Vernal Pool-Soil-Landform Relationships in the Central Valley, California

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Abstract. It is hypothesized and a conclusion is reached, based upon an analysis of present-day mapping of vernal pools, soils, and geomorphology, that the occurrence of vernal pools within the Central Valley can be correlated with specific types of soils, geologic formations, and landforms. A hierarchical framework is proposed that can be used to identify and classify present-day vernal pool landscapes. The present-day relationships between vernal pools, soils, geologic formations, and landforms occur in predictable patterns across the landscape and can, therefore, be projected into the past. The hierarchical framework thereby provides a screening tool to locate potential historic vernal pool areas and help site restoration and mitigation areas. This is especially significant for the identification of historical vernal pool landscapes – which as a result of land use and management techniques such as land leveling, drainage, and/or deep ripping – no longer support vernal pools. Correlation of vernal pool landscapes with soils, geologic formations, and landforms may also provide a methodology for identification of characteristic hydrologic features, correlation with special-status species distribution, assessment of geodiversity and biodiversity, determination of suitability for restoration, and development of appropriate mitigation techniques, and construction density. This approach facilitates optimal regional land-use planning, establishment of preserves, and siting of mitigation banks.

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Introduction

Vernal pools are shallow surficial depressions that temporarily fill with water during winter and spring rains and desiccate during the dry summer months. They occur as small poorly drained depressions perched above an impermeable or very slowly permeable soil horizon or bedrock (Chetham, 1976; Weitkamp et al., 1996). The restrictive soil layers are duripans or claypans, and the bedrock types are volcanic mud or lava flows (Barry, 1995; Holland, 1978; Riefner and Pryor, 1996; Zedler, 1987). The areas generally have mound-depression microrelief. Vernal pools are separated from groundwater or stream channel inflow; they fill by slowly collecting precipitation (Hanes et al., 1990; Zedler, 1987). Surface flow and subsurface flow from mounds and swales into pools are also hydrologic features that define vernal pools and extend their wet-life (Arndt and Richardson, 1995; Hanes et al., 1990; Weitkamp et al., 1996). Vernal pools are often defined by their endemic or regionally restricted flora as well. Vernal pools are important components of ecological systems in parts of the Central Valley, California.

The Central Valley is a flat alluvial plain covering about 19,200 square miles between the Sierra Nevada and the Coast Ranges (Figure 1). The north half is generally referred to as the Sacramento Valley and the south half as the San Joaquin Valley. It is in the California Dry Steppe Province ecoregion as described by Bailey (1995). The area has broad, nearly level valleys bordered by sloping alluvial fans, slightly dissected terraces, and the lower foothills of the surrounding uplands. Climate is characterized by hot, dry summers and cool, moist winters with rainfall occurring mostly during the period of November through April.

Hypothesis

Our premise is that the location of vernal pools within the Central Valley can be correlated with specific soils, geologic for-

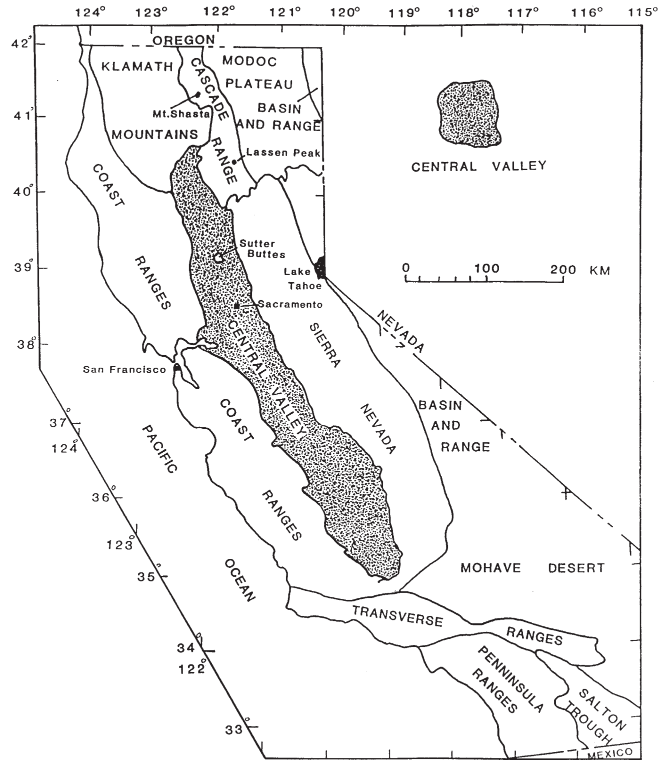

FIGURE 1. Location map of the Central Valley, California.

mations, and landforms, and that these soil-geomorphic relationships provide a hierarchical framework for classification and identification of vernal pools within the valley. The hierarchical scheme can be used to locate historical vernal pool areas and help identify appropriate restoration or mitigation areas.

