Wetlands Ecology and Management **12:** 165–178, 2004.

Changes in vernal pool edaphic settings through mitigation at the project and landscape scale

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Received 25 September 2001; accepted in revised form 25 February 2003

Key words: California, HGM, Mitigation, Regulation, Vernal pools, Wetlands

Abstract

Vernal pool mitigation is a highly controversial process that has been frequently criticized for its inability to adequately replicate the ecosystem functions of the original intact wetlands. We analyzed past mitigation practices in two rapidly growing counties in California's Great Central Valley to determine if mitigation procedures are re-arranging the vernal pool landscape by substituting more common or less ecologically significant pool types (as defined by soil type and geomorphology) for rarer or ecologically richer pool types. Results indicate that most development projects impacting vernal pools conduct at least a portion of their mitigation requirements at a site with similar edaphic settings. However, when examined at a landscape-scale across all development projects, the more common edaphic settings such as Northern Hardpan and Low Terrace pools are increasing while more rare types such as Northern Claypan and Volcanic Mudflow pools are decreasing. Results also show that Drainageway pools, a less-specialized pool type with generally lower species richness, are becoming more common through mitigation. These results are confirmed by an analysis of landscape diversity, which showed that overall landscape diversity was lower at mitigation sites than at project sites. Despite these results, the ecological significance of vernal pool mitigation practices remains unclear for several reasons. The lack of maps showing exact locations of vernal pools at project sites make it difficult to precisely determine vernal pool acreage and distribution among edaphic settings. Additionally, more research is needed to determine precise relationships between edaphic settings and species distributions and the effects of mitigation area management practices on species distribution and persistence.

Introduction

Like many other ecosystems in California, vernal pools have been heavily impacted by California's long history of agricultural development and urban growth. Estimates of vernal pool loss range upwards of 95% in the Great Central Valley (Dahl 1990). These losses will likely continue into the future, with five million new residents projected to move into the Central Valley, where much of the remaining vernal pool habitat is located, in the coming 40 years (California Department of Finance 1998, 2001). A variety of state and federal regulations exist that afford vernal pools some protection, largely by requiring that vernal pool damage caused by land development be mitigated by the preservation and, possibly, the creation of vernal pool habitat elsewhere. The mitigation process has been criticized because many mitigation efforts fail to replicate the landscape setting and ecological functions performed by the original vernal pool ecosystem (Leidy and White 1998).

While some researchers have described and others have quantified the landscape-scale changes that results from the wetland mitigation process (Bedford

1996; Brown and Lant 1999; Kelly 2001), most have not focused on vernal pool systems. We present the results of research that examined selected vernal pool development projects in central California in order to quantify the extent to which mitigation sites replicated the edaphic characteristics at original sites at two scales: a project-by-project scale and a larger 'landscape scale' encompassing large areas of vernal pools and intervening upland habitat. Although edaphic factors only explain a small proportion of observed variation in species distributions within vernal pool ecosystems (Holland and Jain 1981a), the scale at which edaphic factors operate closely corresponds to the scale at which most vernal pool mitigation occurs: within counties or among neighboring counties. Therefore, an analysis of a given mitigation site's ability to replicate the edaphic characteristics of the corresponding project site is an important part of understanding how development and mitigation of vernal pools change the local and landscape-scale functions of these wetland ecosystems.

Background

Vernal pool ecosystems

Vernal pools are ephemeral wetlands commonly found in Mediterranean climates throughout the world (Keeley and Zedler 1998) and widely distributed in California's grasslands and oak savannas (Holland 1998; Smith and Verrill 1998). While vernal pools are classified as palustrine, emergent wetlands (Cowardin et al. 1979), they have unique characteristics in terms of soils, geomorphology, hydrology, and species assemblages that differentiate them from other types of wetlands. Vernal pool soils are generally characterized by sub-surface horizons containing high clay concentrations, silicate-cemented hardpans, or volcanic mud or lava flows (Holland 1978; Holland and Jain 1988). These impervious surfaces restrict water seepage causing pools to form from either direct precipitation or seasonally perched water tables in areas of flat to low slopes or in small basins within larger areas of rolling mima mound topography (Zedler 1987; Holland and Jain 1988; Keeley and Zedler 1998). After the pools form during the rainy season (typically between November and April in California's Great Central Valley), they dry out over a period of several weeks during the ensuing prolonged period of drought that characterizes California's Mediterranean climate (Zedler 1987; Keeley and Zedler 1998).

These unique physical characteristics combine to create an ecosystem that supports many endemic and endangered species of plants, invertebrates, and amphibians adapted to cyclic periods of inundation and desiccation (Holland and Jain 1981a; Zedler 1987; Holland and Jain 1988; Keeley and Zedler 1998; Keeler-Wolfe et al. 1998). A report from the California Department of Fish and Game (Keeler-Wolfe et al. 1998) indicates that over 80 species of Federal- or State of California-listed endangered/threatened/candidate species depend, at least partially, on vernal pool ecosystems to provide various habitat functions. Vernal pools harbor some of the best remaining examples of Californian native plant diversity (Holland and Jain 1988) and are a center of local adaptive radiation for several plant genera resulting in high species endemism (Stone 1990) and a lack of invasive, non-native species. Holland and Jain (1981a) indicate that 91% of the 186 plant species known to occur in vernal pools are California endemics as opposed to 62% of the plant species in the surrounding grasslands. In addition to several endemic plant species, vernal pools support populations of endangered fairy shrimp and tadpole shrimp, small crustaceans that are distributed sporadically in pools throughout the Central Valley (King 1998; Simovich 1998). Vernal pools also provide breeding and larval habitat for amphibians such as the California Tiger Salamander (*Ambystoma californiense*), a United States federally-listed endangered species in Santa Barbara County and a candidate species for listing throughout California (Federal Register 2000), and the Western Spadefoot Toad (*Spea [Scaphiopus] hammondii*), another species that is a candidate for listing under the Endangered Species Act (Keeler-Wolfe et al. 1998). Aside from providing habitat for numerous rare species, vernal pools and the intervening uplands also provide habitat for a wide variety of grassland generalist species and numerous species of waterfowl and other species of vertebrates (Jones and Stokes 1990; Keeler-Wolfe et al. 1998).

