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GEOLOGICAL CONTROL OF PHYSICAL AND CHEMICAL HYDROLOGY IN CALIFORNIA VERNAL POOLS

Mark C. Rains[1], Randy A. Dahlgren[2], Graham E. Fogg[2], Thomas Harter[2], and Robert J. Williamson[2]
[1]*Department of Geology*
University of South Florida
Tampa, Florida, USA 33620
E-mail: mrains@cas.usf.edu

[2]*Department of Land, Air, and Water Resources*
University of California
Davis, California, USA 95616

Abstract: Vernal pools are small depressional wetlands found in seasonal climates throughout the world. In California, they are among the few ecosystems still dominated by native flora and are critical habitat for numerous endemic and rare species. In this study, we show that geology is a dominant control on the physical and chemical hydrology of contrasting vernal pools on clay-rich and hardpan soils, the two most common types of vernal pools in the Central Valley, California. The vernal pools on clay-rich soils formed on alluvium derived primarily from sedimentary and metasedimentary rocks of marine origin and deposited in relatively low-gradient environments. The clay-rich soils are fine grained and moderately to strongly saline and sodic. The vernal pools on clay-rich soils are perched surface-water systems in which surface waters are relatively saline, sodic, and turbid and in which primary productivity may be nitrogen and light limited. The vernal pools on hardpan soils formed on alluvium derived primarily from coarse-grained igneous rocks and deposited in relatively high-gradient environments. Surface soils are coarse grained and underlain by a clay-rich argillic horizon and a silica- and iron-cemented duripan. The vernal pools on hardpan soils are surface-water and perched ground-water systems in which surface waters are relatively fresh and non-turbid and in which primary productivity may be phosphorus limited. While surficially similar, these vernal pools differ in their physical and chemical hydrology, and therefore should be treated differently in resource conservation, restoration, and management efforts.

Key Words: dissolved constituents, geology, ground water, nutrients, soils, surface water, turbidity

INTRODUCTION

In wetlands, geological processes provide the template upon which all other physical, chemical, and biological processes operate. Physical hydrology is largely controlled by the rates of infiltration and transmissivity of the soils and bedrock (Lacey and Grayson 1998), particularly where shallow perching layers reduce rates of recharge to underlying regional aquifers (Bagtzoglou et al. 2000) and redirect water flow along subsurface horizontal flowpaths (Driese et al. 2001, Rains et al. 2006). Chemical hydrology is largely controlled by the larger suite of hydrobiogeochemical processes. Chemical hydrology may initially be controlled by the interactions between water and parent rocks (Munn and Meyer 1990, Dahlgren 1994, Holloway et al. 1998). The resulting water-solute solutions may be further modified by the acceleration of mineral weathering through the production of acids and chelates (Dahlgren 1994), the uptake and release of nutrients by soil microorganisms and vegetation (Likens et al. 1970), solute interactions with organic and mineral colloids, and the concentration of solutes by evapotranspiration (Gremillion and Wanielista 2000).

In this paper, we extend these concepts to West Coast vernal pools, which occur in southern Oregon, California, northern Baja California, and in other seasonal climates of the world (Riefner and Pryor 1996). Vernal pools are small depressional wetlands that pond for portions of the wet season, then drain and desiccate during the dry season (Stebbins 1976, Tiner et al. 2002). Vernal pools typically range from 50–5,000 m^2 in area (Mitsch and Gosselink 2000) and from 0.1 to 1 m in depth (Hanes and Stromberg 1998, Rains et al. 2006). Vernal pools are best known for the biological functions that they perform, and are among the last remaining

California ecosystems still dominated by native flora (Barbour et al. 1993). Many vernal-pool plant and macroinvertebrate species are endemic, and some of which are rare (Holland and Jain 1988, Keeley and Zedler 1998). More than 90% of California's original vernal pools have been lost to human disturbance (Holland 1978, Holland 1998). Therefore, vernal pools should be critical components of regional biological conservation, restoration, and management efforts (Tiner et al. 2002, U.S. Fish and Wildlife Service 2004).

Vernal pools occur on many geological surfaces. However, in all cases vernal pools are underlain by low-permeability layers (i.e., aquitards) such as clay-rich soils (Smith and Verrill 1998), claypans or hardpans (e.g., silica-cemented duripans) (Nikiforoff 1941, Hobson and Dahlgren 1998, Smith and Verrill 1998, Rains et al. 2006), mudflows or lahars (Jokerst 1990, Smith and Verrill 1998), or bedrock (Weitkamp et al. 1996). These low-permeability layers are typically associated with specific geological formations, landforms, and soils. Therefore, vernal pools are typically clustered into vernal-pool landscapes (Smith and Verrill 1998), which are specific forms of the generic hydrologic landscapes described by Winter (2001). Currently, these vernal-pool landscapes cover more than 4,100 km^2 or ~5% of the total land surface of California's Central Valley (Holland 1998). In these vernal-pool landscapes, vernal pools, which are potentially jurisdictional wetlands under the Clean Water Act, typically comprise less than 10% of the total land surface. In many vernal-pool landscapes, surface water flows through integrated 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. Due to the integrated hydrologic nature of vernal-pool landscapes, disturbance of upgradient vernal pools may have appreciable impacts on hydrological and biogeochemical processes in all downgradient vernal pools and streams.

This project is part of a larger interdisciplinary project with the overall objective of informing management and conservation efforts in selected vernal-pool landscapes. Vernal pools formed on clay-rich and hardpan soils are perhaps the most common types of vernal pools in the Central Valley, California (Smith and Verrill 1998). Because these types of vernal pools are surficially similar, they are often treated similarly in resource conservation, restoration, and management efforts. The purpose of this paper is to demonstrate that these contrasting types of vernal pools have distinct physical and chemical hydrological characteristics related to their

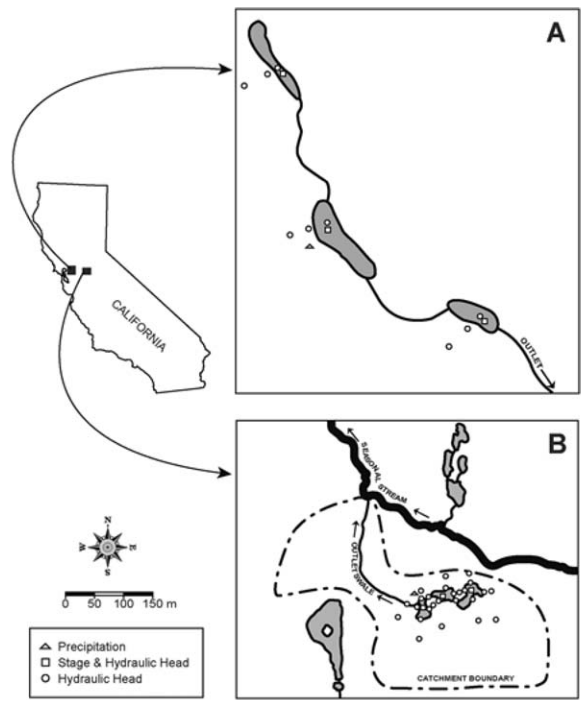

Figure 1. Local setting showing the hydrometric instrumentation locations at A) the clay-rich soil site and B) the hardpan soil site.

geological substrate, which in turn may result in distinct ecological characteristics. As a result, these contrasting types of vernal pools should be treated differently in resource conservation, restoration, and management efforts.

STUDY AREAS

Physiography and Land Use

The clay-rich soil site is located in the west-central Central Valley ~40 km southwest of Sacramento, California (Figure 1). In an undefined catchment, there are three vernal pools connected to one another and a seasonal stream by ephemeral or seasonal swales. The terrain is nearly level, with slope ~0.1% to the southeast. Elevations of the uplands surrounding the vernal pools range from 4.0 to 3.6 m above mean sea level. The site has been periodically grazed throughout recorded history. Vernal pools cover ~3% of the land surface throughout the region.

