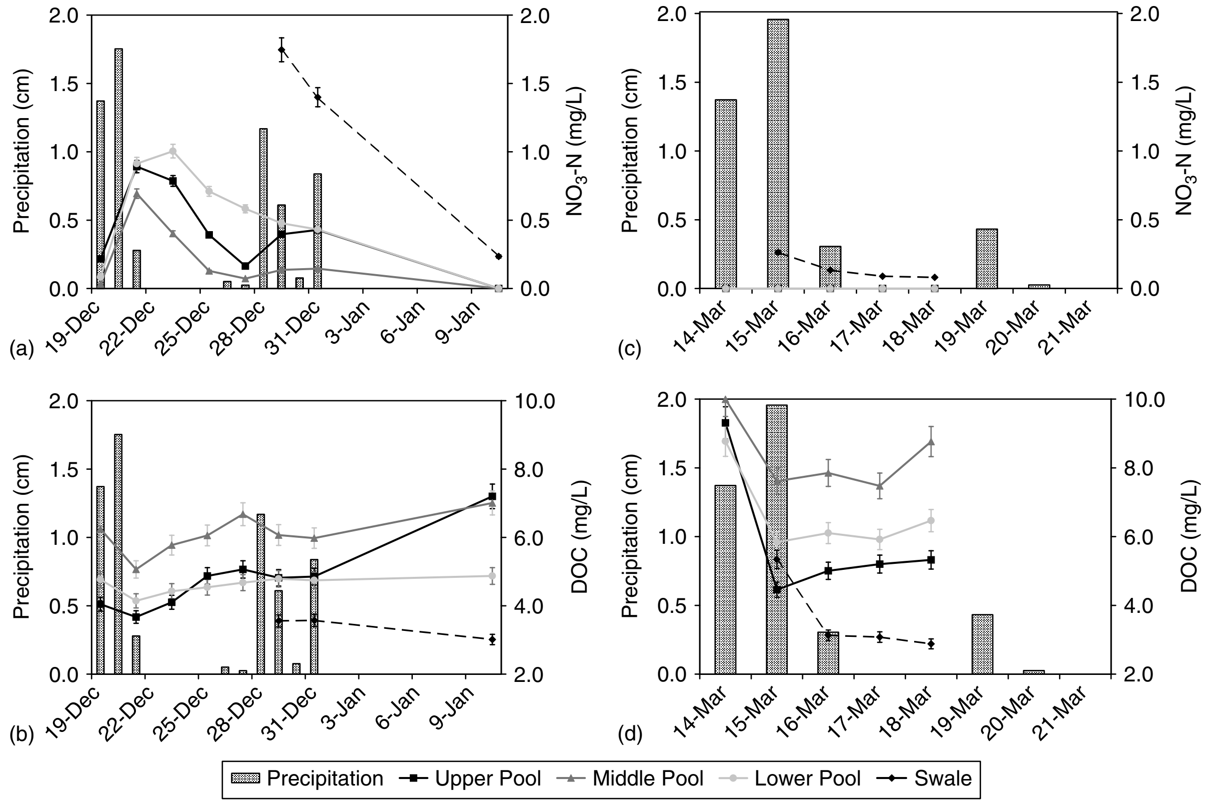

Figure 9. Daily precipitation and (a) NO_3-N and (b) DOC concentrations in vernal pool water during the early-season storm event, and daily precipitation and (c) NO_3-N and (d) DOC concentrations in vernal pool water during the late-season storm event

perched groundwater in the catchment flows under or around the vernal pools or is recharged by annual rainfall downgradient of the vernal pools. Therefore, most outlet swale water discharging to the seasonal stream is perched groundwater that has not flowed through the vernal pools.

