A Draft Regional Guidebook for Applying the Hydrogeomorphic Approach to Assessing Wetland Functions of Vernal Pool Depressional Wetlands in Southern California

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ABSTRACT: This Draft Guidebook is an assessment tool that focuses on the functioning of vernal pool wetlands within the Southern Californian eco-region, specifically San Diego County. Its purpose is to provide trained practitioners the means to achieve efficient, reproducible and logical functional assessment results for vernal pool wetlands in San Diego County, California. Results of these assessments can then be used in a variety of ways, such as evaluation of sites for restoration potential, assessment of impacts from existing or proposed projects and monitoring restoration success. Due to the high degree of variability experienced by temporary wetlands in arid climates, we have developed both direct and indirect functional indices for four of the five functions we identified. Direct assessments can only be made when there is sufficient precipitation to elicit the responses that demonstrate function, and we have sought to objectively define "sufficient." Consistent with an HGM approach, use of this Draft Guidebook should be confined to the geographic region and hydrogeomorphic class, subclass and pool types for which it was developed. Use of this methodology outside the boundaries of the reference domain is wholly inappropriate. We are hopeful that our approach can be modified for other pool types within the region, and to vernal pools in other parts of California and Oregon.

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3 Characterization of the Temporary and Seasonally Ponded Vernal Pool Ecosystems in Southern California

Regional Wetland Subclass and Reference Domain

This Draft Regional Guidebook was developed to assess the functions of depressional, rainfed, temporarily and seasonally ponded herbaceous wetlands in California south of the Transverse Ranges, and from the Peninsular Ranges west to the Pacific Ocean. These pools are commonly called vernal pools in recognition of the seasonality of the habitat and the springtime floral display (Purer 1937, Ramaley 1919). This guidebook should also be used on sites that formally had vernal pools but now lack some or all of these characteristics.

Vernal pools are found throughout California in many geographic settings and subclimates (Keeler-Wolf *et al.* 1998, Figure 3.1). Due to statewide variation in geomorphology, soil profiles and climate, pools have a wide range of hydrological regimes and substrates that support a diverse and locally adapted flora and fauna. The ecosystem is known for endemism and abundant speciation within many plant and animal genera (*e.g*., Simovich 1998, Stebbins 1976), and some endemic pool species have extremely restricted distributions (Bauder and McMillan 1998, Griggs and Jain 1983, King 1998, Ornduff 1976, Simovich 1998, Stebbins 1976).

Within the regional subclass of southern Californian vernal pools, there are 24 possible types based on classification by geomorphologic origin and age (See Chapter 5, Table 2). We have identified pools in 16 cells of the matrix. The reference domain selected to represent this regional wetland subclass included only 5 pool types: coastal mesa/pedogenic (Mira Mesa/Miramar and Otay Mesa), inland valley/pedogenic and alluviated (Ramona), coastal mesa/landslide (Otay Mesa) and inland valley alluviated (Ramona) (Figure 3.2). Under ideal circumstances, the reference domain would have encompassed all of the known pool types and different areas within types. Given the region's immense area (about 15 million acres) and extreme year-to-year variation in precipitation, resources were not available to include all pool types under conditions suitable for assessment. It is hoped that the methodology and analytical techniques developed for the reference domain will be expanded to other pool types within the regional subclass and to other areas of California as well. The pedogenic vernal pools of San Diego County are in many ways intermediate in properties such as soil depth and leakage rates through the resistant, pool-supporting horizons, allowing some extrapolation to other pool types that we could not measure.

Our approach was developed specifically to deal with the assessment challenges presented by the seasonality of the wetlands and the highly variable climate.

(Source: California Wetlands Information System, http://ceres.ca.gov/wetlands/geo_info/vernal_pools_map.html)

Figure 3.1. Vernal pool regions in California.

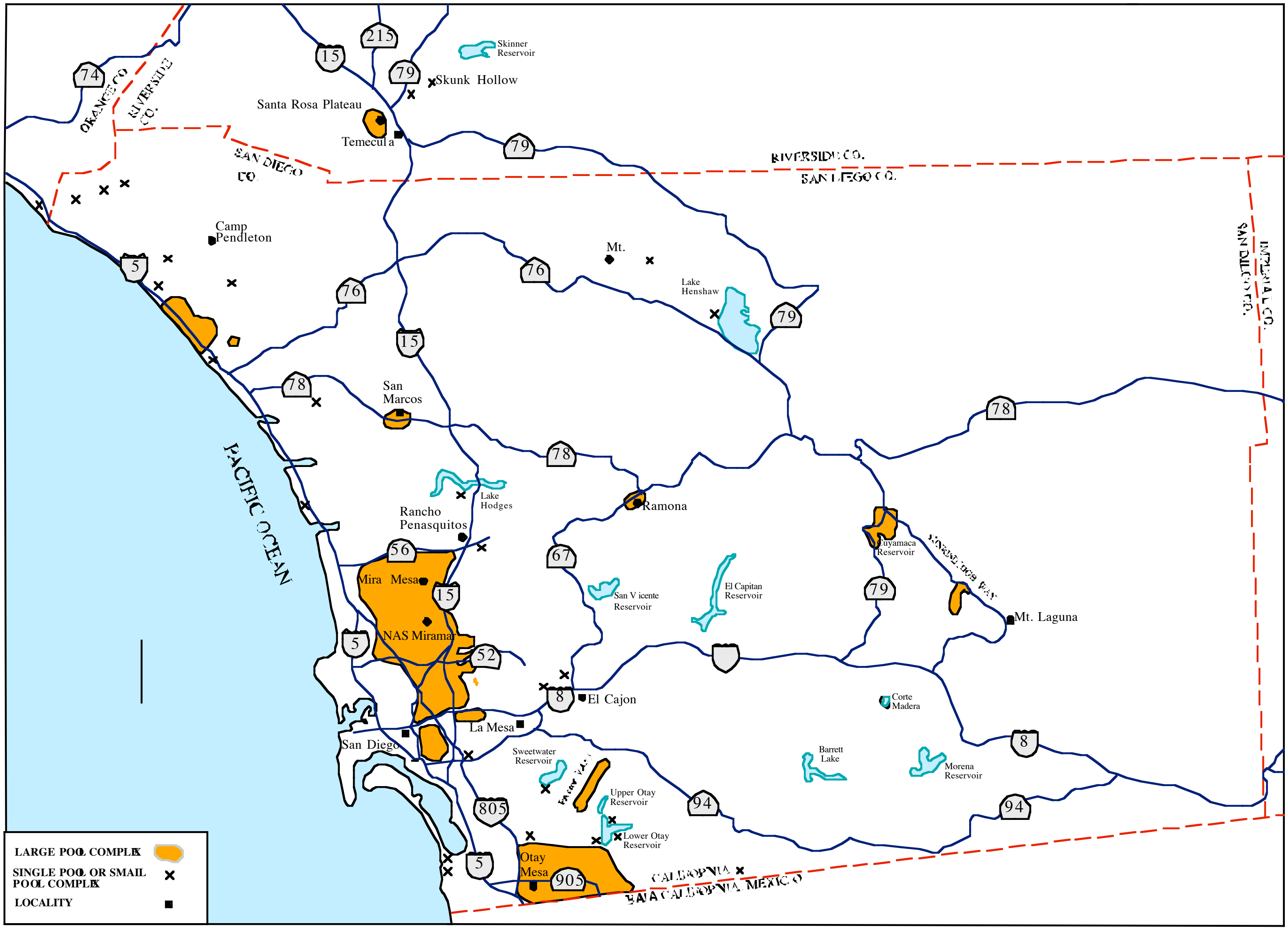

Figure 3.2. Area containing reference pools.