Vernal pool regulation

The vernal pool regulatory process is highly complex and frequently variable and will not be described in detail here. An idealized permitting process for the conversion of vernal pools usually involves several key steps. Using a regulatory framework similar to that of other wetlands, projects that propose the destruction of vernal pools are subject to the permitting requirements of Section 404 of the United States Clean Water Act. If the vernal pools contain a federally listed endangered species, the project must also go through a Section 7 consultation between the United States Army Corps Engineers (Corps) and the United States Fish and Wildlife Service (Service) under the federal Endangered Species Act during which the Service may attach an incidental take statement to the biological opinion. This statement specifies ''reasonable and prudent measures'' necessary for the applicant to undertake as a condition of granting the fill permit under Section 404 (USFWS and NMFS, 1998). Regardless of whether or not endangered species are present at the project site, project applicants are required to submit an initial mitigation plan to the Corps. Based on the incidental take statement, this initial mitigation plan is modified to meet requirements of the biological opinion. Generally, project applicants are required to both preserve existing vernal pools and either restore degraded pools or create new pools. Mitigation may be done on the same site as the proposed project ('on-site' mitigation), at a remote site ('off-site'), or at an agency approved mitigation bank (Leidy and White 1998). Generally, mitigation sites must preserve more vernal pool acreage (not including uplands) at some fixed ratio, usually 2:1, than was destroyed at the development project site. The exact ratio is determined on a project-by-project basis and can vary widely depending on the habitat value of the vernal pools to be destroyed (K. Merriam, Biologist, USFWS Sacramento Field Office, personal communication).

With a focus on the preservation of wetland *acreage* rather than wetland *ecosystems* these policies often result in a piecemeal approach to vernal pool mitigation (Leidy and White 1998). The end result of the mitigation process has been a net loss in vernal pool acreage due to poorly sited and constructed mitigation efforts that, in many cases, fail to meet the landscape functional equivalence of the original wetland ecosystems (Race and Fonseca 1996; Leidy and White 1998; Brown and Lant 1999; Gwin et al. 1999). In particular, little attention has been paid to the equivalency of edaphic factors between original and corresponding mitigation sites. As described above, edaphic characteristics, although they only explain 17% of the statewide variation in vernal pool plant communities (Holland and Jain 1981a), are the primary factor structuring vernal pool communities at the scale of counties or regions (the scale at which most all mitigation efforts take place). There is some movement towards incorporating edaphic conditions in the regulatory process. First, the Corps recognizes the importance of maintaining similar soils between project and mitigation sites in its vernal pool mitigation guidelines (USACE, 1996). Second, efforts are underway within the Corps and among wetland scientists to develop wetland mitigation evaluation heuristics (known as hydrogeomorphic profiles or HGM) that account for the importance of edaphic characteristics in structuring wetland communities (Brinson 1993; Bedford 1996; Butterwick 1998; Leidy and White 1998; Gwin et al. 1999; Whingham 1999). The hydrogeomorphic (HGM) approach to wetland functional assessment is a collection of concepts and methods used to develop and apply indices in the assessment of wetlands by identifying groups of wetlands that function similarly. Despite these advances, there is currently no regulatory requirement that vernal pool mitigation efforts mimic the edaphic settings found at the project site.

Edaphic factors in vernal pool ecosystems

The notion that edaphic factors have a strong influence on plant community composition was first developed in the 1950s (Major 1951) and grew out of the state factor ecosystem model formulated by pedologist Jenny (1941). The original state factor model maintained that soil formation could be quantitatively analyzed as a function of five factors: parent material, time, relief, biota (including human influences), and climate (Jenny 1941). Major (1951) applied Jenny's theory of soil formation to plant communities, essentially substituting vegetation for soil as the dependent variable and retaining the same set of independent variables. Therefore, a change in any one of the five state factors can be assumed to lead to both a different edaphic setting and differences in plant community composition. While the overall effect of edaphic factors in structuring plant species communities is relatively small (Holland and Jain 1981a) edaphic characteristics are most likely responsible for observed differences at an intermediate geographic extent where climatic and biota state factors are held constant (Holland and Jain 1981a).

The relationship between specific edaphic settings and the location of vernal pool ecosystems was first described over 20 years ago (Holland 1978). Since this initial description, plant ecologists have worked to further define the relationship between edaphic setting and specific plant community characteristics. These studies have demonstrated that, in general, certain associations of plants tend to occur on specific soil series and geomorphic surfaces and that species diversity and the presence of vernal pool obligate species varies among different edaphic settings (Holland and Jain 1988; Holland and Dains 1990; Jokerst 1990; Jones and Stokes 1990; Platenkamp 1998). While most of the work on vernal pool community structure has focused on plant species composition and richness, an increasing number of researchers are also attempting to link physical features of vernal pools to vertebrate and invertebrate species distributions. Although much more research is needed to make any conclusive statements, it seems clear that vernal pool type, as defined by edaphic setting, helps determine the function of vernal pools as habitat for amphibians (Morey 1998), invertebrates (King et al. 1996; Helm 1998; Platenkamp 1998; Simovich 1998), and waterfowl (Silveria 1998).