We are analyzing what we know about present-day relationships and projecting them into the past, and therefore making *a posteriori* conclusions about the correlation between vernal pools and related soils, geology, and landforms.

We are building on the following assumptions:
(a) ecosystems involve complex interrelationships between many physical, chemical, and biological components on the landscape;
(b) this complexity can become easier to understand if we subdivide the landscape into systems of different patterns and scales because smaller systems are linked to form larger systems (Bailey, 1996; Brown and Smith, 1993);
(c) soil-geologic formation-landform relationships exist which can be identified and serve to subdivide the landscape into orderly and repeatable patterns at various scales (Parsons et al., 1970; Parsons and Herriman, 1976; Ruhe, 1975; Shlemon, 1967);
(d) the environmental setting described in the "Introduction" defines vernal pools;
(e) vernal pools occur in known locations under present-day conditions (as mapped by Holland (1978) and others);
(f) relationships identified between areas of present-day vernal pools and the soils, geology, and landforms at those locations can be extrapolated and used to recognize and delineate other present-day and historical vernal pool areas within the Central Valley.

HIERARCHICAL CLASSIFICATION OF THE LANDSCAPE

The hierarchy, in sequence of increasing detail and specificity, is landform, geologic formation, soil great groups, soil series, and phase of soil series. The relationships identified within the Central Valley down to the soil series level are listed in Table 1.

Note that the five levels of the hierarchy provide a screening tool to identify potential vernal pool landscapes. We stress that precise identification of existing or remnant vernal pools must incorporate site-specific investigation (which could be considered a sixth, and more definitive level in the hierarchy).

Landforms

A landform is a physical, recognizable feature on the earth's surface, having a characteristic shape and range in composition. Differentiation of the major landforms and geomorphic surfaces of the Central Valley has resulted from episodes of flood and eolian deposition and glacial outwash over the last four million years, volcanic eruptions as old as twenty million years, and coastal plain deposition as old as forty million years (Shlemon, 1972; Shlemon and Begg, 1975; Wahrhaftig and Birman, 1965). Through a combination of subsequent erosion, alternating changes in climate, and pedogenic (soil-forming) processes, vernal pools originated on many of the Central Valley landforms of variant origin.

The landforms to be discussed for the Central Valley are (a) basins, (b) basin rims, (c) low terraces, (d) dunes; (e) high terraces, and (f) volcanic mudflows and lava flows. Figure 2 shows the location of some of these landforms in an idealized cross-section.

Basin is a general term for the nearly-level, broad alluvial flats, or bottom surfaces in the valley in which sediments accumulate. Holocene basins contain the youngest geomorphic surfaces in the Central Valley (Tugel, 1993). Vernal pools, as defined in this paper, are not common in these basins.

Soils which formed in clay-rich Holocene alluvium and that classify as "Vertisols" occur extensively within these basins. Judging from the low landscape position and the soils that have formed, these basins probably once contained seasonal wetlands which were inundated for long periods (from many weeks to months during most years) due to historical flood conditions

TABLE 1. Hierarchical framework showing relationships between soils, geologic formations, and landforms in areas conducive to vernal pool occurrence within the Central Valley, California (the general distribution and mapped extent to the soil series within those areas is also shown in the two columns on the right).