Description of the Regional Wetland Subclass

Vernal pools occur on alluvial or marine terraces and various volcanic substrates (Bauder and McMillan 1998, Holland and Dains 1991, Keeler-Wolf *et al.* 1998, Norwick 1991). Although some may be isolated or approach the size of small lakes (Bauder *et al.* 1998, Lathrop 1976), they are more commonly found in archipelagoes of small ponds situated in depressions among soil mounds or hummocks, connected by a directional network of swales or shallow drainages. Clayey surface soils in the basins are often underlain by a hardpan of cobbles cemented with a combination of iron and silica or, less frequently, by granitic or basaltic rocks that prevent percolation of water into the subsoil (Nikiforoff 1941, Weitkamp *et al.* 1996). The region's Mediterranean climate brings winter rainstorms—often intense—followed by a long summer drought. After the rains begin, pools form in the depressions above the poorly draining soil layer or layers. When they are filled to capacity, their surface area ranges from as small as 50 ft^2 to 20 acres. Vernal pools can remain filled for 3-5 months during wetter years, but may fail to pond water in years of sparse precipitation. Fluctuating water levels during the rainy season can expose and re-inundate the soil surface of pool basins a number of times before they dry completely in late spring. Large pools with a substantial watershed may occasionally retain water year round. Within- and between-year variability in moisture conditions is the crucial factor preventing these wetlands from becoming freshwater marshes or persistent ponds, or from being dominated by upland shrubs and herbs.

Climate

In southern California, climatic variables are most influenced by distance from the coast, topography and elevation (Bauder and McMillan 1998). Yearly average precipitation is lowest along the coast and rises with distance inland, to a peak in the Peninsular Ranges to the east (Table 3.1). It then drops abruptly in the rain shadow of the mountains where the upper Sonoran Desert (Colorado Desert) begins. Long-term means are 8.5-13 inches at coastal locations and 24-49 inches in the mountains. Within a rainfall year (July 1 to June 30), most of the precipitation occurs from November through March and is concentrated in a half dozen storms that may occur within a few months or be spread more evenly over the rainfall season (Bauder 2005, Goldman *et al.* 1986, Mooney and Parsons 1973). Precipitation is greater than potential evapotranspiration (ET_0) only during the winter months (Greenwood 1984, Greenwood and Abbott 1980). At higher elevations to the east, rain from summer convective storms may produce up to 20 percent of the yearly precipitation during the June-August period (Bauder 1994), and a significant portion of the yearly precipitation in the mountains may fall as snow. In the mountains, below freezing temperatures often occur between October/November and April/May (Bowman 1973). On the coastal terraces there is little or no frost.

Table 3.1. Climatic Variables Affecting Vernal Pools and Temporary Lakes in Southern California.

Pool Location		Elevation # (feet)	Annual Precipitation* (inches)
Coastal Mesas	Chula Vista	56	10.9
	La Mesa	530	12.8
	Montgomery Field	414^	13.1
	Otay Mesa	510^	10.5
	Oceanside Harbor	10	10.5
	Laguna Beach~	60	12.7
	Santa Barbara~	14	14.1
Inland Mesas	Santa Rosa Plateau+	2,400	15.0-16.6
Inland Valleys	El Cajon, Gillespie Field (west)	380^	10.7
	El Cajon (east)	520^	14.1
	Ramona	1,450	16.1
	San Marcos	520^	12.6
	Perris~	1470	10.4
	Moorpark~	58	13.1
Mountains	Cuyamaca	4,640	38.7
	Palomar	5,550	49.4

Elevation from NOAA Climatological Data, Station Index; otherwise, from USGS 7 1/2 minute quadrangle maps (^).

* Precipitation from County of San Diego (Cartographic Services) rainfall map and WRCC~.

+ All data from Lathrop and Thorne, 1976.

As with all arid and semi-arid climates, annual variability in precipitation is substantial (Le Houérou 1984). Since record keeping began in the City of San Diego in 1850, yearly precipitation at the Lindbergh Field weather station has ranged from 2.03 inches in 2001/2002 to 25.98 inches in 1883/84. Over a l03-year period at Cuyamaca in the inland mountains, precipitation has ranged from a 13.46 inches to 74.65 inches. Very dry or wet years can follow each other, with no obvious temporal autocorrelations (Bauder 1987a, Bauder 2005).

The inland valleys share characteristics of both the montane and coastal climates, with precipitation higher and frost more common than along the coast, but snow and summer rainfall rare. Although the valleys lie on the coast-to-mountain continuum, anomalies in topography may greatly affect their climate. Cold air often drains through canyons into low-lying valleys, and minor rain shadows can develop as a result of adjacent mountains and hills. For example, El Cajon Valley has occasional frost and lower rainfall than nearby La Mesa, which is situated on the coastal terrace. Although the mean annual precipitation for La Mesa is 12.81 inches, the western end of the El Cajon Valley (in the shadow of Mount Helix and Fletcher Hills) has a mean of 10.71 inches (Cartographic Services, County of San Diego). Three miles further inland, the mean at the east end of the valley increases to 14.13 inches (Bauder and McMillan 1998).

Geomorphic setting and soils

The primary landscape positions of vernal pools in southern California are mesas or valleys. Pools near the coast in San Diego County occur on marine-influenced terraces distributed in a broad arc west of the mountains known as the San Diego embayment (Kennedy 1975). The embayment was geologically active during the Pleistocene Epoch, with sea levels rising and falling numerous times, resulting in wave-cut terraces that were exposed or submerged, depending on the sea level. Many of the inland valleys are filled with granitic alluvium, but weathered sandstone and leucocratic (light-colored) volcanic rocks contributed to the surfaces.

Virtually all soils maps for Southern California are prepared at a scale emphasizing mapping areas larger than 20 to 40 acres (Order 3). Soils within the pools themselves are not mapped; rather, they are considered 'inclusions' which may or may not be discussed in the soil survey texts. Differences between the inclusion and the local soils are least for pedogenic soils and greatest for landslide-related soils. The upland soil series associated with vernal pools all have phases that share similar properties: 1) slopes of 9% or less, 2) a thick clay layer in the B horizon beginning approximately 1-2 feet below the upland soil surface that retards drainage and 3) low permeability, often <0.06 inches per hour, which is the slowest class used by soil scientists.

Within the reference domain, the soil series differ in their origins, distributions and other properties such as pH (Table 3.2). Chesterton, Redding, Olivenhain and Murrietta are acidic in both the surface and subsurface layers. Placentia, Stockpen and Huerhuero soils are acidic at the surface but have alkaline subsurface layers. Willows is alkaline in both the surface and subsurface layers. With the exception of the Placentia and kindred soils, all of the cismontane soil series supporting vernal pools were subject to past marine influences. Chesterton, Huerhuero and Stockpen soils developed from sandy marine sediments. Redding and Olivenhain soils were formed on cobbly alluvium cut from an Eocene alluvial fan by rising Pleistocene sea levels and deposited on wave-cut terraces. They subsequently were exposed in late Pleistocene times. Placentia soils formed in granitic alluvium found in small- to medium-size inland valleys. The likelihood of pools having once been present on the smaller patches of Placentia soils is low, and to our knowledge there are no documented occurrences in these minor drainages.

Table 3.2.
Southern California Soil Series within which Vernal Pools Are Reported[1]