Based on these relationships, a classification system that defines seven different vernal pool community types throughout the state has been adopted by the California Department of Fish and Game Natural Diversity Database (NDDB) program (Holland 1986). It is largely reflective of differences in edaphic setting and large-scale climatic variations (Table 1). These seven classifications have been further refined in the development of 17 vernal pool regions for the state of California (Keeler-Wolfe et al. 1998). A more generic vernal pool classification system, based on landforms, has been used by other researchers (Jones and Stokes 1990; Smith and Verrill 1998; Swanson and Reiner 2000) to classify vernal pools into one of five types according to geomorphic setting (Table 2).

While there are some obvious differences between the two classification schemes, both are based on the underlying premise that edaphic characteristics are the primary agents structuring vernal pool communities at an intermediate geographic range. Under both schemes, the pools found on the highest alluvial terraces surrounding the Central Valley, which are characterized by the oldest soils and most well defined impervious substrates, generally support larger and deeper pools (i.e., longer lasting). Pool size and depth are factors that numerous authors have reported as the strongest determinant of species abundance and diversity in vernal pools (Holland and Jain 1981a, 1981b; King et al. 1996; Helm 1998; Morey 1998; Platenkamp 1998; Silveria 1998; Simovich 1998).

The two schemes also differ in that the Holland system was developed as a means of classifying plant communities and makes no attempt to tie specific vernal pool community types back to invertebrate or vertebrate distributions. The landform-based system, in comparison, does not correlate vernal pool types to species distributions; rather, it makes broad-scale inferences regarding the suitability of pool types for various taxa (Jones and Stokes 1990). Despite these differences, both systems provide valuable information regarding the suitability of a given vernal pool type for certain taxa. Taken together, these two classification schemes illustrate the importance of edaphic characteristics in structuring vernal pool communities. We use both classification systems in this analysis.

Methods

Study area

The study area includes Sacramento County and western Placer County in California's Great Central Valley (Figure 1). These counties are located in the Southeastern Sacramento Valley Vernal Pool Region (Keeler-Wolfe et al. 1998). Within this area there are 15 species either currently listed or proposed for listing under the Federal or state Endangered Species Acts. This includes one species, Sacramento Orcutt Grass (*Orcuttia viscida*), that is endemic to the region. The region contains examples of Northern Claypan, Northern Hardpan, and Northern Volcanic Mudflow vernal pools as classified under the Holland/NDDB scheme (Keeler-Wolfe et al. 1998); all four of the landform-based vernal pool types are represented within this region.

Along with its status as one of the most biologically diverse vernal pool regions in the state, Sacramento and western Placer Counties are the population centers of the Central Valley and have experienced some of the highest rates of population growth in the state. Based on the 2000 Census (California Department of Finance 2001), Placer County was the second fastest growing county in the state with over 43% population growth between 1990 and 2000; Sacramento County grew at a slower rate (17.5%) but still added over 180,000 new residents. Both counties grew at a faster rate than the state as a whole (13.8%).

A preliminary review of databases created by the US Fish and Wildlife Service to analyze development

Table 1. Vernal pool community types used by California Department of Fish and Game natural diversity database.

Northern Hardpan	
Site Factors	Typically acidicFe and Si cemented hardpan soils (Redding, San Joaquin, and similar series). The microrelief on these soils typically is hummocky, with mounds intervening between localized depressions. Winter rainfall perches on the hardpan, forming pools in the depressions. Evaporation (not runoff) empties pools in the spring.
Characteristic plant spp.	*Castilleja (= Orthocarpus) campestris, Deschampsia danthonioides, Downingia bicornuta, D. cuspidata, D. pulchella, Epilobium torreyi (= Boisduvalia stricta), Eryngium vaseyi, Juncus leiospermus, J. uncialis, Lasthenia fremontii, Limnanthes alba, Limosella aquatica, Navarretia leucocephala, Plagiobothrys (= Allocarya) stipitatus micranthus, P. undulata, Pogogyne zizyphoroides, Psilocarphus brevissimus, Veronica arvensis*
Distribution	Primarily found on alluvial terraces on the east side of the Great Valley from Tulare or Fresno counties north to Shasta County.
Northern Claypan	
Site Factors	Similar to Northern Hardpan. Soils generally younger, circum-neutral to alkaline, Si-cemented hardpan soils. Often more or less saline. Intergrades via Cismontane Swale with Cismontane Alkali Marsh which has water present throughout the year.
Characteristic plant spp.	*Cressa truxillensis, Downingia bella, D. insignis, Epilobium pygaeum (= Boisduvalia glabella), Eryngium aristulatum, Lasthenia ferrisiae, L. glaberrima, L. minor, Myosurus minimus, Plagiobothrys (= Allocarya) leptocladus, P. stipitatus stipitatus, Pogogyne douglasii, Spergularia marina,Veronica peregrina xalapensis*
Distribution	On lower terraces and basin rims, toward the valley trough compared to Northern Hardpan Vernal Pools; Central San Joaquin Valley north to Glenn and Colusa counties.
Northern Basalt Flow	
Site Factors	Occur in small depressions on tops of massive basalt flows. These pools fill and empty many times during the winter, and have extremely thin soils over the solid bedrock that prevents downward rainwater percolation.
Characteristic plant spp.	*Blennosperma nanum, Callitriche marginata, Cicendia quadrangularis, Crassula aquatica, Downingia cuspidata, Epilobium (= Boisduvalia) densiflorum, Eryngium vaseyi, Gnaphalium palustre, Lasthenia fremontii, Linanthus ciliatus, Parvisedum pumilum, Psilocarphus brevissimus, P. tenellus*
Distribution	Scattered along the western Sierra foothills between Shasta and Tulare counties, and in the volcanic tablelands of the Modoc Plateau in Shasta, Lassen, Modoc and Siskiyou counties.
Northern Volcanic Mudflow	
Site Factors	Restricted to irregular depressions in Tertiary pyroclastic flows (Lahars–largely on the Mehrten Formation). Shallow soils prevent forests from developing. Pools form in the small depressions following winter rains.
Characteristic plant spp.	*Downingia bicornuta, Lasthenia glaberrima, Limnanthes douglasii rosea, Navarretia tagetina*
Distribution	Scattered on flat-topped mesas (many called ‘Table Mountain’) along the Sierran foothills, mostly between 500–2000 feet elevation in the Blue Oak Woodland and Foothill Pine-Chaparral Woodland.