Landform	Geologic Formation*	Soil Taxa (Great Group)	Soil Series Name	Counties Where Soil Series Has Been Mapped within Central Valley**	Soil Series Acreage within Central Valley**
Basin Rims		Natrixeralfs	Antioch	Contra Costa, Solano	22,885
Basin Rims	Riverbank/basin deposits	Natrixeralfs	Pescadero	Contra Costa, San Joaquin, Solano, Yolo	24,200
Basin Rims	Riverbank/basin deposits	Natrixeralfs	Riz	Glenn, Yolo	8,020
Basin Rims		Natrixeralfs	Solano	Contra Costa, Solano	14,490
Basin Rims		Natrixeralfs	Waukena	Fresno, Merced, Stanislaus	17,970
Low Terraces	Riverbank	Durixeralfs	Exeter	Fresno, Kern, San Joaquin, Sutter, Tulare	67,885
Low Terraces		Durixeralfs	Fresno	Fresno, Madera, Merced, Stanislaus	114,400
Low Terraces		Durixeralfs	Hedge	Sacramento	4,040
Low Terraces		Durixeralfs	Lewis	Madera, Merced, Tulare	40,220
Low Terraces	Riverbank	Durixeralfs	Madera	Fresno, Madera, Merced, Sacramento, San Joaquin, Stanislaus	77,680
Low Terraces		Durixeralfs	Moda	Glenn, Shasta, Tehama	4,675
Low Terraces	Turlock Lake	Durixeralfs	Rocklin	Fresno, Madera, Merced, San Joaquin, Stanislaus	32,170
Low Terraces	Riverbank	Durixeralfs	San Joaquin	Butte, Fresno, Madera, Mariposa, Merced, Placer, Sacramento, San Joaquin, Stanislaus, Sutter, Tulare, Yuba	490,240
Low Terraces		Durixeralfs	Yokohl	Fresno, Merced, Stanislaus	20,540
Low Terraces		Durixeralfs	Yuvas	Sutter	7,565
Low Terraces		Chromoxererts	Galt	Sacramento, San Joaquin, Sutter	37,825
Low Terraces		Palexeralfs	Cometa	Fresno, Madera, Placer, San Joaquin, Sutter	94,265
Low Terraces (?)		Palexeralfs	Herito	Merced	1,590
Low Terraces		Palexeralfs	Hillgate	Colusa, Glenn, Mariposa, Shasta, Tehama, Yolo	67,906
Low Terraces		Palexeralfs	Jahant	San Joaquin	3,260
Low Terraces		Palexeralfs	Jesbel	Madera	291
Low Terraces		Palexeralfs	Kimball	Contra Costa, Glenn, Sacramento, Tehama, Yuba	36,246
Low Terraces		Palexeralfs	San Ysidro	Contra Costa, Solano, Yolo	50,444
High Terraces/Hills		Durixeralfs	Bellota	San Joaquin	3,170
High Terraces		Durixeralfs	Buchenau	Madera	470
High Terraces	Turlock Lake	Durixeralfs	Fiddyment	Placer, Sacramento	43,840
High Terraces	Red Bluff	Durixeralfs	Igo	Shasta	6,710
High Terraces	Laguna/Mehrten	Durixeralfs	Keyes	Fresno, Merced, Sacramento, San Joaquin	16,325
High Terraces	Laguna, Red Bluff, Turlock Lake	Durixeralfs	Redding	Butte, Fresno, Glenn, Madera, Mariposa, Merced, Placer, Sacramento, San Joaquin, Shasta, Stanislaus, Tehama, Yuba	167,365
High Terraces	Red Bluff	Durixeralfs	Tuscan	Butte, Shasta, Tehama	47,720
High Terraces/Hills	Laguna/Valley Springs	Durixeralfs	Vleck	Sacramento	2,930
High Terraces	Laguna, Red Bluff	Palexeralfs	Corning	Colusa, Glenn, Madera, Merced, Placer, Sacramento, San Joaquin, Solano, Stanislaus, Tehama, Yolo, Yuba	112,631
High Terraces	Turlock Lake	Palexeralfs	Positas	Contra Costa, Fresno, Mariposa	3,173
Mudflows/Lavaflows		Durochrepts	Anita	Shasta, Tehama	6,100
Mudflows/Lavaflows		Haploxeralfs	Pardee	Amador, Sacramento, San Joaquin, Yuba	19,080
Mudflows/Lavaflows	Mehrten	Haploxeralfs	Pentz	Amador, Merced, Sacramento, San Joaquin, Stanislaus, Yuba	51,665
Mudflows/Lavaflows	Mehrten	Haploxerolls	Hadselville	Sacramento	9,370
Mudflows/Lavaflows		Haploxerolls	Peters	Amador, Merced, Sacramento, San Joaquin, Stanislaus, Tehama	20,275
Mudflows/Lavaflows	Tuscan	Xerochrepts	Toomes	Glenn, Shasta, Tehama	99,390
Mudflows/Lavaflows		Xerorthents	Exchequer	Placer	7,140
Mudflows/Lavaflows	Valley Springs	Xerorthents	Gillender	Sacramento	2,975
Mudflows/Lavaflows	Mehrten	Xerorthents	Ranchoseco	Sacramento, Yuba	2,230

* Due to time constraints, only a portion of the relationships with specific geologic formations have been worked out to-date.
** Source of information is USDA, Natural Resources Conservation Service “Soil Survey Map Unit Interpretation Records” (MUIR) data base as of September 1993.