SOIL SERIES	SYMBOL of MAPPING UNIT	SYMBOL (urbanized)	TYPE OR TEXTURE OF LOW-PERMEABILITY LAYER[2]	DEPTH OF LO-PERM LAYER (inches)	PERMEABILITY (in/hr)	pH (surface/subsurface)	REPRESENTATIVE POOL LOCATIONS
ALTAMONT	AtC		clay & clay loam	0-36	.06-0.20	6.6/8.0	San Marcos ?
ARLINGTON	AvC		weakly cemented coarse sandy loam	33-48	.06-0.20	6.7/6.5	Ramona ?
AULD	AwC		clay	0-54	.06-0.20	6.8/7.8	San Marcos ?
BONSALL	BlC,BlC2, BmC, BnB		heavy clay loam	10-38	<0.06	6.2/8.0	Ramona ?
BOSANKO	BsC, BtB		clay & sandy clay loam	0-30	.06-0.20	6.3/8.2	Alpine ? Ramona ?
CALLEGUAS	CaF (w/ LeE2)		shaly loam	0-20	0.63-2.0	7.4/8.4	Simi/Moorpark (Tierra Rejada)[3] ?
CARLSBAD*	CbC, CbB	CcC	weakly cemented hardpan	39-50	<.06	6.0/6.5	Miramar Landfill, W series pools;
							San Onofre State Beach
CHESTERTON	CfB, CfC	CgC	sandy clay, cemented hardpan	19-34,34+	<.06	6.0/5.2	coastal mesas?
CHINO	Ce		no distinct layer		.20-.63	7.9/8.4	Hemet-upper Salt Crk
CIENABA	141,142		Sandy loam	0-7; 0-17	2.0 to 6.0	5.6/7.3	Chiquita Ridge (part)
CLAYEY ALLUVIAL	Co		clay, clay loam		slow		Ramona ?
CLEAR LAKE	CeC		clay	0-62	0.06-0.20	7.5/7.9	Simi/Moorpark (Tierra Rejada)[3]
CROPLEY	149		clay	0-65	.06-0.20	6.6/8.4	Costa Mesa
DIABLO	DaC	DcD	clay	0-32	.06-.2	6.8/7.8	Otay Mesa ?
HUERHUERO*	HrC, HrC2	HuC	clay and clay loam	12-55	<.06	5.3-/8.2	coastal mesas and Marron Valley
JAMES CANYON^	JcA, JcD		loam	none indicated	0.6-2.0	6.8/6.8	Cuyamaca Valley
LAS FLORES	LeC, LeC2	LfC	sandy clay	14-38	<.06	5.8/6.8	San Marcos? Pendleton?
LAS POSAS	LpB, LpC, LpC2		clay and clay loam	0-33	.2-.63	7.3/6.8	
LINNE	LsE		clay loam	0-37	.2-.63	7.9/8.1	Simi/Moorpark (Tierra Rejada)[3] ?
LOAMY ALLUVIAL	Lu						SD County mountains
MYFORD	172			12-49	<.06	5.1-8.4	Costa Mesa, San Clemente State Beach
MURRIETTA*	MuE		clay	9-17	.06-0.20	5.6/6.0	Santa Rosa Plateau (Mesas de Burro &
							Colorado, Mesa de la Punta & Redonda Mesa)
OLIVENHAIN*	OhC	OkC	very cobbly clay loam & clay	10-42	<.06	5.7/5.3	coastal mesas
PLACENTIA*	PeC, PeA, PeC2,		sandy clay	13-34	<.06	6.0/8.0	San Marcos, Ramona
	PfA, PfC						
RAMONA	RaA, RaB, RaC, RaC2		sandy clay loam	17-72	.2-.63	6.2/6.8	Ramona? San Marcos?
REDDING*	RdC, ReE	RhC	gravelly clay & indurated hardpan	15-30,30-45	<.06	5.8-4.5	central coastal mesas
SALINAS	SbA, SbC, ScA, ScB		clay	0-46	.06-0.20	7.2/7.9	?
SHINGLETOWN^			loam	10-20	.06-0.20	6.0/6.7	Cuyamaca Valley
SOPER	201,204		gravelly clay loam	8 to 21	0.2 to 0.6	6.1/7.8	Chiquita Ridge (part);
							also, nearby Radio Tower Ridge
STOCKPEN*	SuA, SuB		gravelly clay, clay	21-60	<.06	6.5/8.0	Otay Mesa
TRAVER	Ts		none		6.3-20.0	6.6/7.8	Hemet-upper Salt Crk

[1] Virtually all soils maps for Southern California are prepared at a scale emphasizing mapping areas larger than 20 to 40 acres (Order 3).
Soils within the pools themselves are not mapped; rather, they are considered 'inclusions' which may or may not be discussed in the soil survey texts.
Differences between the inclusion and the local soils are least for pedogenic soils and greatest for landslide-related soils.

[2] Adapted from the soil series description and/or tables describing engineering properties and classifications, engineering test data or physical and chemical properties of soils.

[3] The 4.6-acre pool at Tierra Rejada is part of a 5 to 10 acre area of low slopes on which the soil appears to be Clear Lake clay, not the Calleguas or Linne steep-slope soils that occur on either side of this tectogenic trough (Hecht et al., 1998); hence Clear Lake clays are included in this table.

* = vernal pool soil types in which most Southern California pools occur.
^ = not contained in USDA soils maps for San Diego County (Borst 1984).
? = co-occurrence of soils and pools unknown or uncertain.

Sources: USDA Soil Surveys for San Diego (Bowman 1973), Orange and Western Part of Riverside (Wachtell 1978) and Santa Barbara (Cole *et al*. 1958, Shipman 1981) Counties and Ventura (Edwards *et al*. 1970) and Western Riverside (Knecht *et al*. 1971) areas; Bomkamp 1995; Bramlet 1996; RECON 1995; Riefner & Pryor 1996; and Hecht *et al*. 1998.

In addition to the accumulated (or "illuviated") clays, some pool soils are also underlain by a more impervious hardpan or bedrock beneath the drainage-retarding clay layers. These substrates can range from cemented hard pans composed of cobbles held together by iron and silica cement (as in the Redding soils) to calcic cementation or to granitic and volcanic bedrock. Their role in vernal pool hydrology is essentially unknown. These deeper substrates are clearly not necessary to the formation of pools, although in some cases they may be the primary factor (*e.g.*, Hidden Lake on Mount San Jacinto and the Santa Rosa Plateau in Riverside County). Some of the larger pools in Riverside and Ventura Counties are formed along faults, where tectogenic pools have evolved in sags or topographic lows initially established (or maintained) by faulting. Many pools underlain by marine shales in Orange and San Diego are often formed in pull-away depressions at the heads of very large landslides of probable Pleistocene age. Thick accumulations of clay characterize both these pond types, which have one of the slowest seasonal responses due to the large cracks and heavy clays that must respond to the initial rains of winter before ponding can occur (Hecht *et al.* 1998). These two pool types receive a higher volume and proportion of entering clay particles, which accumulate at rates that exceed the cementation rates of the pedogenic-pool soils.

The majority of pools found in San Diego County occur (and historically were found) on Redding soils. Profiles typical of this soil series are represented in Figure 3.3 (Soil Survey Laboratory 1996). At the site level, the gradient in Redding soil texture from uplands to the lowest elevations of the basin is striking, with the clay fraction increasing with depth (Figure 3.4; Bauder 1987a). Various soil chemistry variables are likewise correlated with position on the upland/basin elevational gradient (Table 3.3; Bauder 1987a). Number of days inundated has a strong negative correlation with elevation and is positively associated with the presence of several nutrients (Table 3.3; Bauder 1987a).

Hydrology

<u>Water sources</u>

All water in vernal pools originates as precipitation. Principal sources for all pool types are rainfall directly onto the pool surface, as well as surface runoff and subsurface inflow from near-pool areas (seldom more than 5 to 10 pool diameters away except in the wettest of years). In the alluviated pools of Ramona and other areas, overflow from adjoining streams can contribute to the pool, or the pools may develop as part of the stream system, bringing in water from more than a mile distant in some cases. Dune-dammed pools and landslide-head pools may also receive surface inflow from a channel with a watershed of several acres or perhaps slightly more. In many cases, pools pond before the surrounding soils are saturated. When this occurs, water may move