Classifications taken from Holland (1986).

projects potentially affecting California Tiger Salamander (*Ambystoma californiense*) habitat indicated that approximately 50% of all vernal pool development projects listed in the database were from one of these two counties. In addition to pressures from urbanization, vernal pools in the Sacramento-Placer region are increasingly lost due to the conversion of land used for livestock grazing to vineyards. According to one estimate, as much as 4,000 hectares of pools and intervening upland habitat may have been lost to vineyard conversion between 1996 and 1997 alone (Keeler-Wolfe et al. 1998). Given these factors, the Sacramento/Placer area provides a suitable combination of high growth coupled with vernal pool landscape diversity to examine the extent to which mitigation efforts replicate project site edaphic settings.

Data collection

Data on project and mitigation site locations was gathered from the Sacramento field office of the US Fish and Wildlife Service. The Service had already digitized both project and mitigation site locations and incorporated this information into a Geographic Information System (GIS) using ArcInfo software (Environmental Systems Research Institute, Inc. 1994) as part of its ongoing efforts to study population distributions and development impacts on the California Tiger Salamander (*Ambystoma californiense*) and

Table 2. Landform based vernal pool classification scheme.

Pool Classification	Landform	Formation(s)	Age of Formation	Soil Series
High Terrace	Remnant alluvial deposits of ancestral river channels and pediment gravels, intermediate and high terraces of Sacramento Valley floor and Sierra Nevada foothills	Laguna formation and Arroyo Seco gravels	Early Pleistocene; 600 K to 1.5 M years	Corning, Mokelumne, Red Bluff, Redding, *Keyes*, *Vleck*, *Fiddyment*
Volcanic Mud/Lava Flow	Exposed, upturned edges of mudflow formations at base of Sierra Nevada foothills	Meherten and Valley Springs	Valley Springs formed in Oligocene; Meherten formed in Miocene of Pliocene; > 3 M years old	Amador-Gillender, Hadselville-Pentz, Pardee-Ranchoseco, Exchequer, *Peters*
Low Terrace	Alluvial deposits of the main floor of the Sacramento Valley, lowest terrace adjacent to central trough along Sacramento River	Riverbank	Late Pleistocene; 100 K to 200 K years old	Galt, Madera, San Joaquin, Tehama, Cometa, *Hedge*, *Kimball*
Drainageway	Alluvial deposits of stream terraces and base toe slopes	Modesto, Recent alluvial deposits over other formations	Holocene; < 20 K years old	Creviscreek, Fiddyment, Hedge, Hicksville

Source: Jones and Stokes (1990); soil series in italics from Smith and Verrill (1998) four different species of fairy/tadpole shrimp (*Branchinecta conservation, B. longiantenna, B. lynchi*, and *Lepidurus packardi*). The specific locations of each project and mitigation area were determined from drawings and maps submitted by the permit applicant. These drawings or maps were aligned to standard 7.5-minute USGS quadrangle maps and then manually digitized using geographic information systems software (Merriam, personal communication).

Attribute data for mapped project and mitigation sites were contained in two separate databases obtained from the Service: a database compiled for development projects and mitigation areas potentially affecting the California Tiger Salamander (*Ambystoma californiense*) and a database compiled to support analysis in response to efforts to de-list the vernal pool tadpole shrimp (*Lepidurus packardi*) and the vernal pool fairy shrimp (*Branchinecta lynchi*). These databases contained a variety of attributes for both project sites and mitigation areas including the project/mitigation site name, size, vernal pool acreage and acres of vernal pools to be created or preserved based on the biological opinion. Although there were many inconsistencies and gaps in the reporting of this data, every record contained a project name, project acreage, and type of mitigation performed (on-site, off-site, or mitigation bank).

Using these two databases, a master listing of development projects and corresponding mitigation areas within Sacramento and Placer counties was compiled. In most cases it was possible to link the project to the corresponding mitigation areas either through the project name or other project information. Based on these procedures, we identified 72 development projects totaling almost 7,400 hectares of vernal pool and associated upland habitat that were mapped by the Service and had identifiable, mapped mitigation site(s). Using these relationships, new databases were constructed to store project and mitigation site information including project name, county, project size, and total vernal pool acreage at the site. For each mitigation area, the mitigation site name, county, size, type (on site, off site or mitigation bank), and the total acreage of vernal pools created and preserved were recorded in a separate database. A common key was created that allowed the two databases to be linked together by matching a project with the appropriate mitigation sites. Based on the data provided by the Service, it was not possible to quantify what percentage of total development projects within Sacramento and Placer counties this sample represented; however, the sample contained several of the major development projects occurring during the past several years and sample development projects and mitigation areas were widely distributed through out the two counties (Figure 1).