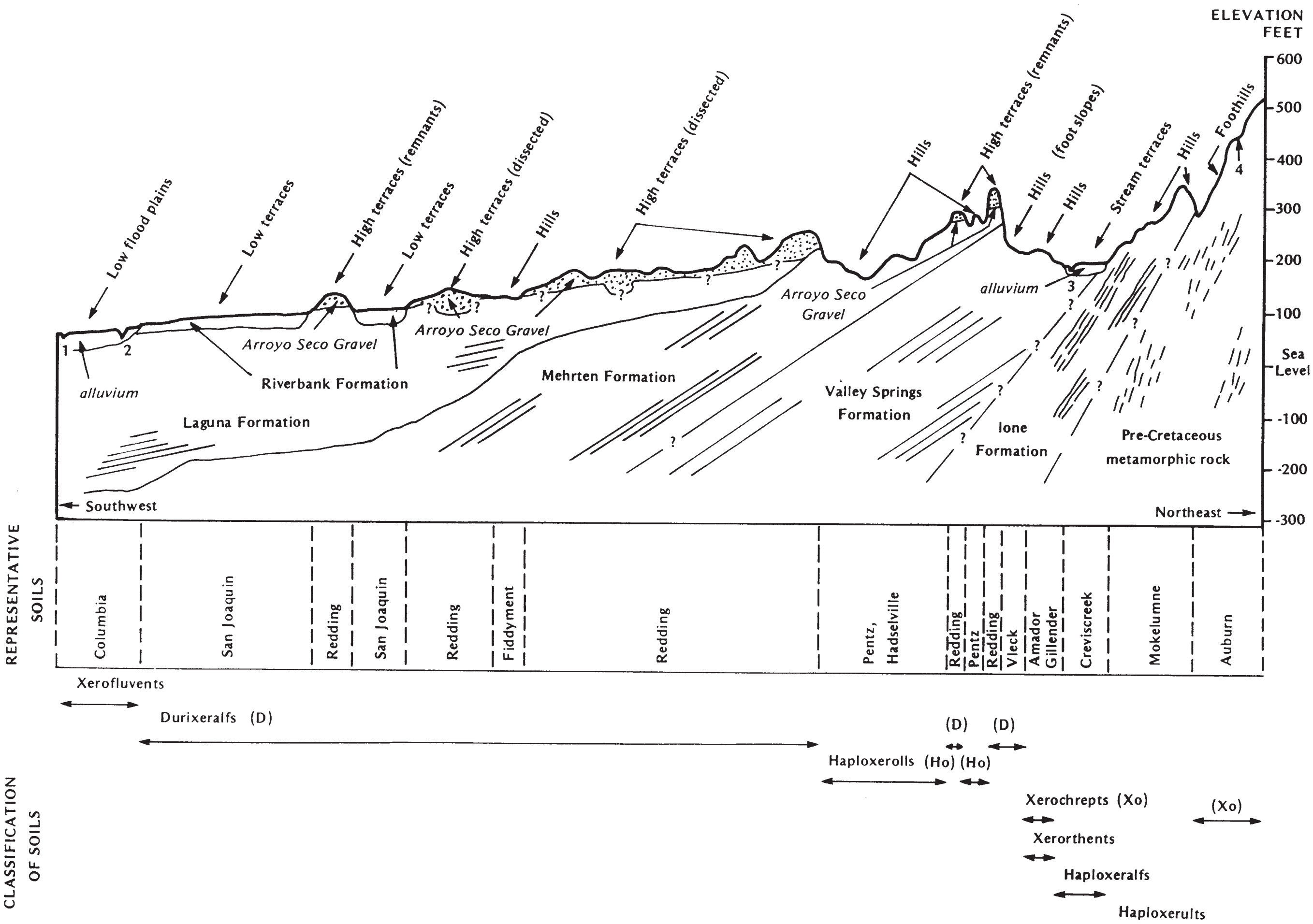

Figure 2. Idealized cross-section showing some relationships between soils, geologic formations, and landforms in the lower Sacramento Valley (from Tugel, 1993; used with permission).

