Influence of geologic setting on slope wetland classification and hydrodynamics

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ABSTRACT - Slope wetlands exist where topographic or stratigraphic conditions allow groundwater to intersect the surface, creating a zone of perennial or near perennial moisture. The condition and resiliency of slope wetlands, therefore, are controlled by their hydrodynamics and recharge mechanisms. Understanding these mechanisms is essential for accurate assessment of potential indirect impacts and development of management actions in slope wetlands. To better understand relationships between geologic setting and the condition of slope wetlands, we characterized the physical and biological properties and hydrodynamics of 20 slope wetlands in the San Juan Creek Watershed in southern Orange County, California. Principal components analysis (PCA) resulted in the slope wetlands being separated into three distinct groups, based on geologic setting: those located in bedrock landslides, those associated with faults, and those associated with alluvial/colluvial deposits. Groundwater monitoring and hydrogeologic analysis showed that wetlands in alluvial/colluvial deposits respond quickly to precipitation, and subsurface water levels stay shallow for extended periods of time. In contrast, subsurface water levels in bedrock landslide wetlands respond more slowly to precipitation, exhibit greater variation, and ultimately decline more quickly. These trends (along with the analysis of groundwater chemistry) indicate that wetlands in alluvial/colluvial deposits are likely supported by relatively stable, large volumes of groundwater. In contrast, wetlands located in bedrock landslides are likely recharged from relatively localized groundwater sources with smaller volumes and greater year-to-year variability. Wetlands located along faults have an intermediate level of variation in moisture regime, indicating that their association with a fault may be providing a conduit for water delivery to the wetland. Plant species diversity did not differ between subclasses, although wetlands in alluvial/colluvial deposits supported slightly greater proportions of alkaline plant species. Understanding the different recharge characteristics of each subclass will allow for more informed decision-making regarding protection and management of slope wetlands.

INTRODUCTION

Slope wetlands occur in a variety of physiographic settings, and are generally defined as saturated areas that occur at breaks in slope, or stratigraphic changes where groundwater discharges to the land surface (Smith *et al.* 1995, Keate 2000). Constant groundwater seepage along these topographic or stratigraphic breaks maintains soil saturation and wetland plant communities for prolonged portions of the growing season. Although they may be smaller than other palustrine or riverine wetlands, slope wetlands have been shown to have high plant diversity compared to other wetland types and rate comparatively high for wildlife habitat function (SAIC 2000). The significance of slope wetlands to overall landscape biodiversity may be even more meaningful in semi-arid climates like southern California, where they may serve as islands of perennial moisture in an otherwise dry landscape.

Slope wetlands typically perform the suite of functions associated with other classes of wetlands (Table 1). However, unlike other wetland classes, the functional capacity of slope wetlands results primarily from unidirectional (i.e., down-gradient) groundwater discharge and interflow from surrounding uplands (Brinson *et al*. 1995). Few published papers assess the function or condition of slope wetlands; however, studies of slope wetlands in Utah and Colorado concluded that the hydrogeomorphic factors most strongly and broadly affecting Rocky Mountain slope wetlands were topographic slope, soil composition (organic versus mineral), and hydrologic inflow and outflow (Johnson 2001).

Groundwater discharge that sustains most slope wetlands usually results from recharge that occurs at

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Table 1. Description of functions typically associated with slope wetlands. Functions were identified and defined using the U.S. Army Corps of Engineers draft HGM guidebook for slope wetlands and the regional slope wetland characterization conducted by the Colorado Geologic Survey (1998), modified for conditions present in southern California.

FUNCTION	DEFINITION
Hydrologic Functions	
Groundwater and Surface Water Interception	The capacity of the wetland to capture water flowing down gradient as either surface or groundwater. This function is a fundamental attribute of slope wetlands and is related to other functions, such as nutrient cycling and maintenance of characteristic plant communities.
Water Retention and Groundwater Export	The capacity of the wetland to retain and temporarily store surface and subsurface water for durations sufficient to modify the rate of surface and groundwater delivery to down slope environments.
Biogeochemical Functions	
Organic Carbon Accumulation and Export	The capacity of the wetland to accumulate and export dissolved and particulate organic carbon. Organic carbon can be exported in either a dissolved form (DOC) or a particulate form (POC), based on the conditions in the wetland and the contributing watershed.
Retention and Release of Compounds	The capacity of the wetland to retain nutrients, contaminants, and other elements and compounds through biotic or abiotic processes. Retention of compounds can occur via adsorption, absorption/biological uptake, and microbial transformations.
Nutrient Cycling/Transformation of Compounds	The capacity of the wetland to convert nutrients from one form to another through biotic or abiotic processes. Cycling of nutrients is a fundamental feature of wetland ecosystems and is necessary to support the diverse plant assemblages associated with wetland ecosystems.
Biologic Functions	
Maintain Characteristic Plant Community Composition/Structure	The capacity of the wetland to provide an environment for a native, characteristic plant community. It represents maintenance of species composition and diversity.
Maintain Characteristic Faunal Community Structure	The capacity of the wetland to support wildlife populations that use wetland habitats for a portion of their life histories. The focus of this function is not the presence or absence of specific species of wildlife, but rather the habitat structure in and around the wetland, as well as its landscape position.
Maintain Regional and Landscape Biodiversity	This function can be expressed at three spatila scales: Diversity of the plant communities within the wetland, the role these wetlands serve in landscape-scale hydrologic and biogeochemical cycling, and the contribution to metapopulation dynamics.