Soils information was obtained from the Natural Resource Conservation Service's Soil Survey Geographic Database, more commonly known as SSURGO. SSURGO data is the most detailed digital soils data available with each soil mapping unit containing no more than three different soil series (National Resource Conservation Service 1995). In the case of Sacramento and Placer counties, no soil mapping unit contained more than two different soil series and most soil polygons represented a single series with possible small inclusions of other soil types within that series (Natural Resource Conservation Service, 1998a, 1998b). The digital maps of soil polygons were intersected with the polygon boundaries of the project and mitigation sites. The resulting GIS coverage depicted the specific soil series occurring at each project and mitigation site. This information was integrated into the attribute databases so that it would be possible to examine the soils occurring at a specific project site and compare than to the soils found at the corresponding mitigation site. Official descriptions for each soil series were obtained from the NRCS website (http://www.statlab.iastate.edu/cgi-bin/osd/osdname.cgi). These descriptions, along with various other references (Helley and Harwood 1985; Jones and Stokes 1990; Smith and Verrill 1998) were used to determine if a given soil series had the potential to support vernal pools and, if so, to assign the soil series to a Holland vernal pool classification and one of the four possible landform-based classifications.

For those soil series that were not conclusively determined to have the potential to support vernal pools (based on a review of the above references) the location of those soil series within Sacramento County was compared to a detailed map of vernal pool locations in Sacramento County (County of Sacramento 1998). In addition, if a soil series polygon contained a mapped vernal pool, that soil series was determined to be capable of supporting vernal pools and was classified according to the two classification schemes (Table 3). Due to the lack of detailed vernal pool maps for Placer County, it was not possible to determine if any of the remaining questionable soil series (five unclassified soils out of 30 total soil series) potentially supported vernal pools. Most of these soils

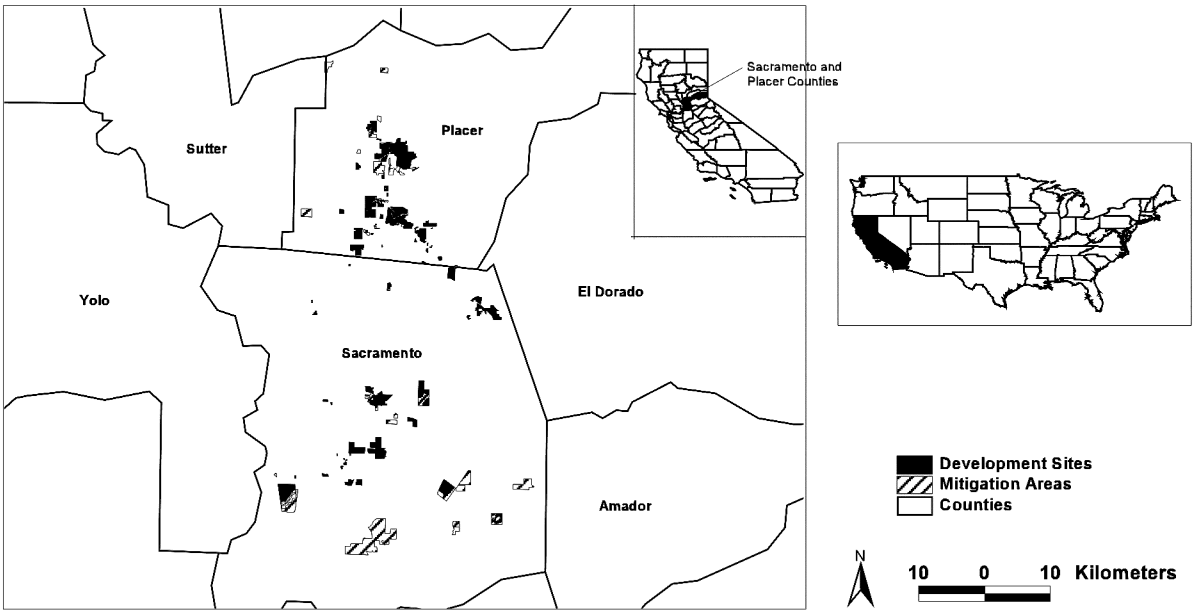

Figure 1. Location of development projects and mitigation sites in Placer and Sacramento Counties, California.

were relatively well-drained, deep soils with weak claypan development and no hardpan. Any errors introduced by omitting these soils from subsequent analysis are most likely insignificant.

Development project scale analysis

To analyze the degree to which project site edaphic settings were replicated at the corresponding mitigation areas, the total hectares of each project site vernal pool type were calculated and compared to the total hectares of the same pool types at all corresponding mitigation sites. These results were summarized across all development projects and within each vernal pool type. Four simple statistics were tabulated, the total number and percent of project sites that had at least one mitigation area with the same edaphic setting as well as the number and percent of project sites where the total acreage of that vernal pool type was greater at the project site than at the corresponding mitigation sites.

Landscape scale analysis

Landscape-scale implications of current vernal pool mitigation practices were analyzed in a similar fashion. The total number, total hectares, and average size of each project site were calculated across all development projects within the two study area counties. The same statistics were calculated across all mitigation areas and were further broken down by each of the three mitigation approaches within the two study area counties. The number of development projects using mitigation banks, on-site mitigation, and off-site mitigation were also tabulated. Several additional statistics were calculated within each vernal pool edaphic setting. These statistics included the total number, total hectares, percent of all development projects, and average size of each edaphic setting across all development projects. These same statistics were reported for all mitigation sites as well as by mitigation method.