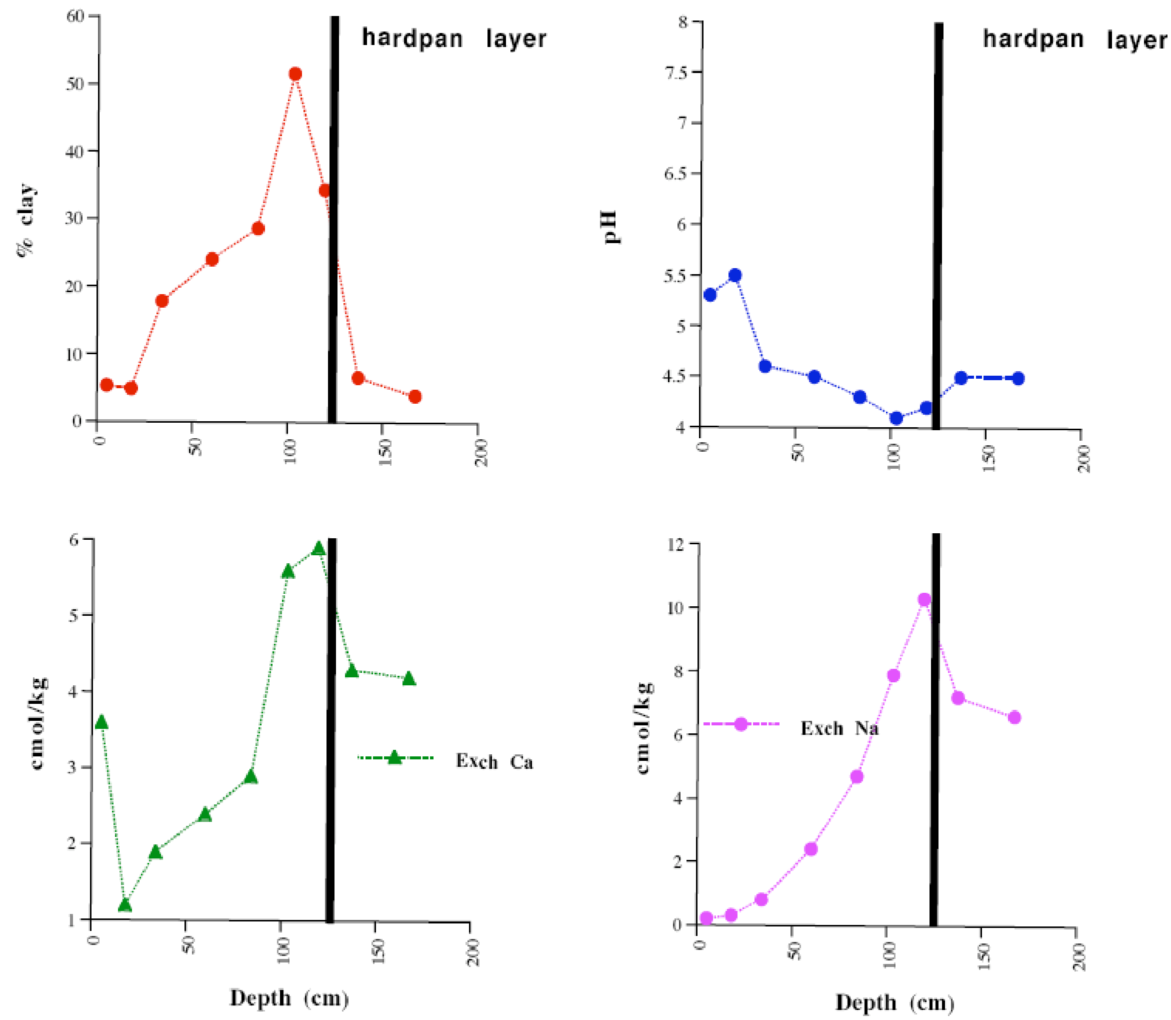

Figure 3.3. Redding soil series profile (Soil Survey Laboratory 1996).

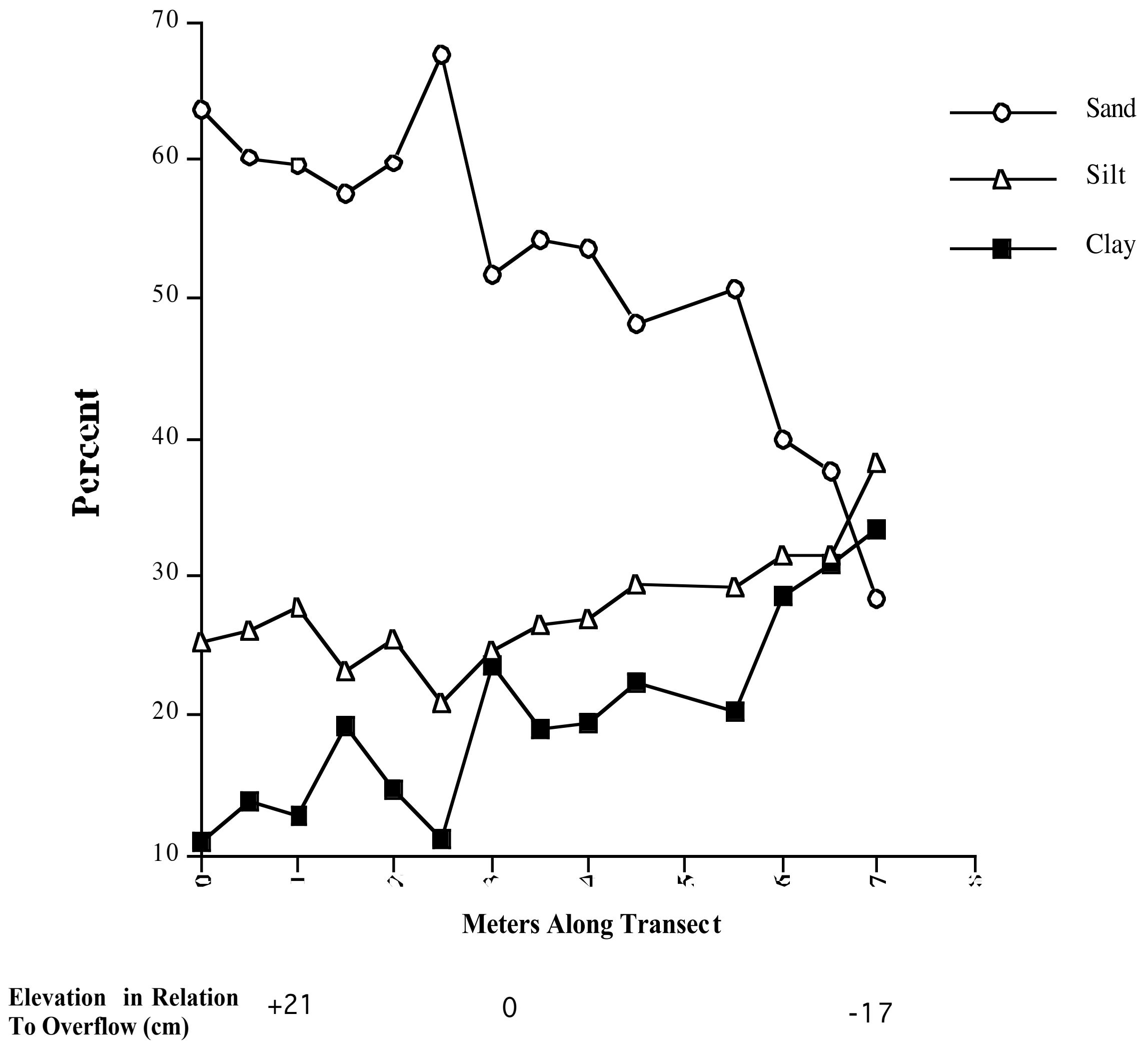

Figure 3.4. Soil texture fractions in relation to elevation in a San Diego vernal pool on Redding soils (Bauder 1987a).

Table 3.3.
Relationship Between Soil Nutrient Concentrations and Elevation, and Between Soil Nutrient Concentrations and Duration of Ponding

NUTRIENT	ELEVATION (cm)	WATER DURATION (days)
TKN~	.311**	.232*
NH4	.215*	0.19
NO3	.491***	.592***
PO4	.322**	.465***
Na+	.479***	.484***
Ca++	0.041	0.076
K+	0.122	0.125
Mg++	.443***	.715***

Entries are Pearson correlation coefficients. Soil samples were taken every other dm along transects spanning the upland/pool basin gradient (n = 87). Elevation was measured as the vertical distance above or below pool overflow. Water duration is the maximum total number of days each dm^2 quadrat was inundated during the 1982/1983 rainfall season.
Length of inundation was calculated for each dm^2 quadrat sampled.
~Total Kjeldahl nitrogen

*, ** and *** indicate significance at the 0.05, 0.01 and .0001 levels, respectively.
Source: Bauder 1987a

from the pool into the surrounding soils, reversing direction later in the season. Shallow-water inflow from the 'contributing area' can be substantial during years of abundant rainfall, extending the ponding duration.