The hardpan soil site is located in the east-central Central Valley ~20 km southeast of Sacramento, California (Figure 1). In a 0.1 km^2 catchment, there are three vernal pools connected to one another and to a seasonal stream by ephemeral or seasonal swales. The terrain is gently sloped, with slope ~2% to the northwest. Elevations of the upper catchment divide, the vernal pools, and the outlet swale just upgradient of the seasonal stream are ~47, 43, and 39 m above mean sea level, respectively. The site was grazed during the late nineteenth and early twentieth centuries but has been used largely as non-managed wildlands since being annexed for military use in 1918 and becoming part of a regional park in 1995. Vernal pools cover ~2% of the land surface throughout the region.

Climate

The climate at both sites is Mediterranean with mild, wet winters and hot, dry summers. Mean (± standard deviation) annual precipitation at the clay-rich soil site is 60.7 cm (± 27.7 cm), with ~98% falling during the months of October–May (Western Regional Climate Center data for Vacaville, California for the years 1971–2000). Mean (± standard deviation) annual precipitation at the hardpan soil site is 50.4 cm (± 18.4 cm), with ~97% falling during the months of October–May (Western Regional Climate Center data for Sacramento 5 ESE, California for the years 1971–2000). Annual precipitation at the clay-rich soil site was 45.6 cm and 36.5 cm for water years 2003 and 2004, respectively, while annual precipitation at the hardpan soil site was 48.3 cm and 41.3 cm for water years 2003 and 2004, respectively. Therefore, during water years 2003 and 2004, precipitation at each site was below but well-within one standard deviation of the mean.

Geology and Soils

The clay-rich soils in the west-central Central Valley developed in fine-grained alluvial basin and deltaic deposits derived primarily from eugeosynclinal sedimentary and metasedimentary rocks of marine origin of the Coast Range (Dickinson and Rich 1972, Jennings 1977, Jennings 1985). Based on the soil survey, the dominant soil at the clay-rich soil site is the Pescadero series, a fine, smectitic, thermic Aquic Natrixeralf (Bates 1977, Smith and Verrill 1998).

The hardpan soils in the east-central Central Valley developed in coarse-grained alluvial fan deposits composed primarily of quartzite and amphibole cobbles in a granitic sand matrix derived from intrusive igneous rocks of the Sierra Nevada Range (Shlemon 1972, Jennings 1977, Jennings 1985). On these deposits, soils with hardpans are typically found on older landscape positions (e.g., low and high terraces formed > 125 ka) that have undergone a high degree of weathering and pedogenic development (Harden 1987). Based on the soil survey, the dominant soil at the hardpan soil site is the Redding series, a fine, mixed, active, thermic Abruptic Durixeralf (Tugel 1993, Smith and Verrill 1998).

Excavation was not permitted in or near the federally-protected vernal pools at either site. Therefore, typical soil characteristics were obtained from the U.S. Department of Agriculture Soil Characterization Database (Soil Survey Staff 2006). Pedon ID 64CA113012 (Pescadero series) was used for the clay-rich soil site. This pedon was located in a similar geological setting ~40 km northwest of the clay-rich soil site. Pedon ID 79CA067001 (Redding series) was used for the hardpan soil site. This pedon was located in a similar geological setting ~8 km southeast of the hardpan soil site. These pedons were in uplands rather than in vernal pools. Dominant soil-forming processes differ along the gradient between uplands and associated vernal pools (Hobson and Dahlgren 1998). Therefore, these pedons do not describe the precise characteristics of the soils in each vernal pool. Rather, these pedons describe the general characteristics of the soils on which the associated vernal pools have developed. Investigation of soil properties from cores obtained during piezometer installation confirmed that the field soils had similar morphological properties to the soil pedons selected from the soil characterization database.

The clay-rich soil is fine textured (> 80% clay + silt) throughout and has sufficient clay translocation to the underlying B horizons to form a clay-rich argillic horizon (Table 1; Figure 2). Soluble salts, particularly sodium, occur in high concentrations (electrical conductivity = 0.5 to 15.8 dS/m and exchangeable sodium percentage = 4% to 44%). Therefore, this pedon is characterized as both saline (electrical conductivity > 4 dS/m) and sodic (exchangeable sodium percentage > 15%). The entire pedon is strongly alkaline (pH = 7.7 to 8.9).

The hardpan soil is relatively coarse textured throughout most of upper pedon with B horizons of the lower pedon that have accumulated silicate clays and have various degrees of cementation with opal silica and iron oxides (Table 1; Figure 2). Silica and iron accumulation has occurred throughout the 71–168 cm zone resulting in formation of an indurated duripan at the 71–117 cm depth. The duripan acts as a barrier to the downward transport of silicate clays resulting in the formation of a clay-rich argillic horizon directly above the duripan. Soluble salts, including sodium, occur in low concentrations (electrical conductivity = 0.05 to 0.11 dS/m and exchangeable sodium percentage = < 0.1% to

Table 1. Typical soil characteristics for the clay-rich and hardpan soil sites. Data for the clay-rich and hardpan soil sites are from pedon ID 64CA113012 and pedon ID 79CA067001 from the U.S. Department of Agriculture Soil Characterization Database, respectively (Soil Survey Staff 2006).

Horizon	Depth (cm)	Lab Texture[1]	pH	EC[2] (dS/m)	Organic C (%)	Exch-Na ($cmol_c$/kg)	Exch-K ($cmol_c$kg)	Exch-Mg ($cmol_c$/kg)	Exch-Ca ($cmol_c$/kg)	ESP[3] (%)
				Clay-Rich Soil Site						
A	0–8	SICL	7.7	6.6	2.84	12.6	1.8	9.5	4.8	44
Bt	8–33	SIC	8.9	7.0	1.01	34.4	0.4	9.6	3.5	72
Btk1	33–66	SIC	8.6	13.0	0.58	32.2	0.3	15.0	4.7	62
Btk2	66–102	SIC	8.1	15.8	0.43	21.6	0.3	18.8	10.2	42
Bk1	102–132	SICL	7.9	9.4	0.26	5.6	0.5	18.8	15.5	14
Bk2	132–170	SICL	8.0	6.2	0.19	3.9	0.4	17.7	18.5	10
Bk3	170–241	CL	8.1	1.6	0.15	1.4	0.4	16.0	16.4	4
C	241–267	SIL	8.3	0.5	0.09	0.9	0.4	14.1	8.8	4
				Hardpan Soil Site						
A1	0–5	L	5.5	0.07	1.66	< 0.1	0.4	1.2	3.6	–
A2	5–18	L	5.5	0.05	0.42	< 0.1	0.3	0.7	2.0	–
Bt1	18–33	L	5.8	0.05	0.20	< 0.1	0.3	1.2	2.4	–
Bt2	33–51	L	5.9	0.09	0.17	< 0.1	0.5	2.2	3.4	–
Bt3	51–64	C	5.9	0.11	0.28	0.2	0.3	9.2	11.5	1
Bt4	64–71	C	5.7	0.10	0.26	0.3	0.3	11.2	13.7	1
Bqm	71–117	ND	7.6	0.07	0.04	0.5	0.1	10.9	16.3	2
Bq	117–168	LCOS	7.4	0.05	0.05	0.4	0.1	9.3	14.4	2
C	168–190	SCL	7.3	0.06	0.06	0.2	0.1	8.1	12.6	1

[1] SICL = silty clay loam, SIC = silty clay, CL = clay loam, SIL = silt loam, L = loam, C = clay, LCOS = loamy coarse sand, SCL = sandy clay loam, ND = not determined due to cementation by silica.
[2] EC = electrical conductivity.
[3] ESP = exchangeable sodium percentage.