some distance away from the point of ultimate discharge (that is, the slope wetland). Subsurface geologic and edaphic features, topography, and land use between the recharge area and the point of discharge, all affect the magnitude and timing of water delivery to the wetland, as well as the resulting wetland condition. Similarly, alteration of these physical features has the potential to indirectly affect slope wetlands by altering the hydrology, sediment delivery, and soil or water chemistry at the wetland. Unfortunately, most state and federal wetland regulations only address activities that directly affect wetlands. For example, Section 404 of the Clean Water Act (which is the primary federal wetland protection regulation) only regulates discharge of dredged or fill material directly to a wetland (33 CFR Part 325). Consequently, the condition or function of slope wetlands can be degraded as a result of upland activities that interfere with recharge and delivery of subsurface water to the wetland, yet fall outside the jurisdiction of wetland regulatory agencies.

Because geologic and topographic attributes impart controls on any hydrogeologic system, understanding geologic setting and recharge mechanism is essential for accurate assessment of potential indirect impacts and/or necessary management actions in slope wetlands (Lewis 2000). To better understand relationships between geologic setting and the condition of slope wetlands in the study area, we characterized the physical and biological properties and hydrodynamics of 20 slope wetlands in the San Juan Creek Watershed in southern Orange County, California. Our goal was to analyze soil properties, underlying geology, groundwater patterns, and vegetation to (1) define specific subclasses of slope wetlands and (2) elucidate the probable recharge mechanism(s) of the slope wetland subclasses. The results of this analysis may be used to provide management recommendations to ensure that future land-use planning minimizes disruption of the physical processes responsible for the persistence of the slope wetlands.

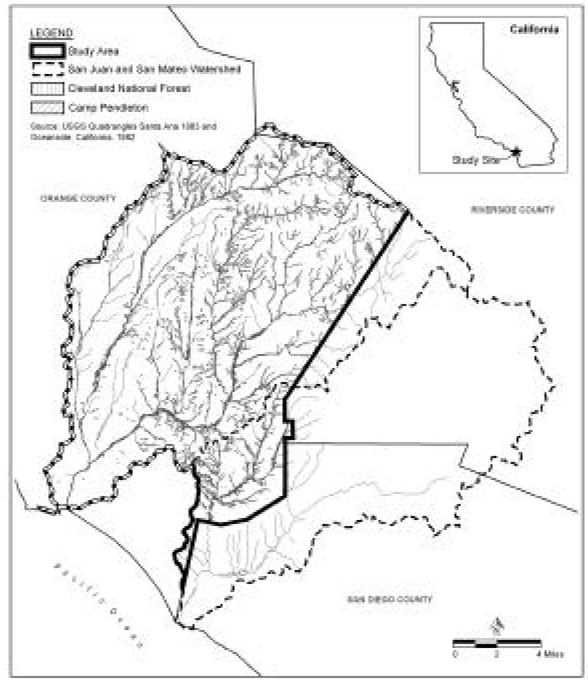

Figure 1. Study area encompassing the San Juan Creek watershed and the southwestern corner of the San Mateo watershed to the San Diego-Orange County border, California.

METHODS

Study Area

The San Juan Creek watershed is located in southern Orange County, California (Figure 1). The watershed encompasses a drainage area of approximately 45,584 hectares (176 square miles) and extends from the Cleveland National Forest in the Santa Ana Mountains to the Pacific Ocean. The watershed includes seven major tributary sub-basins. Elevations range from over 1,768 meters (m) (5,800 feet [ft]) above sea level at Santiago Peak to sea level at the mouth of San Juan Creek.

The geology of the watershed is complex and has been dominated by alternating periods of depression and uplift, mass wasting, and sediment deposition. The vast majority of the San Juan Watershed is underlain by semi-consolidated sandstones and by alluvial terrace sediments derived from the sandstones that have the capacity to store groundwater (Morton 1970). Several of the bedrock geologic units in the central portion of the watershed are moderately sandy and largely uncemented, affording significant opportunities for infiltration and groundwater storage. In addition, sandy deposits in the historic alluvial valleys are permeable and therefore can serve as a major source of groundwater recharge.