Recent work in northern California (Rains *et al.* 2006, Rains *et al.* 2008) has shown that parent geology of the soils strongly affects the manner in which water moves into and out of the soils. Applied to southern California, this work suggests a fundamental difference between perched surface-water systems in clay-rich soils, such as those developed on marine shales or in tectogenic and landslide pools, and the pedogenic (or 'hardpan') pools derived primarily from granitic or volcanic parent materials, which are a combination of surface-water and perched ground-water systems. The clay-rich soils have much higher salinities, with sodium as a predominant cation, while the pedogenic pools of granitic or volcanic origin[1] (such as those in Redding soils) have a more dilute cation suite dominated by calcium. Primary productivity in the

[1] Some of the pedogenic pools developed on marine shales or other sediments in the San Diego area have properties intermediate between the clay-rich and granitic/volcanic pools.

clay-rich pools is often constrained by nitrogen, while phosphorus tends to be the nutrient limiting productivity in most pedogenic pools. Alluviated and bedrock pools of southern California are most likely to share the hydrochemical properties of most pedogenic soils, while dune-dammed pools will be more similar to the clay-rich pools. Rains and colleagues note that although they are morphologically similar, pool types differ by physical and chemical hydrology, and therefore "should be treated differently in resource conservation, restoration, and management efforts." (Rains *et al*. 2008)

Hydrodynamics

Once filled, pools hold water for varying durations. Early in the season, movement of water into the adjoining soils can rapidly lower pool levels, especially during the first few hours after storms. Later in the year or following major storms, water flowing into the pond from the adjoining soil can gradually increase water levels after a rainfall event ends. Deeper pools pond longer (Shaw *et al.* 2006, Brooks and Hayashi 2002). They tend to draw subsurface inflow from a larger area that replaces water lost by evapotranspiration but also lose water to shallow groundwater via infiltration (Brooks and Hayashi 2002). In San Diego County vernal pools, the duration of ponding increases by 4.5 days for each 0.1 foot (3.04 cm) of measured maximum depth (Shaw *et al.* 2006). Landscape position likewise affects the likelihood of ponding and the length of ponding events. Pools may be isolated or part of a network. A network is an integrated set of channels and basins that drain a watershed. Basins within a network will function hydrologically in accordance with their position within the network, the size of the watershed and the antecedent and incident rainfall (Figure 3.5). Pool salinities often reach a minimum during the middle of the winter season. Early ponding events dissolve salts left on the bed and banks of the pool by the prior season's evaporation, or those brought into coastal pools as aerosols. Salinities gradually decrease later in the season as shallow ground water enters the pools. Later in spring, salinities increase rapidly as the pools desiccate (*cf*., Napolitano and Hecht 1991, Rains *et al.* 2008) (Figure 3.6).

Biogeochemical processes

Vernal pool biogeochemistry is largely controlled by hydrological processes (Boon 2006). As indicated above, precipitation is the water source for southern Californian vernal pools as it falls directly on the basin, moves through the surface and subsurface soil and enters via surface flow. Spatial and temporal characteristics of the hydrodynamics affect the frequency, depth and duration of inundation that in turn determine the nature and extent of the biogeochemical processes (Boon 2006). Wetlands such as raised, hydrologically isolated ombrotrophic bogs that receive all of their moisture from precipitation are nutrient poor (*i.e.*, oligotrophic). Rock pools may also be nutrient

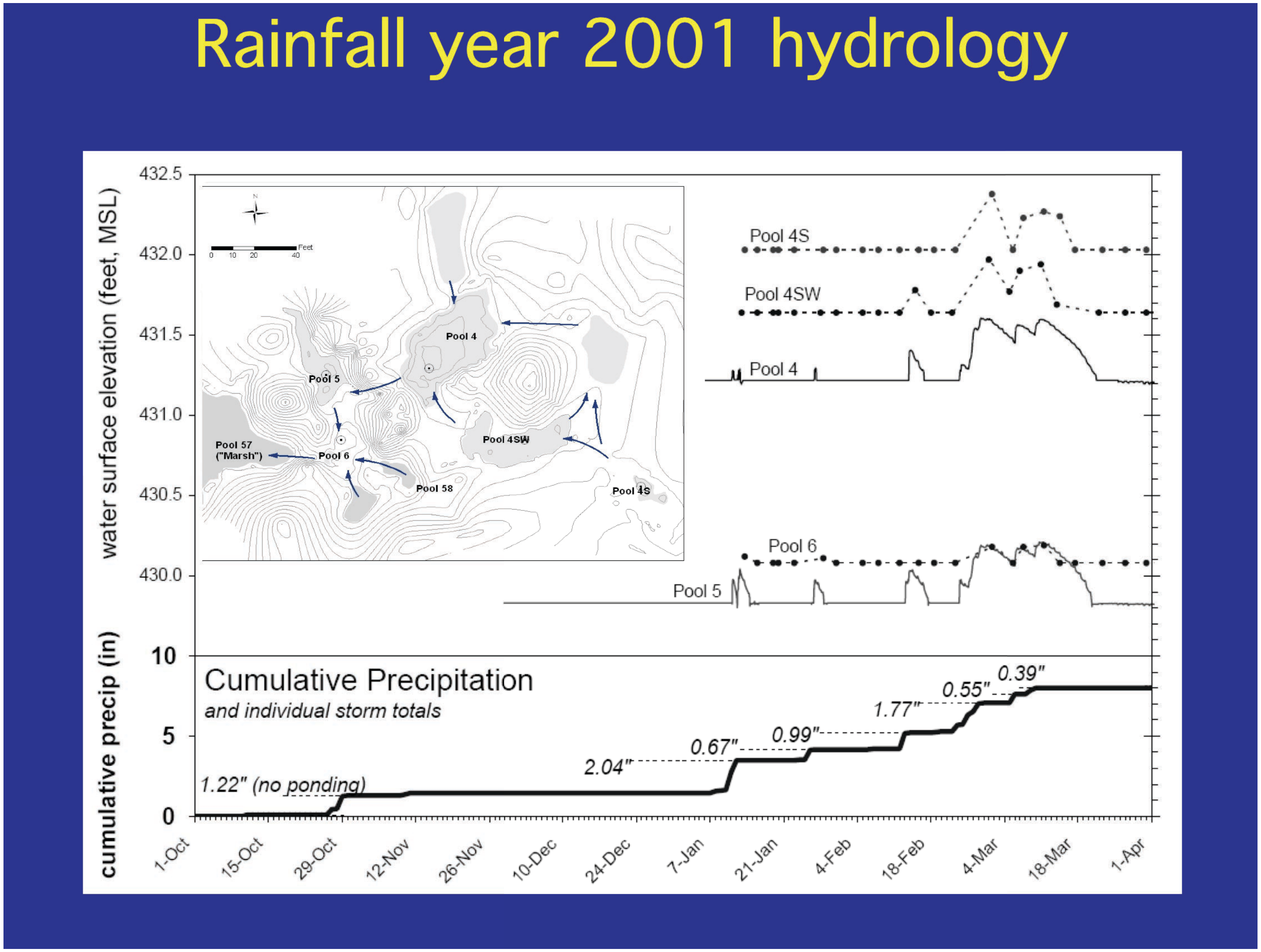

Figure 3.5. Cumulative precipitation and progressive ponding in a network of pools.