0.4%). The upper pedon (i.e., above the duripan) is acidic (pH = 5.5 to 5.9), while the lower pedon (i.e., within and below the duripan) is slightly alkaline (pH = 7.3 to 7.6). Investigation of soil properties from cores obtained during piezometer installation and additional tile probing indicated that the clay-rich argillic horizon and indurated duripan are laterally extensive throughout the catchment. The vernal-pool depressional areas appear to be deflation basins ~0.5 m in depth. Multiple hand-augered holes and tile probe penetrations indicated that the soil thickness above the claypan/duripan is ~0.6 m in the uplands and ~0.1 m in the vernal-pool depressions.

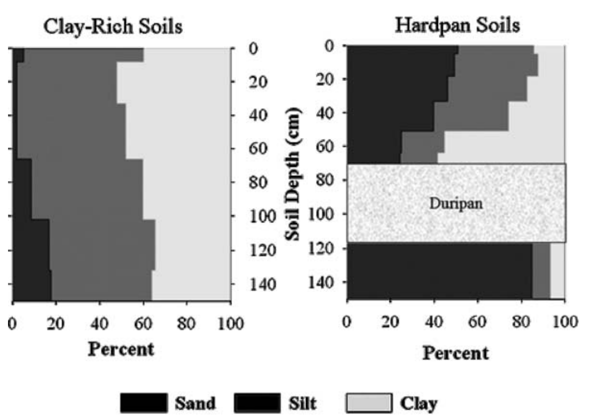

Figure 2. Generic cross-sections of typical pedons for the clay-rich and hardpan soil sites. Data are from pedon IDs 64CA113012 and 79CA067001, respectively, from the U.S. Department of Agriculture Soil Characterization Database (Soil Survey Staff 2006).

Vegetation

The vegetation at both sites is typical of vernal pools in the Central Valley, California, with primarily native annual grasses and forbs. Species composition is typical of Northern Hardpan Vernal 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

Physical Hydrology

Precipitation was measured continuously and solar radiation, temperature, humidity, and wind speed and direction were measured hourly with a HOBO Weather Station System H21-SYS-A (Onset, Pocasset, Massachusetts, USA). Soil temperature, soil volumetric water content, and soil heat flux also were measured hourly with 107-L Temperature Sensors, CS616-L Water Content Reflectometers, and HFT3-L REBS Soil Heat Flux Plates, respectively (Campbell Scientific, Logan, Utah, USA). Net radiation was computed from solar radiation and temperature using standard methods (Allen et al. 1998).

Daily reference evapotranspiration was computed using the ASCE Standardized Reference Evapotranspiration Equation (Allen et al. 2005), which is the most recent update of the FAO Penman-Monteith Equation (Doorenbos and Pruitt 1977, Allen et al. 1998). The ASCE Standardized Reference Evapotranspiration Equation is

$$ET_o = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}U_2(e_s-e_a)}{\Delta+\gamma(1+0.34U_2)}$$

where ET_o is reference evapotranspiration (mm/d), Δ is the slope vapor pressure curve (kPa/°C), Rn is net radiation (MJ/m^{2}day), G is soil heat flux and storage (MJ/m^{2}°C), T is mean daily temperature (°C), U_2 is the wind speed at 2 m height (m/s), e_s is mean saturation vapor pressure (kPa), and e_a is actual vapor pressure (kPa). Working in a variety of locations in California and Italy, including a location ~30 km northeast of the clay-rich soil site and ~40 km west of the hardpan soil site, Ventura et al. (1999) showed that the root mean square of daily reference evapotranspiration computed with the FAO Penman-Monteith Equation with respect to daily reference evapotranspiration measured in lysimeters was ~0.4 mm/d. This is ~10% of the daily reference evapotranspiration computed during the course of this study. Actual evapotranspiration was assumed to be equal to reference evapotranspiration throughout the wet season because the clay-rich and hardpan soil sites were predominantly covered with relatively disease-free, fully-wet, laterally-extensive short grasses that were comparable to the generic short grass reference crops to which all reference evapotranspiration equations are calibrated (Doorenbos and Pruitt 1977, Allen et al. 1998). Fetch was ~150 m in the southeast direction and > 500 m in all other directions at the clay-rich soil site, and > 500 m in all directions at the hardpan soil site.

Stages in the vernal pools were measured hourly with Model 3001 Leveloggers (Solinst, Georgetown, Ontario, Canada). During water year 2004, pressure transducers and dataloggers were deployed late and only middle to late wet season data were collected. Hydraulic heads were measured at least weekly with a Model 101 Water Level Meter (Solinst, Georgetown, Ontario, Canada). At the clay-rich soil site, hydraulic heads were measured at nine piezometers, with piezometers having inside diameters of 5 cm and having open ends and ~5 cm uncased boreholes ~1.8 m below the soil surface (Figure 1). At the hardpan soil site, hydraulic heads were measured at 28 piezometer nests, with piezometers having inside diameters of 2.5 cm and each piezometer nest having piezometers with open ends and ~5 cm uncased boreholes ~0.6, 1.2, and 1.8 m below the soil surface (Figure 1). 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, ensuring a tight fit. Bentonite surface seals were emplaced around the outside of the piezometers. At the clay-rich soil site, all piezometers were in or below the massive clay subsoil. At the hardpan soil site, the shallow (0.6 m) piezometers were generally above the claypan/duripan, while the middle (1.2 m) and deep (1.8 m) piezometers were generally below the claypan/duripan. Regional water levels were obtained from long-term monitoring wells in the California Department of Water Resources monitoring well network. The monitoring well used for the clay-rich soil site was located at the same elevation ~1 km south of the clay-rich soil site (California Department of Water Resources data for California State Well No. 05N02E07R001M). The monitoring wells used for the hardpan soil site were located at the same elevation ~3 km east of the hardpan soil site (California Department of Water Resources data for California State Well Nos. 08N07E20J001M and 08N07E08R001M).

Head changes in piezometers can lag behind head changes in surrounding formations when piezometers are screened in formations with low hydraulic conductivities (Hvorslev 1951, Hanschke and Baird 2001). These potential time lags were a particular problem at the clay-rich soil site. In clay-rich deposits, where saturated hydraulic conductivities are typically on the order of ~10^{-8} cm/s (Freeze and Cherry 1979), even small-diameter piezometers can have time lags on the order of days, weeks, months, or even years, depending upon piezometer construction details and actual hydraulic conductivities. At the clay-rich soil site, using the known piezometer construction details and an assumed hydraulic conductivity of 10^{-8} cm/s, the computed time lag was ~1.5 y. Therefore, piezometers at the clay-rich soil site were not used to obtain data for detailed time-series analyses. Instead, piezometers at the clay-rich soil site were simply used to determine if there were saturated conditions between the surface water in the vernal pools and the regional water table measured at a nearby long-term monitoring well. If saturated conditions between the surface water in the vernal pools and the regional water table measured at a nearby long-term monitoring well were not observed at any time during the course of the study, then that would provide evidence that surface water in the vernal pools was in some way perched above the regional aquifer. These potential time lags were not a particular problem at the hardpan soil site. At the hardpan soil site, using the known piezometer construction details and an assumed saturated hydraulic conductivity of 10^{-1} cm/s above the claypan/duripan, the computed time lag was ~1 min. Therefore, piezometers at the hardpan soil site were used in time-series analyses in which data were analyzed over the course of days and weeks, which eliminated potential time-lag errors that might have occurred over the course of shorter time scales.

The relative importance of evapotranspiration losses to vernal-pool drawdown was assessed with a numerical model. The model was applied to two 10-day time periods when vernal-pool stages were below the outlet swale elevations so outflows were strictly functions of evapotranspiration losses and/or ground-water recharge. Stages were modeled by starting with the initial measured stages and lowering stage each day through evapotranspiration losses alone.