As a final analysis, Shannon's diversity index (O'Neill et al. 1988) was calculated to determine if the overall vernal pool landscape within this region was becoming less diverse as a result of past mitigation practices. Shannon's diversity index is calculated according to the following formula:

$$H = -\sum_{i=1}^{m} P_i \times \ln P_i$$

where m = number of patch types; P_i = proportion of area covered by edaphic setting i.

The obtained statistic is a unitless metric that quantifies landscape diversity as a component of two different landscape components, richness and evenness. Richness refers to the number of patch types,

Table 3. Soil-Landform-Holland classification relationships.

Soil Series	Great Group	Landform	Holland Classification
Corning	Palexeralfs	High Terrace	Northern Claypan
Fiddyment	Durixeralfs	High Terrace	Northern Hardpan
Redding	Durixeralfs	High Terrace	Northern Hardpan
Red Bluff	Palexeralfs	High Terrace	Northern Claypan
Alamo	Duarquolls	Low Terrace	Northern Hardpan
Bruella	Palexeralfs	Low Terrace	Northern Claypan
Cometa	Palexeralfs	Low Terrace	Northern Claypan
Galt	Durixererts	Low Terrace	Northern Hardpan
Hedge	Durixeralfs	Low Terrace	Northern Hardpan
Madera	Durixeralfs	Low Terrace	Northern Hardpan
Natomas	Palexeralfs	Low Terrace	Northern Claypan
San Joaquin	Durixeralfs	Low Terrace	Northern Hardpan
Kaseberg	Durixerepts	Low Terrace	Northern Hardpan
Hadselville	Haploxerolls	Volcanic Mud/Lavaflow	Northern Volcanic Mudflow
Inks	Agrixerolls	Volcanic Mud/Lavaflow	Northern Volcanic Mudflow
Exchequer	Xerorthents	Volcanic Mud/Lavaflow	Northern Volcanic Mudflow
Pardee	Haploxeralfs	Volcanic Mud/Lavaflow	Northern Volcanic Mudflow
Pentz	Haploxerolls	Volcanic Mud/Lavaflow	Northern Volcanic Mudflow
Ranchoseco	Xerorthents	Volcanic Mud/Lavaflow	Northern Volcanic Mudflow
Whiterock	Xerorthents	Volcanic Mud/Lavaflow	Northern Volcanic Mudflow
Columbia	Xerofluvents	Drainageway	Undefined
Clear Lake	Endoaquerts	Drainageway	Undefined
Creviscreek	Haploxeralfs	Drainageway	Undefined
Hicksville	Haploxeralfs	Drainageway	Undefined
Sailboat	Xerofluvents	Drainageway	Undefined

edaphic settings in this case, while evenness represents the distribution of the total landscape area among various patch types. Higher values of Shannon's diversity index represent higher landscape diversity, with maximum diversity reached when all patch types represent the same proportion of the total landscape.

Results

Project and mitigation site attributes in Placer and Sacramento counties

The main characteristics of vernal pool project sites and vernal pool mitigation sites are presented in Table 4. Similar numbers of development projects were needed to mitigate for losses of vernal pool habitat within Placer and Sacramento counties during the timeframe studied and these development projects impacted approximately the same amount of vernal pool and intervening upland habitat. In addition, mitigation practices are relatively similar between the two counties with most development projects satisfying at least a portion of their mitigation requirements at one of the six vernal pool mitigation banks located in the region and fewer numbers of development projects fulfilling their mitigation requirements at either on-site or non-mitigation bank, off-site preserves (see Figure 1).

Despite some general similarities in project and mitigation site characteristics between the two counties, approximately three times more land was preserved in Sacramento County than in Placer County (4,028 hectares compared to 1,369 hectares). The disparity is reflective of differences in the number of mitigation banks, which tended to be larger, and on-site mitigation areas. Sacramento County had twice as many mitigation banks as Placer County. Placer County had almost twice the number of on-site mitigation areas, and the average size of both on- and off-site preserves was several times lower within Placer County.

Project and mitigation sites characteristics by edaphic setting

Breaking down each project and mitigation site into the various edaphic settings described in Tables 1 and 2 shows that Northern Hardpan is the most common NDDB classification found within the region (Figure 2). This result confirms similar analyses by other

Table 4. Summary of project and mitigation site attributes.

	Projects			
	Number	Total size (ha)	Mean size (ha)	
Total	72	7 394.1	102.7	
Sacramento	35	3 555.7	101.6	
Placer	37	3 838.4	103.7	
	Mitigation Sites			
	Number	Total size (ha)	Mean size (ha)	# Projects Mitigated at Sites
Total	43	5 397.6	125.5	
Banks	6	1 166.9	194.5	49
On-site	23	1 428.9	62.1	26
Off-site	14	2 801.8	200.1	16
Sacramento	20	4 028.1	201.4	
Banks	4	768.4	192.1	22
On-site	8	997.9	124.7	10
Off-site	8	2 261.8	282.7	10
Placer	23	1 369.5	59.5	
Banks	2	398.5	199.3	27
On-site	15	431.0	28.7	16
Off-site	6	539.9	90.0	6

researchers (Keeler-Wolfe et al. 1998). While Northern Hardpan is the most common NDDB classification for project and mitigation sites, the relative percentage of this edaphic setting is much higher within mitigation sites. Apparently, this increase came at the expense of the Northern Volcanic Mudflow and Northern Claypan edaphic settings, both of which were less commonly seen in mitigation than development project sites (Figure 2). Similar trends were found for the various landform-based edaphic setting classifications (Figure 3). While there was a fairly even split between the total area of High Terrace and Low Terrace edaphic settings among project sites, Low Terrace settings dominated the mitigation sites. Furthermore, Volcanic Mud/Lava Flow pools were reduced to approximately one-third of their original extent at mitigation sites while Drainageway pools almost tripled in extent. The distribution of various edaphic settings within mitigation banks, by far the most commonly used form of mitigation, may help explain these results. Generally, the edaphic settings that predominately characterized mitigation banks were those that increased or remained stable in relative extent while the settings that declined were generally underrepresented at mitigation banks (Figures 4 and 5.