Rates of silica dissolution are low (Iler, 1979), so silica is likely reasonably conservative over short periods of time in direct precipitation and upgradient perched groundwater. However, silica fluxes from the beds of shallow freshwater systems are typically negative due to the low rates of silica dissolution and the high rates of diatom frustule synthesis (Thorbergsdóttir, 2004), so silica is likely not as conservative over short periods of time in vernal pool water. Therefore, the three-end, mass-balance mixing model results may underestimate the contribution of upgradient perched groundwater to vernal pool water during and immediately following storm events. Similarly, the upgradient perched groundwater end members had δD and δ^{18}O compositions typical of the weighted average of regional rainfall, whereas the vernal pool water end members had δD and δ^{18}O compositions typical of the weighted average of regional rainfall that had undergone fractionation due to evaporation (Criss and Davisson, 1996). The upgradient perched groundwater end members had much more time to mix and were, therefore, assumed to be reasonably stable. However, the vernal pool end members were likely becoming heavier as the vernal pool water evaporated throughout the wet season. Therefore, the two-end, mass-balance mixing model results may underestimate the contribution of vernal pool water to downgradient perched groundwater. Accordingly, the mass-balance mixing model results should be considered indicative of trends in and not absolute quantities of perched groundwater flux through the vernal pools.

The trends indicate that these vernal pools are surface water and perched groundwater flow-through depressional wetlands. Flow-through lakes and depressional wetlands have long been recognized. Born *et al.*

(1979) found that 23 of 63 study lakes in the Midwestern USA were flow-through lakes. Flow-through prairie pothole wetlands were first described by Sloan (1972) and were further described by Richardson *et al*. (1992). However, vernal pools at this site represent a special case, because the flow-through phenomenon is supported by a seasonal perched aquifer that is unconnected to the underlying regional aquifers.

Vernal pools are not simply isolated depressions that pond largely due to direct precipitation and drain and dry largely due to evapotranspiration. If evapotranspiration were the primary water loss from the vernal pools, then electrical conductivity of the vernal pool water would increase over time due to evapoconcentration. This was not the case. Rather, electrical conductivity tended to decline or remain relatively stable, indicating that continued surface water and perched groundwater flow through the vernal pools provided a continuous source of fresh water that limited the local effects of evapoconcentration. Evapoconcentration only occurred when small volumes of water remained, such as when the upper vernal pool temporarily dried during a prolonged dry period in late March and when the upper, middle, and lower vernal pools permanently dried at the end of the wet season in late May.

Biogeochemistry

The first and second rainfalls of the early-season storm event and the late-season storm event were similar in magnitude and duration. NO_3-N concentrations in the vernal pools, however, were relatively high following the first rainfall of the early-season storm event, noticeably lower following the second rainfall of the early-season storm event, and below detection limits ($[NO_3\text{-N}] < 0{\cdot}006$ mg l^{-1}) following the late-season storm event. This trend is unlikely due to variations in nitrate-nitrogen concentrations in direct precipitation because nitrate-nitrogen concentrations averaged 0·07 mg l^{-1} in December 2002 when the early-season storm event occurred and 0·05 mg l^{-1} in March 2003 when the late-season storm event occurred (National Atmospheric Deposition Program Site CA88). It is more likely that the amount of nitrate-nitrogen transported from the upland soils to the vernal pools declined with each successive rainfall. This trend has been previously observed and explained as an asynchrony between hydrological and biological processes in annual grasslands in Mediterranean-type climates (Tate *et al*., 1999; Holloway and Dahlgren, 2001). Upland annual grasses senesce in the dry season. However, microbial activity continues, nitrogen is mineralized, and nitrate accumulates in the upland soils. Annual grasses germinate early in the wet season, but do not develop substantial biomass until the middle- to late-growing season (i.e. March–April). Thus, during the early-season storm events, there is little biological demand for nitrate and it is readily leached from the upland soils into the perched groundwater that ultimately discharges to the vernal pools. Later in the wet season, much of the nitrate in the upland soils has been flushed and the upland annual grasses are flourishing, which produces a large biological demand for the remaining nitrate. Therefore, the amount of nitrate leaching into the perched groundwater and subsequently discharging to the vernal pools decreases. Concurrently, the vernal pool rim and basin plant communities apparently remove the remaining nitrate from the perched groundwater, because the perched water table intersects the root zone both in the immediate vicinity of and within the vernal pool.