Chemical Hydrology

Surface-water samples were collected periodically from each vernal pool throughout the period of inundation. Each surface-water sample was a composite sample of two depth-integrated subsamples, with equal volumes collected at 10 cm depth intervals and mixed to form each depth-integrated subsample. Water samples were filtered through 0.2 μm polycarbonate membranes and stored at 4°C through completion of analyses. A total of 98 surface-water samples were collected and analyzed for silica, nitrate-N, phosphate-P, and dissolved organic carbon (DOC) concentrations in water year 2003, and a total of 74 surface-water samples were collected and analyzed for major cations and anions and turbidity in water year 2004.

Electrical conductivity and pH were measured in the field with a YSI 556 MPS (YSI, Yellow Springs, Ohio). Major cations (Na^+ [0.05], NH_4^+-N [0.08], K^+ [0.05], Ca^{2+} [0.08], and Mg^{2+} [0.08] [detection limit ppm]) and anions (Cl^- [0.01], NO_3^--N [0.01], PO_4^{3-}-P [0.01] and SO_4^{2-}[0.04] [detection limit ppm]) were measured on a Dionex 500x ion chromatograph (Clesceri et al. 1998). 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). Dissolved organic carbon (DOC) was measured by UV-persulfate oxidation/IR detection using a Tekmar-Dohrmann Phoenix 8000 TOC analyzer (detection limit 50 ppb) (Clesceri et al. 1998). Silica was measured by the molybdosilicate method on a Lachat Quik-Chem 8000 autoanalyzer (detection limit 0.1 ppm as SiO_2) (Clesceri et al. 1998). Turbidity was measured in the laboratory on unfiltered water samples using an Orbeco-Hellige Model 966 Turbidometer. Analytical precisions were typically $< \pm 5\%$ for all analyses. Laboratory quality assurance/quality control included replicates, spikes, reference materials, setting of control limits, criteria for rejection, and data validation methods.

Major ion data were plotted in a Piper diagram (Piper 1944). In a Piper diagram, each water sample is plotted in three locations based upon the percentage composition of the major ions, with trilinear diagrams in the lower left and right where cations and anions are plotted separately, and a diamond-shaped diagram at the upper center where cations and anions are plotted together. The Piper diagram was used to facilitate a rapid visual analysis of the percentage composition of the major ions in the vernal pools on clay-rich and hardpan soils and to determine the dominant hydrochemical facies based upon the percentage composition of the major ions in the vernal pools on clay-rich and hardpan soils. Two-sample t-tests assuming equal variances were used to test for significant differences in silica, nitrate-N, phosphate-P, and DOC concentrations in the vernal pools on clay-rich and hardpan soils (Zar 1984). Normality was checked with histograms, and the assumption of equal variances was tested with two-sample F-tests for equal variances. All of the tests had 96 degrees of freedom. All statistical tests were conducted in Microsoft Office Excel 2003.

The relative importance of evapoconcentration in controlling solute concentrations in the vernal pools on clay-rich soils was assessed with a mass-balance mixing model. The model was applied when the vernal pools were drying and vernal-pool stages

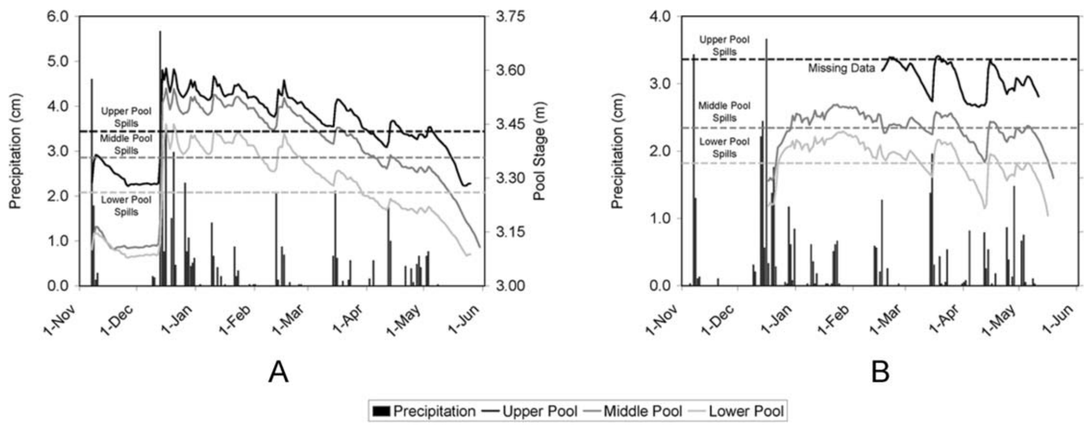

Figure 3. Daily precipitation in cm and stages in m above mean sea level for A) vernal pools on clay-rich soils and B) vernal pools on hardpan soils during water year 2003. Horizontal dashed lines indicate the stages at which surface water flows out of each vernal pool via an outlet swale.

were below the outlet swale elevations. Drawdown was assumed to be entirely due to evapotranspiration. The mass-balance mixing model was

$$EC_{MOD} = \frac{EC_{INI}}{f}$$

where EC_{MOD} was the modeled electrical conductivity, EC_{INI} was the initial electrical conductivity measured just prior to the vernal-pool stages dropping below the outlet swale elevations, and f was the fraction of water remaining at each time step, i.e., the volume of water in the vernal pools at that time step divided by the volume of water in the vernal pools just prior to the vernal-pool stages dropping below the outlet swale elevations. Stage-volume curves in closed-basin depressions are often approximately linear at moderate stages and nonlinear at high and low stages (Haag et al. 2005, Lee and Haag 2006). The vernal pools on clay-rich soils had relatively steep banks and flat beds so it was assumed that stage-volume curves in these closed-basin depressions also were approximately linear at moderate stages. Therefore, the fraction of water remaining at a given time step was computed with a linear function where

$$f = 1 - \frac{d_d}{d_i}$$

and where f was as previously defined, d_d was the drawdown depth over the course of a given time step, and d_i was the initial depth at the beginning of the first time step. This model was not applied at stages below 0.2f because it was assumed that stage-volume curves in these closed-basin depressions were nonlinear at low stages. Measured and modeled electrical conductivity were compared in all three vernal pools at three different time periods over the course of approximately one month.

RESULTS

Physical Hydrology

The vernal pools on clay-rich soils responded immediately to rainfall (Figure 3). Approximately 7 cm of rain fell from November 7–10, 2003 during which time the vernal pools accumulated ~7 cm of water. During subsequent storm events, vernal-pool stages began to rise at the onset of rainfall, with low hydraulic gradients and subsequently slow overland flow velocities causing stages to continue to rise for one to two days after the cessation of rainfall. Stage continued to rise longer after the cessation of rainfall in the middle and lower vernal pools that received overland flow through interconnecting swales from upgradient vernal pools. There was little infiltration, with shallow core and neutron probe data indicating that soil saturation was limited to the upper few cm even after months of inundation (R. Williamson, unpublished data). Piezometers remained dry throughout the period of record, with the regional water table remaining ~3 m below the soil surface throughout the period of study. Therefore, surface water was perched on the clay-rich surface soil.

During periods of time when there was little to no rainfall, drawdown rates were approximately equal to evapotranspiration rates (Figure 4). From March 30 to April 8, when there was just ~7 mm of total rainfall spread between two non-consecutive days, both measured and modeled drawdown rates were 4 mm/d. From May 5–14, when there was just a trace of rainfall on one day, measured and modeled drawdown rates were 6 and 5 mm/d, respectively.