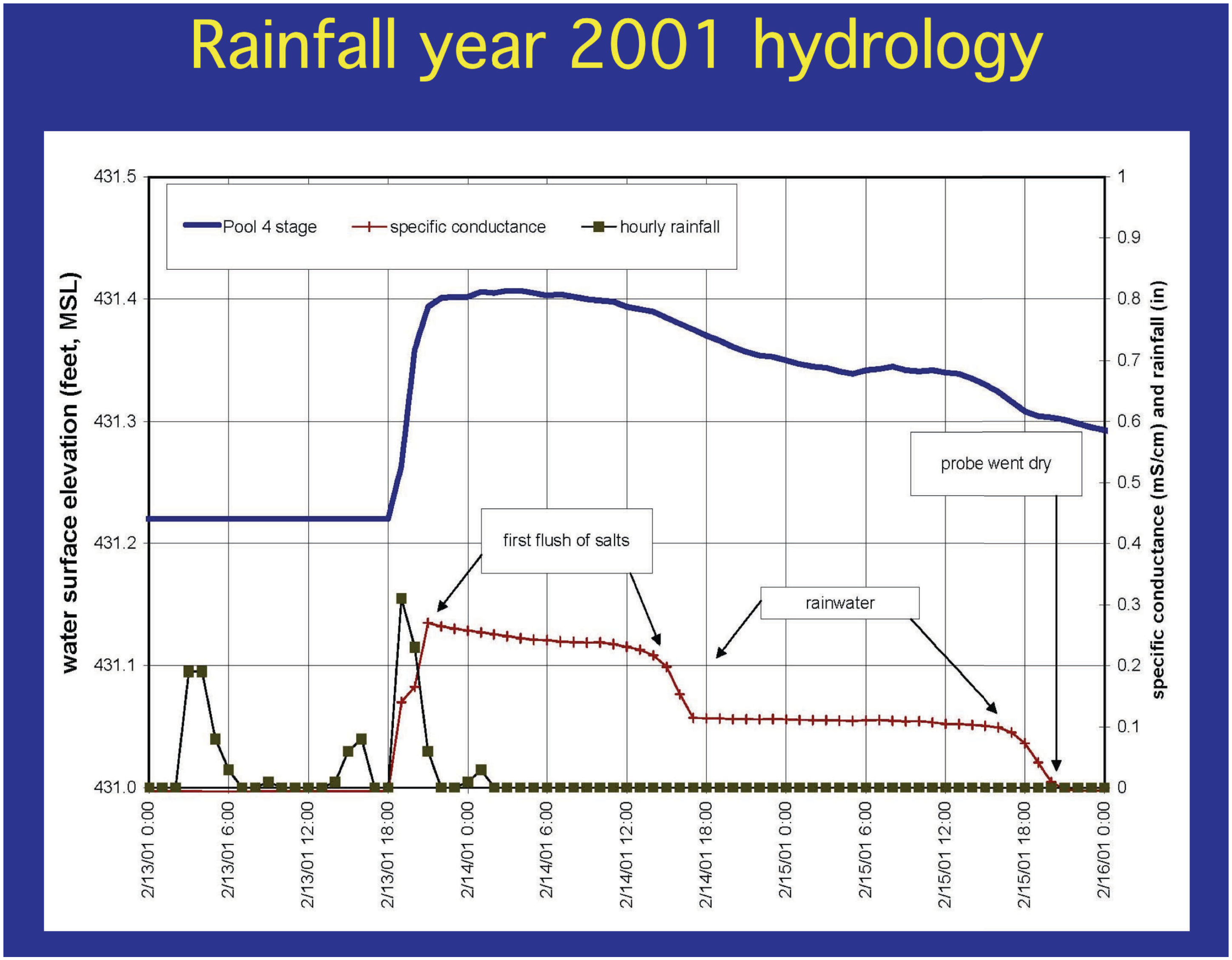

Figure 3.6. Seasonal progression of specific conductance.

poor due to the lack of soil development in their watersheds (Joqué *et al*. 2007). Vernal pools are rain-fed, and in southern California receive little precipitation, even for a Mediterranean climate (Table 3.1). In general, they are surrounded by nutrient-poor soils and large nutrient accumulations in woody shrubs and dead biomass and litter (McMaster *et al*. 1982, Rundel and Vankat, 1989) making their low nutrient levels and water chemistry similar to "…oligotrophic lacustrine habitats found at higher elevations and latitudes." (Keeley and Zedler 1998)

Surface flows are infrequent in southern Californian vernal pool networks due to the region's aridity and unpredictable precipitation patterns. When they do occur, flowpaths are important because they control water-sediment contacts and contact times. Flowpaths vary depending upon underlying geology (Rains *et al.* 2006, Rains *et al.* 2008, Weitkamp *et al.* 1996). Clay-rich soils have low infiltration rates, so infiltration-excess overland flow typically is the dominant flowpath even during low-intensity storms (Rains *et al.* 2006, Rains *et al.* 2008). In studies of claypan vernal pools in northern California, water remained on the surface while moving rapidly toward local topographic lows occupied by vernal pools. Conversely, in nearby pool landscapes on hardpan soils with high infiltration rates at the surface and low infiltration rates in the shallow subsurface, shallow groundwater flow typically is the dominant flowpath even during high-intensity rainfalls (Rains *et al.* 2006, Rains *et al.* 2008). In these cases, water remains in the subsurface while moving slowly toward local topographic lows occupied by the vernal pools (Hanes and Stromberg 1998). Over a 2-year period, Weitkamp *et al.* (1996) studied water movement from the upper-slope soils to the footslope in a group of 10 large pools underlain by basaltic-topped mesas. At the footslope, downward movement was slowed, due to a sharp change in soil texture. Water began to accumulate first at the footslope/pool edge, and the basin soils followed after the pool edge became saturated. Surface soils at the toeslope and in the basin were rich in clay (> 40%) and those of the backslope and footslope contained < 20 and 30% clay, respectively.

Rapid overland flow can erode and transport sediments and organic carbon from the surface of the uplands to the vernal pools, where sediments release adsorbed phosphorus and organic carbon dissolves and contributes to the *in-situ* stocks of dissolved organic carbon (Rains *et al.* 2008). Shallow groundwater flow can dissolve and transport silica and nitrate from the subsurface of the uplands to the vernal pools, allowing ample time for dissolved organic carbon (DOC) to be adsorbed to the iron oxides in the upland soils (Rains *et al.* 2006, Rains *et al.* 2008). Differential transport and accumulation of minerals also occurs in bedrock pool systems (Weitkamp *et al.* 1996). In simple terms, the manner in which surface water is delivered to vernal pools is the primary determinant of initial water chemistry. Rapid overland flow typically yields high phosphorus and DOC concentrations, and relatively low silica and nitrogen concentrations.

Shallow groundwater flow is characterized by relatively high silica and nitrogen concentrations, and relatively low phosphorus and DOC (Rains *et al.* 2008).

As discussed above (Hydrology: Water Sources and Hydrodynamics), water also moves into and out of the immediately adjacent upland soils over the course of the rainy season (Hanes and Stromberg 1998, Napolitano and Hecht 1991). This provides additional nutrient inputs and affects the concentration of salts and other constituents of the pool water.

Timing of water movement is important because of the asynchrony between hydrological and biological processes in Mediterranean-type climates (Tate *et al.* 1999, Holloway and Dahlgren 2001, Rains *et al.* 2006). In the dry season, annual species senesce but microbial activity continues, nitrogen is mineralized, and nitrate accumulates in upland soils. During early-season storms (usually late fall), there is little biological demand for this nitrate, so it is readily dissolved and transported to vernal pools. This nitrate is largely flushed in the early wet season. During late-season storms, there is high biological demand on the remaining nitrate, so there may be little remaining nitrate to be dissolved and transported to the vernal pools. As a result, early-season storms may produce relatively large flushes of nitrate while late-season storms may produce little more than water.

Position in a network of pools and individual pool basin morphology are important factors affecting pool biogeochemistry. Joqué *et al*. (2007) found that shallow rock pools in Utah had higher temperatures and percent oxygen, greater turbidity and lower concentrations of nutrients compared to deeper, persistent pools lower in the watershed. We found pools higher in the network were the last to fill (Figure 3.5 and Chapter 4 Hydrologic Networks function), and in drier years do not fill at all (Bauder unpublished data). The depth and structure of the surface soil profile and the type and percentage of clay affect water storage capacity, soil pore sizes, movement of oxygen and water, heat capacity, adsorption of cations and surface cracking.

Algae are important primary producers in wetland ecosystems, but aquatic food webs are predominantly detrital, and bacteria are the most important of the secondary producers (Boon 2006). They dominate the uptake and release of nutrients and dissolved organic matter in wetlands (Boon 2006). Bacteria, fungi and actinomycetes depolymerize cellulose, releasing glucose that is used by a wide array of heterotrophic soil microbes. Various specialized members of the soil microbial community produce enzymes that mineralize nutrients. Root exudates are an important source of carbon, as well as other organic substrates that are readily degradable by soil microbes. The rhizosphere supports larger populations of bacteria (both ammonifying and denitrifying), actinomycetes (Gram positive bacteria) and other soil microbes compared to surrounding soils, although clayey soils show more modest differences (Bannister 1976, Russell 1977).