(overbank flooding and rising groundwater). The lowest areas were probably flat marshes.

Nine major basins are distinguished by geographic location along the central axis of the Valley, six in the Sacramento Valley (Butte Basin, Colusa Basin, Sutter Basin, American Basin, Yolo Basin, Sacramento Basin) and three in the San Joaquin Valley (Kern Basin, Tulare Basin, San Joaquin Basin). They are partially separated by encroaching alluvial fans and the Sacramento-San Joaquin Delta.

Basin rims occur bordering the basins, near the distal end of low terraces (the next older geomorphic surfaces). They have mound-depression microrelief and saline-sodic soils with perched water tables. Vernal pools occur in these locations. Of the six Sacramento Valley basins, the western margins of Yolo and Colusa Basins were the site of extensive basin-rim pools. Saline-sodic basin rim soils and associated vernal pool landscapes are generally absent on the east side of the Sacramento Valley because of the more abrupt geomorphic transition from basins to low terraces and the lesser amount of salts contained in Sierran-derived alluvium. Basin rim landforms did not develop in the transition from basins to natural levees bordering the Sacramento River.

Given the more gradual transitions from basins to alluvial fans and the higher salinity of alluvium, the three major basins of the San Joaquin Valley, support (or supported) extensive vernal pool landscapes along the circumscribing basin rims. The major basins are connected by narrower low areas with flooded (historically) seasonal wetlands which are also bordered by saline-sodic vernal pool landscapes.

Low terraces lie topographically above the Holocene basins. They contain late Pleistocene-age geomorphic surfaces which are underlain by stream alluvium. These low terraces are of great aerial extent within the Central Valley, and have been referred to as the “main valley floor,” the “alluvial plain,” or the “old alluvial fan” of the valley (CDWR, 1974; Huntington, 1980; Parsons and Herriman, 1976). Their nearly level surfaces are more than 10,000 years old. Soils have been forming long enough to have undergone significant pedogenesis, and claypans and duripans are common. Vernal pools occur extensively in certain areas of these low terraces.

Dunes consist of sandy deposits on top of low terraces close to basin rims. Based on evidence from old soil surveys, these areas of wind-laid sands containing wind-scoured hollows with poorly drained soils occurred along the east-side of the San Joaquin Valley near the basin rim. Areas of this landform are not extensive. Vernal pools occur in these locations.

High terraces are the oldest alluvial surfaces in the Central Valley. They are mid to early Pleistocene to late Pliocene in age and lie topographically above low terraces. Very strong soil development has occurred in relatively flat areas on these terraces where the geomorphic surfaces are very old. The most pronounced erosion-induced mound-depression microrelief and vernal pool landscapes are found on the high terraces.

Volcanic mud and lava flows extend from their source in the ancestral Sierra Nevada to form low, nearly level to gently sloping ridges and fans along the eastern edge of the Central Valley. They range in age from early Pleistocene to Miocene, the oldest being the Lovejoy Basalt originating approximately 20 million years ago. Soils are shallow over impermeable bedrock. The flatter areas commonly contain a disjunct network of vernal pools and connecting swales.

Geologic Formations

Landforms in the Central Valley can be further subdivided by specific geologic surficial deposits (or formations). The geologic formations referred to in this paper are differentiated by various criteria including age, lithology, stratigraphy, induration, compaction, texture, depositional environment, geomorphic expression, and soil-profile development (Helley and Harwood, 1985).

No formations are named within the basins. They have been mapped simply as Holocene stream channel deposits, alluvium, and overbank deposits.

The *Modesto Formation* comprises the youngest Pleistocene alluvial deposits mapped on the low terrace landform. The Modesto Formation lies topographically above and adjoins the basins along the entire east side of the Central Valley and the west side of the Sacramento Valley. Few vernal pools occur on these youngest low terrace deposits. Too short a period of time has elapsed for the necessary surface erosion and soil development (i.e. claypan or duripan) to have taken place.

The *Riverbank Formation* underlies the major extent of low terrace landform. It too is a Pleistocene deposit mapped along the east side of the entire Valley and the west side of the Sacramento Valley, but is older than the Modesto Formation. Ranging from almost coalescing old alluvial fans in Sacramento and adjoining counties to stream terraces along present day creeks in the northwestern Sacramento Valley, the Riverbank Formation was almost everywhere characterized by a relatively subdued but well-developed erosion induced mound-depression topography and strong soil development. Soils with claypans and duripans are common. Vernal pools are common.