The vernal pools are characterized by dense coverage with primarily native annual grasses, forbs, and pool-bed algae and are inundated for $\sim$150 days per year, whereas the surrounding uplands are characterized by moderate coverage with primarily non-native annual grasses and are not inundated at any point during the year. The vernal pools are relatively high productivity islands in a relatively low productivity landscape and support anaerobic soils when inundated. Nitrate concentrations in vernal pool water decline immediately following the cessation of rainfall, indicating that nitrate is rapidly assimilated by biota or denitrified by anaerobic bacteria (Ponnamperuma, 1972). Therefore, nitrate concentrations in vernal pool water are lower than in groundwater. DOC accumulates in vernal pool water through leaching of particulate organic matter (Orem *et al*., 1986) and desorption from mineral surfaces (Jardin *et al*., 1989). The high iron oxide content of upland and vernal pool soils strongly sorb and, therefore, immobilize DOC in perched groundwater (Hobson and Dahlgren, 1998). Furthermore, though temperatures are relatively low, residence times are relatively short, and DOC is a relatively recalcitrant form of organic matter; nevertheless, microbial decomposition in the shallow subsurface may consume some DOC in perched groundwater. Therefore, DOC concentrations in vernal pool water are higher than in perched groundwater.

Wetlands have long been known for the biogeochemical functions they perform, such as denitrification (Ponnamperuma, 1972) and DOC production (Fogg, 1977), and the water quality benefits of these biogeochemical functions are often assumed to be translated to downgradient aquatic ecosystems (Brinson *et al.*, 1995). However, the water quality benefits of wetlands will be translated to downgradient aquatic ecosystems only if the wetlands provide substantial amounts of water to the downgradient aquatic ecosystems. This is often the case in river systems, where nitrogen loss (Hill *et al.*, 1998; Alexander *et al.*, 2000) and DOC production (Moore, 2003) are readily translated to downgradient locations in the same river system. In this case, however, the primary source of water to the seasonal stream is perched groundwater that has not flowed through the vernal pools. Therefore, the water quality benefits of these vernal pools can be observed at the pool scale, but not at the catchment scale.

Potential implications for vernal pool biota

Perched groundwater discharges from uplands to vernal pools stabilize vernal pool water levels, causing them to be inundated over larger areas for longer periods of time than would be the case if they were recharged only by precipitation. Hydrological conditions can be expressed through soil chemical reactions that influence plant productivity, such as redox reactions limiting root oxygen and nutrient availability (Hobson and Dahlgren, 2001). Holland and Jain (1984) and Bauder (2000) noted that competitive niche partitioning along hydrological gradients determines floral distributions in and around vernal pools, and that annual variations in hydrological conditions cause annual shifts in floral distributions in and around vernal pools. Hydrological conditions can also be expressed through habitat availability for faunal support. Gallagher (1996) noted that branchiopod species differ in life history duration and, consequently, in inundation duration requirements. Therefore, the stabilizing effect of perched groundwater discharge from the uplands to the vernal pools may increase the likelihood that certain vernal pool flora and fauna will flourish.

Perched groundwater discharge from uplands to vernal pools also buffers the electrical conductivity of vernal pool water by limiting the local effects of evapoconcentration. Gonzales *et al.* (1996) found that the ability to regulate the ionic composition of haemolymph (i.e. the blood analogue used by those animals, such as all arthropods and most molluscs, that have an open circulatory system) plays an important role in restricting some fairy shrimp species to low electrical conductivity vernal pools, restricting other fairy shrimp species to high electrical conductivity vernal pools, and allowing yet other fairy shrimp species to persist in both low and high electrical conductivity vernal pools. Therefore, the buffering effect of perched groundwater discharge from the uplands to the vernal pools may increase the likelihood that certain vernal pool flora and fauna will flourish.