During water year 2003, the upper, middle, and lower vernal pools had standing water for 200, 205, and 200 days, respectively. Surface-water outflows from the upper, middle, and lower vernal pools were

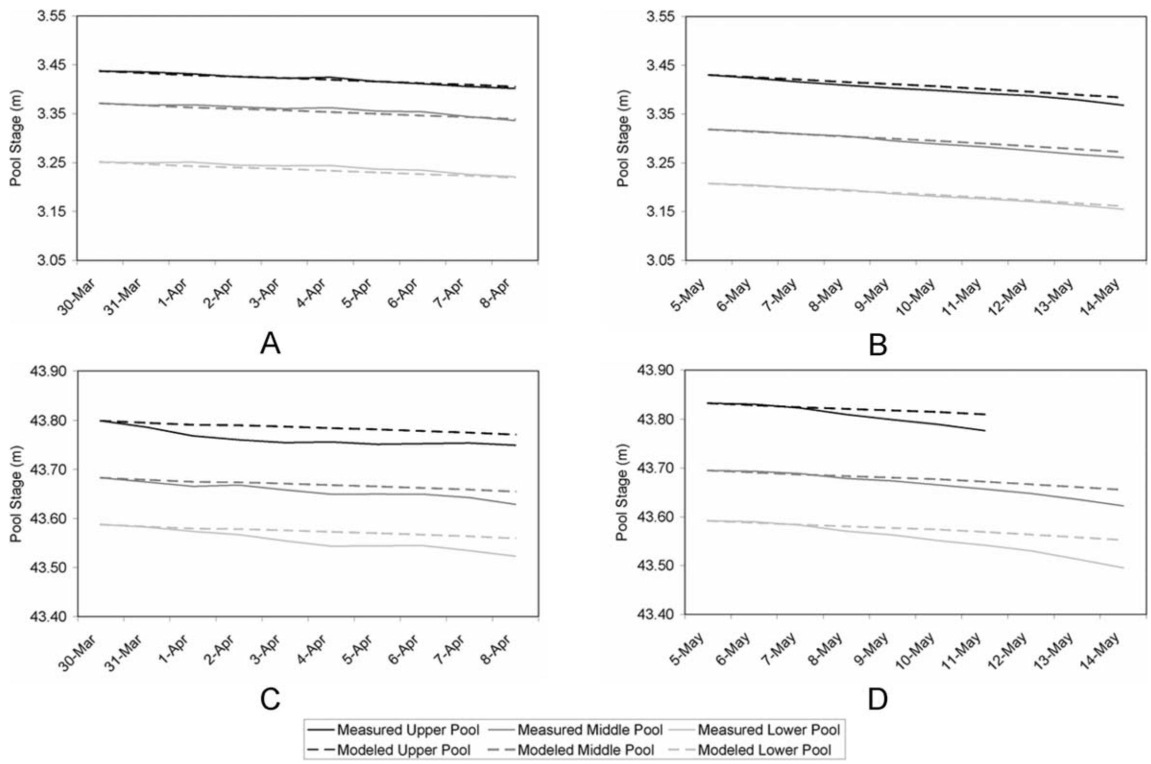

Figure 4. Measured and modeled stages in m above mean sea level during periods of time when there was little to no rainfall for A) vernal pools on clay-rich soils in the middle of the wet season, B) vernal pools on clay-rich soils at the end of the wet season, C) vernal pools on hardpan soils in the middle of the wet season, and D) vernal pools on hardpan soils at the end of the wet season during water year 2003.

seasonal, and the surface-water connections between the upper, middle, and lower vernal pools and the outlet stream were maintained for ~60% of the days during which vernal-pool water was present.

The vernal pools on hardpan soils responded more slowly to rainfall (Figure 3). Approximately 15 cm of rain fell in a series of storms between November 5 and December 16, 2003. During this time, there was no surface-water accumulation within the vernal pools. Approximately 75% of the piezometers above the claypan/duripan had ground water during or immediately following the early wet season storms. In contrast, ~80% of the piezometers below the claypan/duripan remained dry following the early wet season storms and ~30% of the piezometers below the claypan/duripan remained dry for the entire period of record. The regional water table remained ~40 m below the soil surface throughout the period of study. Therefore, shallow ground water 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 lower parts of the catchment (Figure 5). The perched ground water flowed through, under, or around the vernal pools (Rains et al. 2006).

Once the soils above the claypan/duripan were saturated, subsequent rainfall caused the vernal pools to fill beginning December 17, 2003 (Figure 3). During subsequent storm events, vernal-pool stages began to rise at the onset of rainfall and continued to rise until one to two days after the cessation of rainfall. At no time was overland flow observed delivering water from the uplands to the vernal pools. Surface water flowed between vernal pools through the connecting swales, but surface-water outflows always equaled or exceeded surface-water inflows for a given vernal pool (Rains et al. 2006). Ground-water discharge from the perched aquifer to the vernal pools accounted for ~35%–60% of the vernal-pool water during and immediately following storms, and ground-water recharge from the vernal pools to the perched aquifer accounted for ~30% of the ground water down-gradient of the vernal pools during inter-storm periods (Rains et al. 2006).

During periods of time when there was little to no rainfall, drawdown rates were much greater than evapotranspiration rates (Figure 4). From March 30 to April 8, measured and modeled drawdown rates

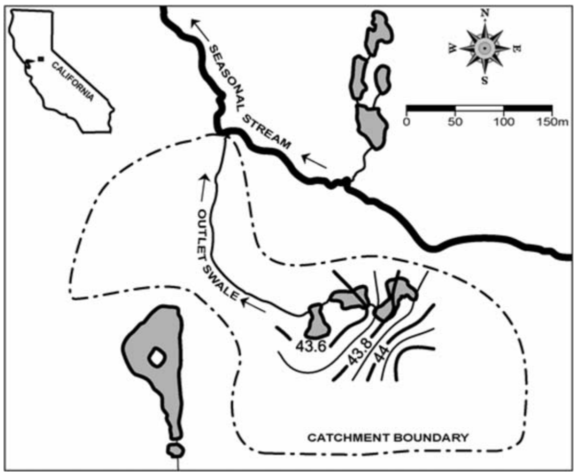

Figure 5. Hydraulic head above the claypan/duripan at the hardpan soil site in meters above mean sea level. Stages in the vernal pools were neglected in generating these contours. Data are from late February 2003, and are similar to data from earlier and later in the wet season.

were 6 and 3 mm/d, respectively. From May 5–14, as the vernal pools were drying, measured and modeled drawdown rates were 10 and 4 mm/d, respectively.

During water year 2003, the upper, middle, and lower vernal pools had standing water for ~150, 154, and 151 days, respectively. A datalogger failure on the upper vernal pool resulted in missing data during the early wet season. 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 seasonal stream were maintained for ~60% of the days during which vernal-pool water was present.

Chemical Hydrology

Electrical conductivity was relatively high in the vernal pools on clay-rich soils and relatively low in the vernal pools on hardpan soils (Figure 6). In the vernal pools on clay-rich soils, electrical conductivity was ~100–200 μS/cm through most of the wet season, then increased to ~1,000–2,000 μS/cm at the end of the wet season. The sharp increases in electrical conductivity at the end of the wet season were largely functions of evapoconcentration that occurred after vernal-pool stages dropped below the outlet swale elevations and outflows were largely functions of evapotranspiration losses (Figure 7). Overall, electrical conductivity averaged 304 μS/cm and ranged from 90–2,290 μS/cm. In the vernal pools on hardpan soils, electrical conductivity was < 100 μS/cm through most of the wet season, and remained < 200 μS/cm at the end of the wet season. Overall, electrical conductivity averaged 68 μS/cm and ranged from 24–188 μS/cm.