The *Turlock Lake, Red Bluff, and Laguna formations* make up the high terraces on the east side of the Central Valley. The *Tehama and Red Bluff formations* underlie high terraces on the west side of the Sacramento Valley. Soils formed in most of these deposits are well developed and contain vernal pools. The exception is the Tehama Formation which has eroded to the degree that soils with sufficiently reduced subsoil permeability have not developed and slopes exceed the limits on which pools can form.

The andesitic *Mehrten Formation* and rhyolitic *Valley Springs Formation* are eroded, high standing remnants of fans from volcanic mud and lava flows in the areas where vernal pools are associated with them near their distal edge. Eastward of their distal edge, slopes increase to preclude pool development. A surface exposure remnant of the *Lovejoy Basalt Formation* caps the dramatic Table Mountain north of Oroville and has numerous shallow pools. A vernal pool preserve on Table Mountain is dedicated to the memory of James Jokerst, a distinguished botanist who was also a pioneer in the application of geomorphology and soils to the study of vernal pools.

Soil Great Groups

Soils are classified in a six level pedologic hierarchy called *Soil Taxonomy*, based primarily on vertical sequence of diagnostic horizons and features, hydrology or moisture regimes, and texture (Soil Survey Staff, 1994). The categories in order of increasing specificity are Order, Suborder, Great Group, Subgroup, Family, and Series.

Relationships exist between the occurrence of vernal pools on specific landforms and certain soil taxa at the Great Group level. These relationships are as follows.

Natrixeralfs are soils with a subsoil accumulation of sodium-rich clay and a xeric soil moisture regime. The pH of the sodium-rich clay subsoil is commonly greater than 9, and the clay and organic fractions are dispersed. As a result of this de-flocculated subsoil layer, the permeability of these soils is generally so low that water ponds in micro-relief depressions and passes through only very slowly. Natrixeralfs are mapped where vernal pools occur on basin rim landforms.

Palexeralfs are older, well developed soils with a strong accumulation of clay in the subsoil and a xeric soil moisture regime. They can be considered to have a "claypan." The permeability can be very slow because of the claypan. Palexeralfs are mapped in certain areas where vernal pools occur on both low terraces and high terraces.

Durixeralfs have a silica-cemented hardpan or "duripan" in the subsoil (with or without a claypan) and a xeric soil moisture regime. The duripan is impermeable or very slowly permeable. Durixeralfs are mapped extensively in areas where vernal pools occur on both low terraces and high terraces.

Soils mapped on volcanic mud and lava flows are characteristically shallower with less developed subsoil than in other vernal pool terrain. Such soils may range from *Haploxeralfs*, moderately deep soils darkened by organic matter accumulation with moderate subsoil clay accumulation, to *Xerorthents*, very shallow, rocky soils with no pedogenic development. The relatively impermeable volcanic bedrock is the restrictive edaphic feature that allows for seasonal ponding.

Soil Series

Soil great groups are comprised of individual soil series, some of which can be specifically associated with occurrence of vernal pools.

The differentiae used for soil series are mostly the same as those used for classes in the other categories of *Soil Taxonomy*, but the range permitted in one or more properties is less than permitted in a higher category. The purpose of the series category is mainly pragmatic and is closely allied to interpretive uses of the system.

Soil series are commonly used as part of the name for an area shown on a soil survey map where that series is dominant, for example, San Joaquin silt loam, 0 to 3 percent slopes. It is essential, however, to understand that a soil series is conceptual; the meaning is not identical with the meaning intended on soil maps, for an area mapped as dominantly San Joaquin series has small inclusions of soil of other series. Vernal pools themselves often occur as small unnamed inclusions within a soil series. Keeping this in mind, certain soil series have been consistently mapped as the dominant soil in areas that coincide with the occurrence of vernal pools. Thus, there is a correlation between vernal pools and certain mapped soil series.

Most of these soil series are associated one-to-one with geologic formations, although some series may occur on two or more formations. For example, the *San Joaquin soil series*, a Durixeralf that has been nominated as the California State Soil, is the most extensive soil series mapped in vernal pool areas, covering almost one-half million acres of low terraces on the east side Central Valley. The San Joaquin soil is the principal soil that defines the Riverbank Formation. The *Redding soil series*, a more weathered and gravelly Durixeralf that is the second most extensive soil series mapped in vernal pool terrain at almost 200,000 acres, primarily defines the Laguna Formation on the eastside Central Valley as far north as Oroville, and defines the Red Bluff Formation in the northern and western Sacramento Valley. The *Corning soil series* is a Palexeralf associated with the Redding series on both the Laguna and Red Bluff Formations on high terraces.