These results correlate with those generated by the analysis of changes in landscape diversity (Shannon's diversity index). Under either classification scheme, landscape diversity decreased through vernal pool mitigation (Table 5). These changes were slight for both vernal pool classifications, although greater reduction was observed for the NDDB classification scheme. This was most likely due to the distribution of soil series between the low terrace and high terrace landform-based classifications and the Northern Claypan and Northern Hardpan NDDB classifications.

Despite the observed differences in project and mitigation site edaphic settings at the landscape level, it appears that the majority of project site edaphic characteristics are being replicated at the corresponding mitigation sites (Table 6). In fact, almost all development projects with Northern Claypan and Northern Hardpan edaphic settings under the NDDB classification and High Terrace and Low Terrace settings under the landform-based classification are satisfying their mitigation requirements at sites with similar soil and geomorphic characteristics. Slightly lower rates were observed for the Volcanic Mudflow and Drainageway classifications; although, even in these instances, most mitigation sites were placed in the same edaphic settings.

A further analysis of the total acreage of edaphic settings present at mitigation sites compared to the corresponding project site shows that, while most development projects conducted at mitigation sites with the same edaphic setting, the total area of that particular setting preserved at the mitigation site is often lower. This result is expected given the previously noted differences in total size of project sites as compared to mitigation sites. As shown in Table 6, as

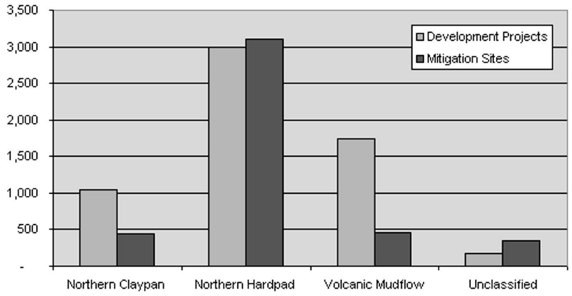

Figure 2. Area of development project versus mitigation site by NDDB classification.

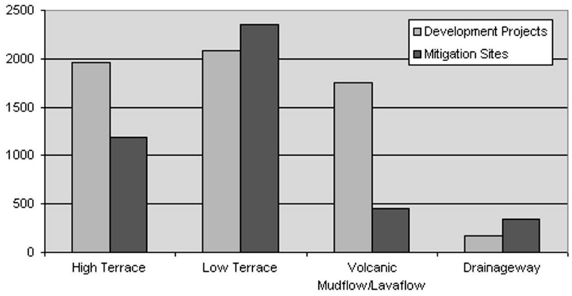

Figure 3. Area of development project versus mitigation site by landform classification.

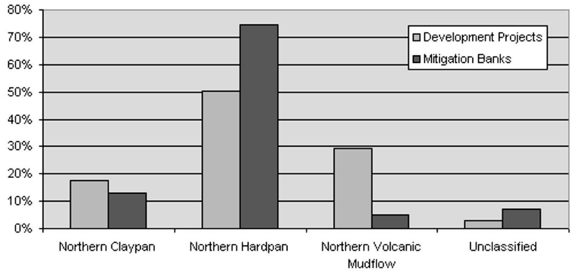

Figure 4. Percent of development project versus mitigation bank by NDDB classification.

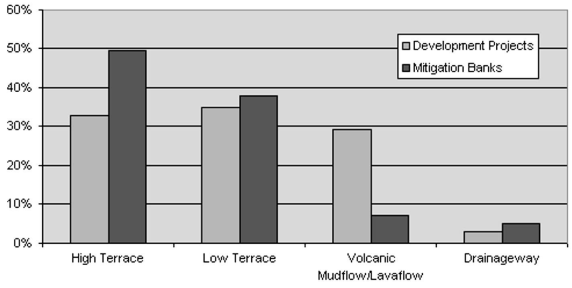

Figure 5. Percent of development project versus mitigation bank by landform classification.

many as 30% to 60% of the project sites, depending on edaphic setting, do not provide at least the same aeral extent of a particular edaphic setting.

Discussion

Overall it appears that the impacts of vernal pool mitigation in the rapidly growing Sacramento Metropolitan Area differ depending on whether one examines mitigation on a project-by-project basis or across all projects in the larger area. At the scale of individual projects, most mitigation sites usually have the same edaphic settings as the corresponding development project site (although with the same or more pool habitat and significantly less upland habitat). At a larger scale across all projects, mitigation has resulted in relatively rare settings, such as Volcanic Mudflow pools, becoming more rare and relatively common settings, such as Northern Hardpan and Low Terrace, becoming even more common. This pattern of rearrangement within the vernal pool landscape has been highlighted as a shortcoming of current wetland regulations (Leidy and White 1998), and researchers have observed similar patterns of substitution and rearrangement within non-vernal pool wetland landscapes as a result of mitigation programs in other regions (Gwin et al. 1999).