Water in the vernal pools on clay-rich and hardpan soils differentiated with respect to absolute concentrations, as well as the relative dominance of the various cations and anions (Table 2; Figure 8). Waters in the vernal pools on clay-rich and hardpan soils had distinctly different percentage compositions of sodium+potassium, calcium, and magnesium, with vernal pools on clay-rich soils having higher percentage compositions of sodium+potassium and relatively lower percentage compositions of calcium and magnesium. Therefore, waters in the vernal pools on clay-rich and hardpan soils plotted in distinctly different fields on a Piper diagram (Figure 8). Waters in the vernal pools on clay-rich

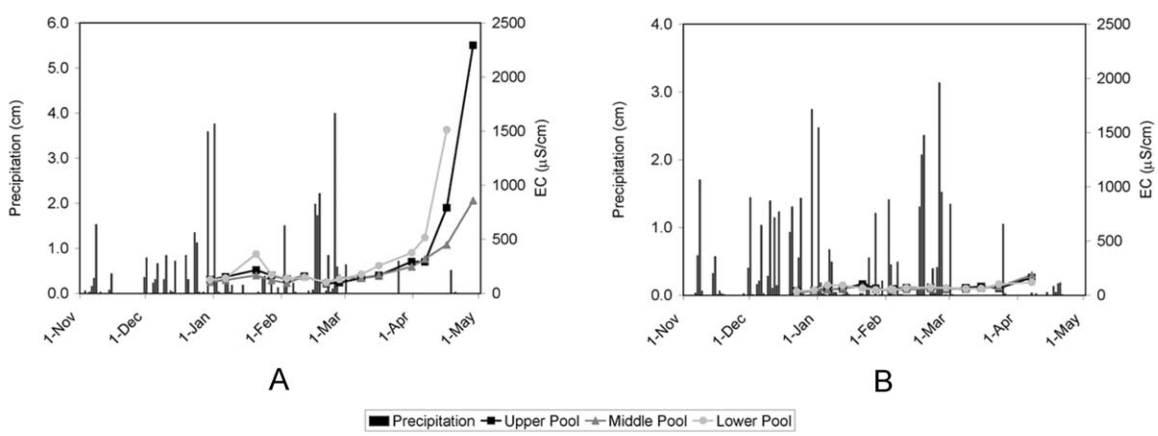

Figure 6. Daily precipitation in cm and electrical conductivity in μS/cm for A) vernal pools on clay-rich soils and B) vernal pools on hardpan soils during water year 2004.

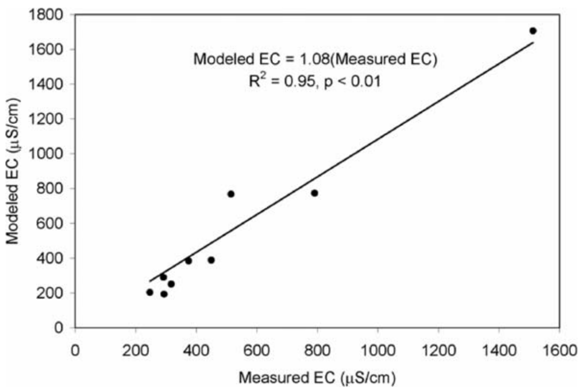

Figure 7. Scatterplot and least-squares regression line of the relationship between modeled and measured electrical conductivity indicating that the sharp increases in electrical conductivity at the end of the wet season in the vernal pools on clay-rich soils were largely functions of evapoconcentration that occurred after vernal-pool stages dropped below the outlet swale elevations and outflows were largely functions of evapotranspiration losses.

soils were largely Na+K (with no dominant anion) or Na+K, HCO_3 water types. In contrast, waters in the vernal pools on hardpan soils were largely HCO_3 (with no dominant cation) water types, and were typical of regional rainfall of recent origin that has undergone slight alteration due to short-term contact with soils or sediments. Water in the vernal pools on clay-rich soils had relatively higher sodium concentrations and relatively lower magnesium and calcium concentrations and, therefore, relatively higher sodium adsorption ratios (SAR = $Na^+/(Ca^{2+} + Mg^{2+})^{1/2}$; ion concentrations reported in mM/L). The SAR of water in the vernal pools on clay-rich soils averaged 7.2 and ranged from 3.1–13.9, while the SAR of water in the vernal pools on hardpan soils averaged 0.7 and ranged from 0.6–0.9.

Turbidity was relatively high in the vernal pools on clay-rich soils and relatively low in the vernal pools on hardpan soils (Figure 9). In the vernal pools on clay-rich soils, turbidity varied widely. Overall, turbidity averaged 43.0 NTU and ranged from 1.9–199 NTU, with some of the highest values occurring when small volumes of water were present in the early and late wet seasons. In the vernal pools on hardpan soils, turbidity varied little and had no apparent seasonal trend. Overall, turbidity averaged 3.5 NTU and ranged from 0.2–14.1 NTU.

The vernal pools on clay-rich and hardpan soils differed with respect to the concentrations of silica, nitrate-N, phosphate-P, and DOC (Table 2). In the vernal pools on clay-rich soils, silica averaged 3.8 ppm and ranged from < 0.1 to 18.0 ppm, nitrate-N averaged 0.07 ppm and ranged from < 0.01 to 2.23 ppm, phosphate-P averaged 0.13 ppm and ranged from < 0.01 to 0.73 ppm, and DOC

Table 2. Means, medians, and standard deviations for geochemical properties of rainfall, water samples from vernal pools on clay-rich soils, and water samples from vernal pools on hardpan soils. The high standard deviations for many of the geochemical properties of the vernal pools on clay-rich soils are largely due to evapoconcentration in the late wet season.

Constituent	Rainfall (n = 1)[1]	Water Samples from Vernal Pools on Clay-Rich Soils (n = 42)			Water Samples from Vernal Pools on Hardpan Soils (n = 31)		
		Mean	Median	S.D.	Mean	Median	S.D.
EC[2] (µS/cm)	12	304	157	413	68	62	30
pH	6.6	7.2	7.1	0.4	6.7	6.7	0.2
Na (ppm)	1.3	59.4	29.5	48.3	6.0	6.1	0.9
K (ppm)	0.7	1.5	0.8	2.0	1.0	0.9	0.4
Mg (ppm)	0.3	3.2	1.8	3.0	3.1	3.0	0.7
Ca (ppm)	1.1	3.9	2.9	2.6	6.6	6.1	1.9
Cl (ppm)	1.0	29.0	14.1	27.4	5.4	5.2	1.8
SO_4 (ppm)	0.7	6.5	3.3	12.2	1.9	2.0	0.6
HCO_3+CO_3 (ppm)	6.5	70.1	38.6	60.2	51.4	51.4	9.6
SiO_2 (ppm)	0.2	3.8	1.6	5.5	6.3	5.8	3.1
NO_3-N (ppm)	-	0.07	< 0.01	0.39	0.18	0.02	0.31
PO_4-P (ppm)	-	0.13	0.01	0.21	< 0.01	< 0.01	< 0.01
DOC[3] (ppm)	-	17.0	18.5	7.8	4.7	4.8	2.2
SAR[4]	0.3	7.2	5.7	3.4	0.7	0.7	0.1
Turbidity (NTU)	-	43.0	26.3	46.4	3.5	2.5	3.4

[1] Just one sample, so no mean, median, or standard deviations are reported.
[2] EC = electrical conductivity.
[3] DOC = dissolved organic carbon.
[4] SAR = sodium adsorption ratio.