A number of soil series occur as interwoven complexes in a landscape. In some mound-intermound vernal pool landscapes, soil series complexes are differentiated with one series on the mounds and the other in the intermounds (this is especially true in the most recent modern soil surveys, where need for more detailed mapping in these areas has been recognized). Examples are the mound *Pentz soil series* and the intermound *Hadselville soil series* and the mound *Pardee soil series* and intermound *Ranchoseco soil series* on the Mehrten Formation, and the mound *Amador soil series* and the intermound *Gillender soil series* on the Valley Springs Formation. Where the *Galt soil series* occurs in a complex with the San Joaquin series on the Riverbank Formation, the San Joaquin series is on the mounds and the Galt series in the intermounds.

Phases of Soil Series

Phases of soil series are the fifth and last of the landscape classification categories used for the purposes of this paper, and are the most specific. Soil phases differentiate such things as slope ranges, frequency of flooding, degree of altered drainage, or surface soil texture within a soil series. Phases of soil series are the components used in the soil map units of most modern detailed soil surveys. Most significant for vernal pools is their general limitation to slopes ranging from 0 to about 3 percent. Even if all the higher categories of landform, geologic formation, soil great group, and soil series are indicative of potential vernal pool landscapes, pools may be sparse or absent because the slope is excessive. Soil survey map units using soil phases with specific ranges in degree of slope (less than 3 percent) can most accurately define the spatial boundaries of vernal pool landscapes.

MODERN GEOMORPHIC AND SOIL MAPPING OF THE CENTRAL VALLEY

Geomorphic and soil mapping has been completed for most of the Central Valley and published by the US Geological Survey and USDA, Natural Resources Conservation Service respectively. These maps should be referred to in applying this hierarchical framework.

Geomorphic mapping of the Sacramento Valley (except for the southeastern edge) has been completed by Helley and Harwood (1985) at a scale of 1:62,500 and by the California Division of Mines and Geology (1981) at a scale of 1:250,000. The geomorphic maps probably need to be updated for some areas (particularly where soil surveys have been completed since publication of the geomorphic maps) to reflect the continued advance in knowledge and interpretation of landscapes. Most of the San Joaquin Valley has been geomorphically mapped by three principal investigators, Marchand and Allwardt (1981) on the east side, and Lettis (1982) on the west side. Only certain portions of the Tulare Basin have been geomorphically mapped; there is not comprehensive coverage (although landforms have been determined in soil surveys).

The first modern soil surveys within the Central Valley were completed for eastern Madera and Merced Counties and published in 1962. The last of this generation of soil surveys, which will complete soil mapping of the Central Valley, are now in progress in Butte, Colusa, eastern Stanislaus, Fresno, and Tulare counties, and parts of Kern County. This new information should be referred to in applying the hierarchy presented in this paper when the data becomes available. Most of these modern surveys are mapped at a scale of 1:24,000, with a few of the older modern ones at 1:20,000. The next generation of soil surveys needed to update the oldest modern surveys is in the planning stage.

Historical Soil Surveys

The first soil surveys of the Central Valley, covering the Fresno and Hanford areas, were published in 1901. By 1921, reconnaissance soil surveys had been published for the entire Central Valley and more detailed soil surveys for many portions of the valley. These historical documents are an extremely valuable source of information for the identification and study of historical vernal pool landscapes. Although alteration of the extensive mound-depression landscapes in the valley was already underway, much of the valley still retained natural vegetation, microtopography, and hydrology, or had just recently undergone alteration. Although vegetation descriptions in the historical soil surveys are generalized at best, the historical surveys contain detailed descriptions and mapping of microtopography and hydrologic conditions. The study of these documents allows the identification of vernal pool landscapes now long obliterated and provides a means of evaluating the degree of alteration to existing vernal pool landscapes.