While Volcanic Mudflow pools generally support fewer vernal pool obligate plant species than Northern Hardpan vernal pools (Jokerst 1990) and, because they are usually small and shallow, provide lower quality habitat for various species of waterfowl, amphibians, and invertebrates (Jones and Stokes 1990), they often support the highest levels of plant species diversity of any vernal pool type (Jokerst 1990) and are one of the rarest and most endangered vernal pool types found in the Sacramento/Placer region (Keeler-Wolfe et al. 1998). Given that many developers choose to fulfill their mitigation requirements with mitigation banks, the relative lack of Volcanic Mudflow vernal pools within mitigation banks indicates that additional mitigation banks supporting this vernal pool type should be established in the region if future losses (and a resultant decrease diversity within the overall vernal pool landscape) are to be avoided.

Although the vernal pool landscape may be losing diversity in edaphic settings as a result of mitigation practices, the ecological consequences of this observed pattern are unclear for several reasons. First, this study only dealt with relative amounts of vernal pool edaphic settings present at both project and

Table 5. Landscape diversity indices.

NDDB Classification	H	
	Projects	0.484
	Mitigation Sites	0.395
Landform Classification	H	
	Projects	0.519
	Mitigation Sites	0.489

mitigation sites. Due to limitations in available data, it was not possible to map the exact locations of individual vernal pools both at project and mitigation sites and classify each vernal pool according to its edaphic characteristics. Obviously, the presence or absence of particular edaphic settings at mitigation sites or losses in area of edaphic settings at mitigation sites indicates the possibility of changes in individual pools but preclude any conclusive statements about changes in actual vernal pool habitat relative to specific soil and geologic characteristics.

Even if it were possible to conclusively demonstrate that specific pools were shifting from one edaphic setting to another as a consequence of mitigation, it would not be possible to state conclusively that those changes were leading to the establishment of different plant and animal communities at the mitigation sites without detailed field studies. Mitigation sites are usually established specifically because they already contain populations of threatened and endangered species, and most vernal pool creation development projects are designed and managed to increase the chances that certain species will persist at the mitigation sites. These activities could lead to the establishment of plant and animal communities at mitigation sites that under more natural circumstances would tend not to occur.

Finally, there is a large amount of variability in species distributions within vernal pool ecosystems (Keeley and Zedler 1998). While edaphic setting is an important factor in controlling the distribution of various taxa within vernal pools (Holland and Jain 1988; Holland and Dains 1990; Jokerst 1990; Jones and Stokes 1990; King et al. 1996; Helm 1998; Morey 1998; Platenkamp 1998; Silveria 1998; Simovich 1998), it is only one of several factors that determine the specific species that are capable of colonizing and surviving within a vernal pool. Given the complexity inherit within vernal pool ecosystems, and in the absence of conclusive field data, it is possible that a set of vernal pools with different edaphic settings could support some of the same species, particularly when the other state factors, especially climate and source biota, are held constant. Although not specifically addressed in this paper, issues of size, shape, and distribution are additional important factors in the design of vernal pool preserves. It may be that even properly sited preserves, in terms of edaphic and geomorphic factors, may be nonfunctional if they do not allow for metapopulation processes to operate between adjacent preserves.

Conclusions

This research has demonstrated that most development projects impacting vernal pools in Sacramento and Placer counties tend to select mitigation sites that contain the same edaphic characteristics. However, if we view vernal pools in a complex, the overall vernal pool landscape is becoming less diverse as rare edaphic settings, primarily Volcanic Mudflow, lose total area relative to more common settings, such as Northern Hardpan pools or High Terrace and Low Terrace pools. Although restructuring of the vernal pool landscape and loss of upland habitat could have

Table 6. Equivalency between project and mitigation site edaphic characteristics.

	Project/Mitigation Matches	% All Projects	Project Hectares > Mitigation Hectares	% Matches
NDDB Classification				
Northern Claypan	35	94.6%	18	51.4%
Northern Hardpan	59	98.3%	17	28.8%
Northern Volcanic Mudflow	17	81.0%	11	64.7%
Unclassified	8	66.7%	4	50.0%
Landform Classification				
High Terrace	43	91.5%	15	34.9%
Low Terrace	49	98.0%	17	34.7%
Volcanic Mudflow/Lavaflow	17	81.0%	11	64.7%
Drainageway	8	66.7%	4	50.0%

important ecological consequences, the magnitude and extent of these consequences are largely unknown.

We have also tried to show how a relatively simplistic GIS analysis based on a hydrogeomorphic approach can be applied to assessing the potential impacts of current wetlands regulations. Although studies conducted in other regions (Gwin et al. 1999; Kelly 2001) have demonstrated a similar restructuring of the wetland landscape, few studies have attempted to analyze the potential ecological effects of current wetlands regulations. This analysis and others like it can help guide better management of wetland resources by highlighting areas where large shifts in vernal pool siting have occurred as a result of mitigation. Development of HGM profiles for all wetland types can also improve wetlands regulation by allowing researchers to conduct similar analyses for other types of wetlands by having defined standards against which to quantify the extent that mitigation wetlands differ from reference wetlands within each defined HGM profile.

Additionally, improvements in the regulatory process are necessary to allow more precise comparisons of the various effects of wetland regulations and mitigation practices on vernal pool ecosystems. In particular, agencies charged with regulating the discharge of fill materials into vernal pools and the destruction of endangered species habitat could do a more thorough job of collecting initial data from permit application files, including detailed locations of vernal pools that can be mapped and incorporated into a GIS, and managing the permit approval process, including precise tracking of mitigation site locations and mitigation site attributes. Aside from improvements in the regulatory process, research is needed to precisely determine the degree to which distributions of vernal pool dependent species vary among edaphic settings and, under what conditions physical conditions or management regimes, different edaphic settings are capable of supporting the same associations of species. With improved record keeping by regulatory agencies and more detailed understanding of the ecological factors that structure vernal pool habitat, more precise evaluations of the ecological implications of natural resource regulations will be possible in the future.

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