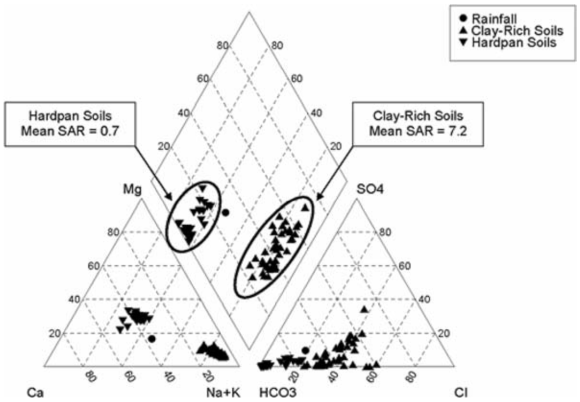

Figure 8. Piper diagram (Piper 1944) indicating that water in the vernal pools on clay-rich and hardpan soils had distinctly different percentage compositions of sodium+potassium, calcium, and magnesium, with vernal pools on clay-rich soils having higher percentage compositions of sodium+potassium and relatively lower percentage compositions of calcium and magnesium.

averaged 17.0 ppm and ranged from 3.1–27.6 ppm. In the vernal pools on hardpan soils, silica averaged 6.3 ppm and ranged from $<$ 0.1 to 13.6 ppm, nitrate-N averaged 0.18 ppm and ranged from $<$ 0.01 to 1.40 ppm, phosphate-P was always $<$ 0.01 ppm, and DOC averaged 4.7 ppm and ranged from 0.9–10.0 ppm. In the vernal pools on clay-rich soils, nitrate-N concentrations were below detection limits in 16 of the 17 samples in which phosphate-P concentrations were measurable. Conversely, in the vernal pools on hardpan soils, phosphate-P concentrations were below detection limits in all 65 samples including all 35 samples in which nitrate-N concentrations were measurable. Silica, phosphate-P, and DOC concentrations were significantly different between the vernal pools on clay-rich and hardpan soils ($p < 0.01$), while nitrate-N concentrations were not significantly different between the vernal pools on clay-rich and hardpan soils ($p = 0.13$). Ammonium-N concentrations were almost always less than the detection limit (0.08 ppm) and are therefore not reported.

DISCUSSION

Controls on the Hydrology of Vernal Pools on Clay-Rich Soils

The clay-rich soils developed on alluvium derived primarily from sedimentary and metasedimentary rocks of marine origin and deposited in relatively low-gradient, quiescent environments. These source rocks are predominantly mudstones and siltstones (Dickinson and Rich 1972). Therefore, sediments derived from these source rocks tend to have a high proportion of clay- and silt-sized particles ($>$ 80%). Sediments derived from fine-grained sedimentary rocks of marine origin also can have high sodium concentrations (Gunn and Richardson 1979). Furthermore, regional tectonic compression results in the expulsion of diluted and modified connate seawater from cold and hot springs throughout the upper watershed and surrounding regions (White et al. 1973, Peters 1993, Davisson et al. 1994). Therefore, sediments derived from these source rocks in this region tend to have high sodium concentrations, with these high sodium concentrations enhancing colloidal dispersion (Singer and Munns 1996).

The fine-grained sediments, the swelling of the smectite clays due to interlayer water adsorption, and the clogging of pores by dispersed clays results in very low hydraulic conductivities of $\sim 10^{-8}$ cm/s throughout the entire pedon (Quirk and Schofield 1955, Bates 1977). Soil cracking occurs in the dry season. However, the smectite clays expand due to interlayer water adsorption, so the depth of soil

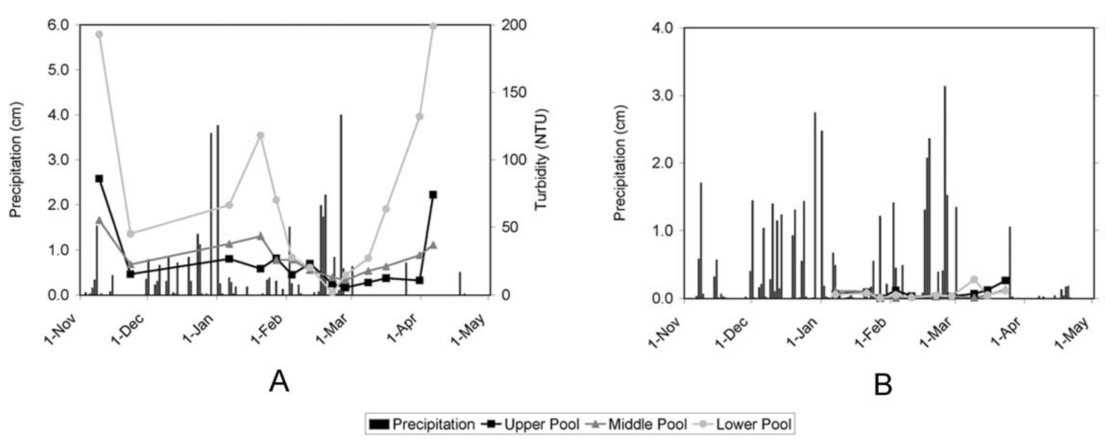

Figure 9. Daily precipitation in cm and turbidity in NTU for A) vernal pools on clay-rich soils and B) vernal pools on hardpan soils during water year 2004.

cracking may be limited by capillary rise from the shallow regional water table and, regardless, soil cracks are quickly sealed by early wet-season rainfall. Although early wet-season flow through soil cracks and wet-season flow through the matrix allow some leaching to occur, the depth to which leaching can occur appears very limited, with the relatively lower pH, electrical conductivity, and exchangeable sodium percentage in the surface horizon (i.e., 0–8 cm), possibly reflecting the effective depth of leaching. This is consistent with field observations of the depth of soil wetting during the study.

Due to low permeabilities throughout the pedon, the vernal pools on clay-rich soils are perched surface-water systems. Precipitation perches on the low-permeability surface soils and flows overland to the vernal pools in topographic low positions. When vernal-pool stages rise above the elevations of the outlet swales, outflows are largely by surface-water flow through the outlet swales. When vernal-pool stages fall below the elevations of the outlet swales, outflows are largely by evapotranspiration. These flowpath characteristics largely control the chemical nature of the vernal-pool water.

The high electrical conductivity of the vernal-pool water is largely a function of evapoconcentration, particularly toward the end of the wet season. For most of the wet season, direct precipitation and overland flow provide relatively fresh water to the vernal pools. Toward the end of the wet season, there is little inflow due to direct precipitation and overland flow and little outflow beyond evapotranspiration. Therefore, remaining surface water evapoconcentrates and electrical conductivity increases. At the end of the wet season, supersaturation of vernal-pool waters occurs, leading to formation of a thin crust of evaporites on the dry vernal-pool beds. Evaporites not removed by aeolian processes during the dry season are dissolved when the vernal pools fill in the subsequent wet season. Some of these solutes are leached from the surface to the shallow subsurface, primarily through cracks, where they accumulate in relatively high concentrations and contribute to the moderately- to strongly-saline and sodic soil conditions below the surface horizon (i.e., below 0–8 cm). The balance of these solutes remain dissolved in the vernal-pool surface water. Therefore, even in the early wet season, the electrical conductivity of the vernal-pool surface water is an order of magnitude greater than precipitation.

The vernal pools on clay-rich soils have relatively turbid surface water. Overland flow suspends and transports clays from the uplands to the vernal pools, and inflowing water and wind-driven, water-column circulation suspend clays from the vernal-pool beds. Erodibility of the clay-rich soils is enhanced by the high sodium concentrations, which enhance colloidal dispersion (Miller and Baharuddin 1986, Shainberg et al. 1992). Overland flow also suspends and transports particulate carbon from the uplands to the vernal pools, where it adds to the pool of *in situ*-formed particulate carbon (Maybeck 1993). The high sodium concentrations in the vernal-pool water keep the clays and DOC dispersed and in suspension (Singer and Munns 1996). Both the suspended clays and the high DOC concentrations contribute to the relatively high turbidity.

Silica and nutrient concentrations appear to be strongly controlled by the hydrologic flowpaths. For most of the wet season, inflow to the vernal pools is largely due to direct precipitation and overland flow. Dissolved silica concentrations are relatively low due to the low degree of solution-solid contact associated with the dominantly surface-water flowpath. Similarly, with limited contact time between water and sediments, there are limited opportunities for the mobilization of the nitrate that accumulates within the upland soils when the annual grasses in the uplands senesce and are mineralized by microbial activity during the dry season. Therefore, nitrate-N concentrations in the vernal-pool water were typically below detection limits (< 0.01 ppm). In contrast, the high suspended-sediment concentrations associated with surface-water flows readily transport adsorbed phosphorus to the vernal pools (Meyer 1979, Smeck 1985, Klotz 1988). Therefore, phosphate-P concentrations in the vernal-pool water are relatively high. DOC concentrations in the vernal-pool waters are also elevated due to enhanced dispersion by the sodium-rich runoff waters in contact with the organic-rich soil surface.