Regulatory context and management implications

In 2001, the US Supreme Court ruled that the US Army Corps of Engineers exceeded its statutory authority by asserting Clean Water Act (CWA) jurisdiction over non-navigable, isolated, intrastate waters based solely on their use by migratory birds (Solid Waste Agency of Northern Cook County versus US Army Corps of Engineers, 531 US 159, 2001). The Supreme Court's reasoning was that the CWA implies that non-navigable, isolated, intrastate waters need a 'significant nexus' to navigable waters to be jurisdictional. To date, neither the courts nor the agencies have defined 'significant nexus', though making a significant contribution to the physical, chemical, and biological integrity of navigable waters seems a reasonable definition.

In this case, the uplands, vernal pools, and seasonal stream are connected at the catchment scale by an integrated seasonal surface water and perched groundwater system. However, questions remain regarding the significance of this connectivity to the physical, chemical, and biological integrity of navigable waters. For example, the results of this study are from a single catchment in which vernal pools cover $\sim$2% of the catchment area. In catchments where vernal pools cover a larger fraction of the catchment area, one would expect greater effects of vernal pool biogeochemical processes on the chemistry of the water discharged from the outlet swales. At what fraction would the vernal pools make a significant contribution to the physical, chemical, and biological integrity of navigable waters and do these fractions commonly occur in nature? Additional hydrogeological investigations of other vernal pool landscapes would elucidate this important issue.

Large changes in regional aquifer management, such as substantially increased groundwater pumping from wells, will have no effects on the vernal pools because perched groundwater flows laterally and downward at rates that are unaffected by the position of the regional water table. On the other hand, small changes in local land use, such as the development of irrigated agriculture or parkland, may have considerable impacts on the vernal pools. The degree to which small changes in local land use might affect the vernal pools is poorly understood, because the fundamental hydrogeological characteristics of perched aquifers remain relatively unexplored. The management of perched aquifers should rest on a scientific foundation that provides a general understanding of the conditions necessary to maintain perched aquifers capable of supporting the physical and biological functions of dependent wetland ecosystems. This scientific foundation, though within reach of current technologies and methods, appears to be virtually nonexistent because hydrogeologists have largely pursued analyses of regional aquifers that can be exploited for water supply purposes rather than perched aquifers that typically are too local and/or shallow to be exploited for any appreciable water supply purposes. The recognition that perched aquifers play important roles in maintaining some wetland ecosystem functions provides a renewed impetus to study and understand shallow perched groundwater systems better.

CONCLUSIONS

The results of this study show that some vernal pools are supported by perched aquifers wherein seasonal surface water and perched groundwater hydrologically and biogeochemically connect uplands, vernal pools, and streams at the catchment scale. However, the degree of connectivity between the various stores is apparently governed by issues of spatial and temporal scale. The vernal pools and adjacent uplands are quite obviously hydrologically and biogeochemically connected. Perched groundwater flowed through the vernal pools, largely controlling vernal pool stage, electrical conductivity, and nitrate and DOC dynamics, particularly during and immediately following storm events. The vernal pools and seasonal stream also are quite obviously hydrologically connected. Surface water flowed out of the lower vernal pool, though the outlet swale, and into the seasonal stream for approximately 90 days, and the perched aquifer maintained a saturated connection between the vernal pools and the seasonal stream throughout the wet season. However, the vernal pools and seasonal stream are not as obviously biogeochemically connected. The vernal pools comprise $\sim$2% of the total catchment area, so most outlet swale water discharging to the seasonal stream was perched groundwater that had not flowed through the vernal pools. Therefore, though the uplands, vernal pools, and seasonal stream are part of a single surface water and perched groundwater system, the vernal pools apparently play a limited role in controlling landscape-scale water quality.

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