In southern California, vernal pools may dry and re-pond up to 6 or 7 times within one rainy season. Alternating episodes of wetting and drying promote the loss of gaseous nitrogen from the soils (Boon 2006). Repeated episodes of soil drying and wetting affect the soil microbial fauna. Bacteria, yeasts, fungi and actinomycetes differ in their tolerance of water stress, with bacteria the most sensitive and actinomycetes the least (Killham 1994). The bacterial community can respond to alternating aerobic and anaerobic periods as short as 2 days (Boon 2006). There may be flushes of nutrients due to the release of intracellular solutes when soil microbes adjust cell solutes to changing moisture conditions (Boon 2006, Killham 1994). However, review of the research on the effects of drying and rewetting indicates that soil microbes do not produce a net liberation of nutrients into the water column, nor do they accelerate organic-matter decomposition or leaf litter breakdown (Boon 2006). Some soil animals such as protozoa and rotifers that need soil pores for locomotion can be particularly affected by the sealing of soil cracks and pores during hydration of shrink/swell clay soils and by the drying out of the soil pore spaces during dry interludes in the rainy season.

Vernal pools are biogeochemically distinct from the surrounding uplands. They are inundated for many days or even months annually, and are often densely covered with annual grasses, forbs and pool-bed algae. The surrounding uplands are never inundated, and are characterized by moderate coverage with shrubs and/or annual grasses, aerobic soils and relatively low productivity. Therefore, vernal pools are islands of mesic, often anaerobic soils and relatively high productivity in a matrix of xeric, aerobic soils and relatively low productivity. Though comparative data are lacking, it is likely that these conditions result in nutrient uptake in vernal pools being greater than nutrient uptake in surrounding uplands. A study in Australia found that during wet periods, temporary wetlands were more productive (as measured by turtle growth and body condition) than permanent lakes (Roe and Georges 2008). The reverse was true during dry periods. Vernal pools may be local sinks for nutrients. Soil chemistry data taken along the upland-basin gradient in soils formed in the Redding soil series support this conclusion (See Table 3.3) although Weitkamp *et al*. (1996) found the reverse in larger, less connected pools underlain by basalt bedrock.

Wetlands are well known for performing critical biogeochemical functions, such as denitrification (Ponnamperuma 1972, 1984) and DOC production (Fogg 1977). The shallow waters of wetlands favor biogeochemical processes because of the high degree of sediment-water interface (Cronk and Fennessy 2001). Ponnamperuma (1984) discusses how standing water impacts biotic zonation (aerobic and anaerobic interfaces), electrochemical changes (redox potentials, pH, specific conductance[2], ion exchanges and sorption and resorption), and chemical transformations (accumulation of carbon dioxide, reduction of minerals and nitrogen transformations). However, in four vernal pool catenas in California's Central Valley, O'Geen *et al*. (2008) found that redoximorphic features corresponded better with the thickness of the soil above restrictive horizons (when they were duripans) than with the length of ponding duration.

Vegetation Communities

Vernal pools support a distinct flora dominated by endemic species, many of which are exceedingly narrow in their distribution (Bauder and McMillan 1998, Keeley and Zedler 1998, Stebbins 1976, Thorne 1984). Over 200 plant species are restricted to or commonly occur in the vernal pools of California (Holland 1976). Of these, 91% are considered native to California and 55% have ranges entirely within the state (Holland 1976, Holland and Jain 1981). *Pogogyne nudiuscula* (Otay mesa mint) is an extreme example of narrow endemism. It is strongly associated with a particular soil series with an area of <8 mi^2 in southern San Diego County and a small area in adjacent Baja California, MX (Bauder and McMillan 1998).

Pools form on an array of substrates across many degrees of latitude and thousands of feet of elevation (Holland 1978). Therefore, it is not surprising that entire suites of unique species are found in vernal pools with distinct soils and climate (Bauder and McMillan 1998, Holland and Dains 1990, Holland and Jain 1981, Keeler-Wolf, *et al.* 1998, Norwick 1991). A species list developed for coastal San Diego County has 37 native species primarily found in vernal pools and an additional 17 native species that are common in pools but not restricted to them (Bauder 1997 and Appendix D.3). The list would contain additional species if the area of focus were enlarged from the coastal mesas and valleys to include the mountains and inland valleys and mesas and similar areas in adjacent counties (Bauder and McMillan 1998).

The vegetation matrix surrounding pools also changes with elevation, latitude and soil substrate. Pools may be embedded in forests and savannas, grassland, chaparral, coastal sage scrub or even maritime succulent scrub in San Diego County and northern Baja California, MX.

Vernal pools are populated by species with various adaptations for living in an ephemeral and unpredictable environment. Most of the species are annuals so that they spend the drought season as seeds in the soil. If rainfall is sparse during the wet season, they often fail to germinate

[2] Specific conductance, electrical conductance and electrical conductivity are terms that are functionally synonymous and may be used interchangeably for the purposes of this guidebook. Specific conductance is used preferentially in this document, especially where use of this term can avoid confusion with hydraulic conductivity (permeability).

primarily due to lack of moisture, rather than an innate dormancy (Bauder unpublished data). Temperature also affects germinability, with most species germinating at lower rates or not at all when temperatures are higher than those commonly experienced during the winter rainy season (Bauder unpublished data, Bauder 1992, Bauder *et al.* 2002). This protects vernal pool seeds from germinating after the occasional summer rainstorm or during an unusually warm winter when maturity to reproduction is unlikely.

Geophytes are another important component of the pool vegetation. Plants with bulbs, corms or thickened caudices can store up resources during good years to carry them through ones unfavorable for growth.

Many pool species have physiological or morphological plasticity. A typical inundation response is elongation of the stem internodes. This has been observed in *Downingia concolor* spp. *brevior, Downingia cuspidata*, *Pogogyne abramsii* and *P. nudiuscula*, *Marsilea vestita* and *Callitriche marginata*. *Downingia concolor* ssp. *brevior* plants had an average height of 9.0 cm when grown without inundation, compared to 16.7 cm after 8 weeks of inundation. After 8 weeks of inundation, 4 weeks of exposure was sufficient to allow development of flowers equal in number to those of plants only inundated 2 weeks, but plants never inundated had nearly twice as many flowers as plants inundated for 2 or 8 weeks (Bauder 1992). *Pogogyne abramsii* plants were grown in pots exposed to three moisture conditions: no inundation, 21 days of inundation and 60 days of inundation. After 21 days of inundation, the longest stem on the tallest plant in each submerged pot averaged 14.5 cm. The tallest stems of plants never inundated were on average 8.0 cm. The longest stem in each pot submerged for the full 60 days was on average 16.4 cm tall (Bauder unpublished data). Stems of *Downingia*, *Pogogyne* and *Eryngium* species are hollow (aerenchymatous) when water is standing and become fibrous and often hairy or prickly as the ponds begin to dry. In *Callitriche* species, two leaf forms are produced: terrestrial strap-shaped leaves and paddle-like floating aquatic leaves that develop after water has ponded for several weeks (Deschamp and Cooke 1983, 1984). Physiological plasticity (shifts in photosynthetic pathways) has been observed in vernal pool species of *Isoetes*, *Callitriche*, *Crassula*, *Downingia*, *Eryngium* and *Orcuttia*, among others (Keeley 1999).

Although pool species are adapted for periods of inundation, they are not truly aquatic and mortality rises with length of inundation (Bauder 1987a, 2000). The response to inundation period varies by species. Those commonly found in shallow pools or edges of deeper pools have less inundation tolerance than species associated with deeper pools or elevations within pools where water stands longer (Bauder 2000). The presence of dense stands of perennial sedges like *Eleocharis macrostachya* is an indication of long inundation periods, natural or artificial. Modest changes in the pattern of precipitation during the rainy season or the total amount of seasonal precipitation could potentially have profound impacts on the floral composition of southern Californian vernal pools as well as the dominant species in pool basins (Bauder 2005). Human-caused alterations to pool hydrology also affect pool vegetation, tipping the balance towards species, both native and introduced, that tolerate more or less moisture than is typically found in undisturbed pools.