Controls on the Hydrology of Vernal Pools on Hardpan Soils

The hardpan soils developed on alluvium derived primarily from coarse-grained igneous rocks and deposited in relatively high-gradient environments. These sediments have a high sand content and would have high hydraulic conductivities throughout the entire pedon were it not for the development of the indurated duripan and the overlying clay-rich argillic horizon. Saturated hydraulic conductivities for this soil series range from 10^{-4}–10^{-1} cm/s above the claypan to 10^{-7} cm/s in the claypan/duripan (Tugel 1993). Wet-season lateral flow through the upper pedon allows leaching to occur, with the relatively lower pH, electrical conductivity, and exchangeable sodium percentage above the duripan (i.e., 0–68 cm) possibly reflecting the effective depth of leaching. These flowpaths largely control the chemical characteristics of the vernal-pool water.

Due to high permeabilities in the upper pedon and low permeabilities in the lower pedon, the vernal pools on hardpan soils are integrated surface-water and perched ground-water systems. Precipitation infiltrates but perches on the claypan/duripan, and this perched ground water flows downgradient toward the seasonal stream. The upper layer of soil above the claypan/duripan is $\sim$0.6 m thick in the uplands and $\sim$0.1 m thick in the vernal pools. When hydraulic heads in the perched aquifer exceed $\sim$0.1 m above the claypan/duripan, some perched ground water flows through the vernal pools by discharging primarily at the upgradient ends of the vernal pools and recharging primarily at the downgradient ends of the vernal pools (Rains et al. 2006). When vernal-pool stages rise above the elevations of the outlet swales, outflows are largely by surface-water flow through the outlet swales and ground-water recharge. When vernal-pool stages fall below the elevations of the outlet swales, outflows are largely by ground-water recharge. Much of this ground water remains in the perched aquifer and continues to flow downgradient (Rains et al. 2006). However, $\sim$70% of the piezometers below the claypan/duripan had ground water at some point during the period of record. Therefore, some of this ground water passes through the claypan/duripan. The spatial and temporal variability of the ground water suggests that ground water passes through the claypan/duripan by preferential flowpaths and may move vertically and laterally along multiple, staggered perching horizons. However, it also is possible that this ground water passed through the claypan/duripan by preferential flow down the piezometer annuli.

The low electrical conductivity of the vernal-pool water is largely a function of the ground-water throughflow. For most of the wet season, direct precipitation, swale flow, and ground-water discharge provide relatively fresh water to the vernal pools. Toward the end of the wet season, there is little inflow from direct precipitation and swale flow. However, there is continued inflow due to ground-water discharge which provides a continuous source of fresh water that limits the local effects of evapoconcentration. Slight evapoconcentration only occurs when small volumes of water remain, such as when the upper vernal pool temporarily dried during a prolonged dry period in late January and when the upper, middle, and lower vernal pools dried at the end of the wet season in late June.

The vernal pools on hardpan soils have relatively non-turbid surface water. Infiltration into the high-permeability upper pedon is relatively rapid, so overland flow rarely occurs except for slow channelized flow through the vegetated swales. The uplands and swales are characterized by moderate coverage with primarily non-native annual grasses, while the vernal pools are characterized by dense coverage with primarily native annual grasses, forbs, and pool-bed algae, all of which secure sediments and reduce erosion (Gray 1974, Prosser et al. 1995). Therefore, the limited overland flow that may occur does not suspend and transport substantial sediment from the uplands to the vernal pools. However, it may suspend and transport some particulate carbon from the uplands to the vernal pools where it may add to the pool of *in situ*-formed particulate carbon (Maybeck 1993). Much of the vernal-pool water, however, is derived from ground-water discharge, which contains almost no suspended sediment and has low DOC concentrations because the DOC is strongly adsorbed during transport to the abundant iron oxides in the upland soils (Hobson and Dahlgren 1998, Rains et al. 2006). The relative lack of suspended sediments and relatively low DOC concentrations contribute to the relatively low turbidity.

Silica and nutrient concentrations are strongly controlled by the flowpaths. Throughout the wet season, some perched ground water flows through the vernal pools by discharging primarily at the upgradient ends of the vernal pools and recharging primarily at the downgradient ends of the vernal pools (Rains et al. 2006). With hydraulic conductivities of 10^{-4}–10^{-1} cm/s, effective porosities of $\sim$0.25, and hydraulic gradients of $\sim$0.02, mean ground-water flow velocities above the claypan/duripan may range from $\sim$0.008–8 m/d. Dissolved silica concentrations are relatively high due to the high degree of solution-solid contact associated with the dominantly subsurface flowpath. Similarly, with ample contact time between water and soils, there are sufficient opportunities for the mobilization of the nitrate that accumulates in the upland soils when the annual grasses in the uplands senesce and are mineralized by microbial activity during the dry season. Nitrate fluxes are largest in the early wet season when upland annual grass biological demand is low, and smallest in the late wet season when most of the nitrate has been flushed and upland annual grass biological demand is high (Rains et al. 2006). Therefore, nitrate-N concentrations in the vernal-pool water are relatively high throughout the wet season, although somewhat higher in the early wet season than in the late wet season. In contrast, the contact between water and soil during subsurface flow results in ample opportunities for the adsorption and immobilization of phosphorus by iron oxides in the upland soils (Smeck 1985). Therefore, phosphate-P concentrations in the vernal-pool water were always below detection limits ($<$ 0.01 ppm).

CONCLUSIONS

Although surficially similar, vernal pools on clay-rich and hardpan soils differ with respect to geology, soils, and physical and chemical hydrology. In both cases, different source rocks resulted in different soils, and different soils resulted in different physical and chemical hydrological characteristics.

The vernal pools on clay-rich soils formed on alluvium derived from sedimentary and metasedimentary rocks of marine origin. The soils that developed on these sediments are fine grained, saline, and sodic. These soils support vernal pools that are perched surface-water systems, have relatively saline, sodic, and turbid surface water, and may be nitrogen and light limited. The vernal pools on hardpan soils formed on alluvium derived from coarse-grained igneous rocks. The soils that developed on these sediments have coarse-grained surface horizons underlain by clay-rich argillic horizons and silica- and iron-cemented duripans. These soils support vernal pools that are surface-water and perched ground-water systems, have relatively fresh and non-turbid surface water, and may be phosphorus limited.

Vernal pools on clay-rich and hardpan soils are perhaps the most common types of vernal pools in the Central Valley, California. However, vernal pools on clay-rich and hardpan soils have developed in a variety of geological settings. For example, vernal pools on clay-rich soils also occur on the alluvial fan deposits of the eastern Central Valley, California. In these cases, geological conditions are unlikely to support saline and sodic soils and regional water tables are likely too deep to allow capillary rise to the shallow subsurface. Furthermore, vernal pools also occur on other geological surfaces, including mudflows or lahars and bedrock. The degree to which geology controls the physical and chemical hydrology of these other vernal pools remains largely unknown due to an almost complete lack of attention.

There is abundant ecological literature indicating that physical and chemical hydrology control species composition and abundance in vernal pools. Therefore, it is tempting to suggest that geology controls species composition and abundance in vernal pools. However, the linkages between geology, soils, and the measured physical and chemical hydrology are rarely articulated in this abundant ecological literature. Therefore, geological control of species composition and abundance in vernal pools remains a hypothesis to be tested by further studies. If true, the distribution and abundance of many endemic and rare floral and faunal species are controlled by geological processes operating on millennial time scales, information that could be critical to the success of many resource conservation, restoration, and management efforts.

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