Two examples, one from Yolo County and one from Fresno County, will help to illustrate the value of the historical documents. Between Davis and Woodland and east of Woodland on the western rim of the Yolo Basin lies an area of now level, saline- and sodium-affected marginal farmland. In a 1911 soil survey of the area (Mann, 1911), this land was described as hogwallow land, occupying "low, flat, poorly drained areas...where the surface is generally slightly uneven, owing to the presence of hogwallow depressions." The accompanying 1:62,500 scale map shows a dozen or more large to very large vernal pools, some larger than Olcott Pool at the Jepson Prairie Preserve. The modern geomorphic and soil mapping of the area is basin rim with Pescadero and Willows soil series (Andrews, 1972). The 1911 soil type was mapped as extending in a "number of long, narrow, areas or small bodies ... subject to overflow during seasons of high water," north along the western rim of the Yolo and Colusa Basins. The 1911 recommendation that the area was "unfit for the production of cultivated crops and is best suited to permanent pasture" was not adhered to in the years to come.

On the alluvial fan of the Kings River west of its present channel and south of the city of Fresno, sand dunes were once extensive. In a 1919 soil survey (Holmes, 1919), the surface is described as "...uneven, slightly rolling, or undulating. Winding streamways, numerous circular depressions, and segments of old stream channels are common. Some of the deeper depressions partly fill with water." The modern soil survey, conducted in the early 1960's adds more detail, "the Dello series formed under somewhat poorly drained to poorly drained conditions ... from wind-laid sands. These...gently undulating soils occupy bottoms of wind-scoured hollows... In the past, when the water table was closer to the surface, the depressions in which the soils were located were intermittent ponds (Huntington, 1971)."

Landscape Alterations Affecting Vernal Pool Distribution

The advent of large scale agriculture in the Central Valley initiated the alteration of vernal pool landscapes. The riverine floodplains and natural levees of the major rivers were the first landforms to be developed for agriculture, but in the latter decades of the nineteenth century, agriculture quickly developed on the alluvial fans and terraces of the Central Valley. Landscape-altering techniques such as cut and fill land leveling of mounds and depressions, excavation of drainage ditches to lower shallow water tables, and ripping and blasting to increase permeability of subsoil horizons was widespread in the early years of this century. With the development of major surface water delivery systems and advances in drainage management, the basins and basin rims were also developed for agriculture. Increasing urbanization in recent decades has resulted in further alteration of high terrace and volcanic mud and lava flow landscapes.

The result of over a century of landscape alteration is that certain historical vernal pool landforms, formations, and soils are now reduced in extent. The formerly extensive vernal pool landscapes on basin rims and historically rare pools in dune depressions are now largely leveled, drained, and converted to agriculture. The extensive and agriculturally productive low terrace Riverbank Formation landscape has been almost completely leveled and developed for agriculture. Other vernal pool landforms and formations that may be locally rare, such as the low terrace Turlock Lake Formation in Sacramento County, have been nearly completely urbanized. Other relatively unproductive (agriculturally speaking) landscapes, such as the high terrace Red Bluff, Laguna, Valley Springs formations and the volcanic mud and lava flow Mehrten Formation that were not developed for agriculture and support the most extensive remaining vernal pool landscapes, are now undergoing increasing urbanization.

ADVANTAGES AND APPLICATIONS OF A VERNAL POOL SOIL-GEOLOGIC FORMATION-LANDFORM CLASSIFICATION SYSTEM

The soil-geologic formation-landform classification system outlined in this paper has a number of distinct advantages and productive applications.

First, this system provides a natural physical basis for pool classification that is a framework for understanding modes of landscape origin and geomorphic evolution, relative landform and land surface age, vernal pool hydrologic and chemical characteristics, active landscape and biogeochemical processes, distribution of vernal pools by size and shape, and the landscape density and geographic distribution of vernal pools (Jones & Stokes Associates, 1990).

Second, this system allows for a detailed determination of the historical versus present distribution of vernal pools. Correlation of the microtopographic and hydrologic descriptions in historical soil surveys with the detailed mapping of modern soil surveys would allow for the eventual production of 1:24,000 scale maps of historical vernal pool distribution throughout the Central Valley for comparison with present distribution. This approach also identifies which pool types and landforms are presently most or least abundant.

Third, this system provides the framework for a vernal pool database that will allow for the identification of correlations between vernal pool plant and invertebrate distributions and landform and soil characteristics. Such correlations could be used to predict other occurrences of species, best locations for mitigation of habitat loss, and could provide a tool for conservation planning.

Fourth, this system provides an increasingly specific screening tooling to identify potential vernal pool landscapes, and a basis for both site-specific evaluation and comprehensive planning of vernal pool preserves and mitigation banks that will allow preservation and restoration of vernal pool landscapes that approximate their natural diversity and distribution (Jones & Stokes Associates, 1994).

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