Until recently, introduced species were generally kept in check by their intolerance of standing water (Bauder 1987a, 2000; Holland and Jain 1988). Most of the introduced species in and around vernal pools are easily dispersed rangeland annuals originating in Asia. During drier years, they germinate and thrive in pool basins. In wetter years, they may germinate when the rainy season begins but experience near complete mortality in pools or portions of pools where water stands continuously for 10 days or more (Bauder 1987a, 2000). Many pool species react adversely to competition—inter- or intra-specific—with reduced biomass or fecundity, increased mortality or both (Bauder 1987a, 1989; Bauder *et al.* 2002). Standing water provides them with an escape from competition with the rangeland annuals. Ponding does not provide relief from the competitive effects of a number of wetlands exotics that have become established in many southern Californian vernal pools (Bauder 1988, Bauder *et al.* 2002). These include *Polypogon monspeliensis* (annual beard grass or rabbitfoot grass), *Lolium* spp. (ryegrass), *Lythrum hyssopifolium* (grass poly) and *Agrostis avenacea* (blown grass or Pacific bent grass).

Faunal Communities

Vernal pools provide habitat that is used by a wide variety of animals throughout their life cycle. Vernal pools that have a high degree of faunal functionality maintain this characteristic set of species that are uniquely adapted to the bi-phasic nature of the resource. In addition to the opportunities for food and reproduction provided by the pool itself (during either the wet or dry phase), connectivity among pools at the landscape level may also be important for some species. This is because 1) their life cycle requires access to both ephemeral pools and other habitat types, or 2) the ecological and evolutionary consequences of dispersal and gene flow among pools in a complex are essential for persistence in individual pools. The second set of processes may be addressed in terms of metapopulation processes, source sink dynamics or maintenance of genetic diversity, depending on the context. Spatial linkages among vernal pools and adjacent habitats within the surrounding landscape facilitate the long-term persistence of a diversity of habitats and characteristic vernal pool plant and animal communities (Ebert and Balko 1987, Hanski 1996, Hansson *et al.* 1995, Holland 1976, Holland and Jain 1981, Simovich, 1998, Thorp and Leong 1998).

Some animals found in vernal pool are "obligates" whose entire life cycle is completed within the pool. The most obvious examples are crustaceans, but this group also includes nematodes, rotifers and other taxa. The life cycle of obligates is precisely tied to the pools, and these species typically persist through the dry phase as dormant propagules in the pool sediment. Dormant propagules (typically encysted eggs or embryos) hatch when the pools fill, and the organisms quickly mature and reproduce before the pool dries. Some are generalists found in pools that span a variety of abiotic conditions. However, most exhibit limited tolerance ranges for water temperature, chemistry (pH, salinity, alkalinity, turbidity, etc.) and pool duration (due to minimum developmental times). As a result, most vernal pool obligates are narrow endemics found only in a limited geographic area. These organisms feed on those lower in the food chain including algae, bacteria, smaller animals and detritus. They are in turn fed upon by amphibian larva and migratory waterfowl (Baker *et al.*1992). Dispersal among pools and pool complexes is often mediated by vectors such as birds and mammals. Thus, gene flow, recolonization and potential rescue of pools with low density are all dependent upon maintenance of appropriate vectors.

Vernal pools in the reference domain contain at least three species of fairy shrimp that are obligates: the San Diego fairy shrimp *Branchinecta sandiegonensis*, Lindahl's fairy shrimp (also known as the versatile fairy shrimp) *B. lindahli* and the Riverside fairy shrimp *Streptocephalus woottoni*. The San Diego fairy shrimp and the Riverside fairy shrimp are federally endangered species, so appropriate USFWS permitting issues must be addressed before sampling pools in which these species may be present.

A second set of organisms are "lifestyle dependent," since they spend only a part of their life cycle in the pools, or are dependent on other pool organisms at a certain stage. The most obvious in this group are the amphibians. While some species such as tree frogs can breed in intermittent streams as well, spadefoot toads are in large part dependent on predator-free ephemeral pools. The adults spend the dry season under the ground or in the uplands, rather than the pools. Spadefoots take advantage of rodent burrows to help them get up to a meter deep in the ground. Although tree frogs may exhibit an extended period of activity in the wet season, spadefoots are more precisely adapted to the pool cycle. After emerging during heavy rains (thought to be cued by the sound) they quickly move to pools and breed in one or a very few nights. The adults then return to shallow burrows in the uplands and emerge at night to feed for a short period of time. Tadpoles develop quickly eating pool vegetation, and even more quickly if fairy shrimp are available as prey. Upon metamorphosis, they too return to the uplands.

A large variety of lifestyle dependent insects also utilize vernal pools, generally for the development of their larval stage. Terrestrial (aerial) insect adults come to the pools to deposit eggs. Many insect larva are predators on other vernal pool animals. Most vernal pool insects with aquatic larvae will also utilize other water sources, and are thus not totally reliant on ephemeral pools. However, some insect pollinators are obligately dependent on vernal pool plants, with which they have co-evolved specific pollination syndromes.

Finally, some vernal pool animals are best characterized as “opportunists” that take advantage of pools when available. Included are some insects and migratory waterfowl (which may have been more dependent on these pools in the past when they were more abundant). These use the pools as resting and feeding stations. Some species breed around pools. Mammals will also use pools for water sources, and garter snakes feed on tadpoles when available.

In general, it is widely recognized that vernal pools support a unique assemblage of fauna due to the timing and duration of inundation phases; these are in turn dictated by climate, soil characteristics, hydrology and the microtopography of the pool basin (*e.g.*, Bauder *et al.* 1998, Hanes and Stromberg 1998, Holland and Jain 1988, Keeley and Zedler 1998, Smith and Verrill 1998, Sutter and Francisco 1998). Although vernal pools are sometimes thought of as isolated "bathtubs" driven solely by precipitation and evaporation, they are often linked hydrologically to the remainder of the landscape by groundwater flow through perched aquifers (Rains *et al.* 2006). As in many other areas, both rainfall patterns and vernal pool inundation patterns are highly variable in southern California (*e.g.*, Bauder 2005). For animals such as crustaceans that live in these temporary habitats, the fraction of cysts that hatch has evolved to match environmental predictability. To persist in a pond that does not always remain full long enough for maturation and mating, < 100% of cysts hatch during any particular hydration. This phenomenon has been very well studied theoretically and empirically (*e.g.*, Brendonck 1996, Philippi *et al.* 2001, Brendonck and De Meester 2003, Brock *et al.* 2003). For example, in the San Diego fairy shrimp, only 6% of *B. sandiegonensis* cysts hatch during laboratory hydrations (Simovich and Hathaway 1997), and the average pool containing *B. sandiegonensis* fills long enough to allow reproduction approximately once in every three inundation events (Philippi *et al.* 2001).

Cultural Alteration of Wetland Basins and the Landscape

Vernal pools were once a common feature in southern California, from the Transverse Ranges in the north, across the Los Angeles Basin to western Riverside County, coastal Orange County and both coastal and inland San Diego County. They used to dominate San Diego’s coastal mesas. The losses to development have been extensive, although a firm number or percentage is hard to determine. Examination of old aerial photographs and soils maps is one of the few ways to estimate the original and remaining acreage of suitable landscape for vernal pools (Bauder and McMillan 1998). When the first endemic pool species attained Federal and State Endangered

Status (*Pogogyne abramsii*—FE 1978, SE 1979), two intensive pool mapping efforts were launched in San Diego County (Beauchamp 1979 and Villasenor and Riggan 1979). The pools mapped in 1978/1979 were revisited in 1986 to determine how many had been preserved or lost and how many remained (Bauder 1986). The development of Habitat Conservation Plans in the 1990's spawned yet another intensive mapping effort (City of San Diego 1998). It is generally agreed that over 95% of the original number of pools has been lost, that pools continue to be lost, and that those remaining are, with only a few exceptions, contained within small parcels that are often not adequately preserved, protected and/or managed.

As with other parts of California, the pools in southern California were subject to grazing, often intensive, after the Spanish introduced cattle and sheep in the late 1700's. By the mid-20th century, the aridity of the climate coupled with accelerating development led to a decrease in grazing, and it is at present a minor disturbance. Today, the major habitat alterations are direct losses due to development; reduction, fragmentation and disturbance of surrounding landscapes; changes in catchment areas (augmentation and truncation) and drainage patterns; grading and brushing; fires; and disturbance of basins by vehicles, dumping and various edge effects, including the introduction of exotic plants and animals (Bauder 1987b).