Field Data Collection

Locations of the slope wetlands were identified by review of historic ranching records, maps, personal accounts, and reports that indicated the occurrence of springs or seeps. This information was supplemented by review of aerial photographs that were flown between July 14 and 16, 1999, and field investigation of areas with topography and soils conducive to the formation of slope wetlands. All areas confirmed in the field to be slope wetlands were delineated based on the presence of hydrophytic vegetation and mapped using a Trimble GeoExplorer GPS that was post-processed and differentially corrected for accuracy.

Data within each wetland were collected along a transect placed through the longitudinal axis of the wetland from a position upslope to a position downslope of the wetland boundary. The physical, chemical, and vegetative characteristics of the wetland (including zonation and plant species composition) were measured in the field, and soil and water samples were collected for laboratory analysis. Vegetation data were collected using a point-intercept method moving down-gradient along the transect through the approximate center of the wetland. Within each vegetation zone, the percent of cover of each species was estimated visually, and species presence was recorded at one-meter intervals along the transect.

Soil samples were collected at three positions along the transect through each wetland: at the upslope boundary, in the approximate center, and at the downslope boundary of the wetland. Soil pits were dug to a depth of 45 cm (18 inches) to be consistent with the depth used to determine hydric soils in the 1987 Corps of Engineers manual for Wetland Delineation (Environmental Laboratory 1987). Furthermore, this horizon is the area most likely to exhibit indicators of biologic or biogeochemical function, such as reduced conditions and organic matter accumulation (Craft 2001). At each soil pit, data were recorded on the color, texture, and thickness of hydric soils, thickness of organic layer, and depth to shallow subsurface water (if applicable). When subsurface water was present, the pH, electroconductivity (EC), temperature (T), and total dissolved solids (TDS) were measured using a Hanna HI 991300 meter. Soil samples were collected from each pit and placed in labeled Ziploc® bags for storage and transport to the laboratory for detailed chemical analysis. Laboratory analysis included interstitial properties (half saturation percentage, pH, EC), ionic properties (Na adsorption ratio, total exchangeable cations), major nutrients (NO_3^-, NH_4^+, PO_4^{3-}, K^+, Ca^{++}, Mg^{++}, Mn^{++}, Fe^{++}, and Na^+), total organic matter, bulk density, and total nitrogen. To minimize the effects of seasonality on soil data analysis, all soil samples were collected during the late winter and early spring of 2000.

Statistical Analysis

Principal components analysis (PCA) was used to explore the relationships among wetlands with regard to their physical properties, and to reduce the data to key synthetic variables that explain overall differences between the wetlands. Prior to analysis, the raw data were transformed, as needed, to improve normality, and values from the three soil pits within each wetland were averaged. Organic ash data were arcsine square-root transformed. The EC; concentrations of NO_3^-, NH_4^+, PO_4^{3-}, K^+, Ca^{++}, and Na^+; eSAR; half saturation percentage; total nitrogen; and organic matter were log transformed. The remaining data (TEC, pH, Mg, H^+Fe, and bulk density) were left untransformed. Scores derived from the PCA were plotted along the first two PC axes and examined visually for relationships between wetlands. Factor loadings resulting from the PCA provided a measure of the relative importance of each variable in differentiating among the wetlands and were used to determine which variables best served as indicators to distinguish wetland subclasses. In addition to PCA, two types of statistical classification methods were used to further elucidate wetland subclasses, discriminant analysis (DA) and hierarchical cluster analysis (HCA) (JMP Software 2001). "Backward stepwise" DA was employed to separate the slope wetlands into classes based on geologic setting. In addition to establishing classification criteria for wetlands, this method provides information about which variables are most important in determining wetland class membership. Unlike DA, HCA does not utilize *a priori* information about class membership, but rather joins individuals together, one at a time, based on their similarity with regard to the variable measured. The result of HCA is a tree diagram showing the relationship among wetlands. For this study, HCA was performed using the PC1 and PC2 scores generated from the PCA.

One-way ANOVA was used to test for variation in specific physical variables between identified wetland subclasses (Zar 1984). If a given ANOVA revealed significant differences among wetlands, a *post hoc* multiple-comparison analysis, Tukey's test, was used to determine the significance of each pairwise difference between the wetlands.

Plant species diversity (H) and evenness (J) were calculated on a wetland-by-wetland basis using the Shannon Index (Magurran 1988). In addition, the prevalence index (PI) was used to compare plant community composition between wetland subclasses based on differences in the hydrophytic or halophytic nature of the vegetation (Tiner 1999). Because *H'*, *J*, and PI are sensitive to changes in transect length, transect length was included as a covariate in separate ANCOVAs used to compare vegetation data between wetland subclasses.

Unless otherwise stated, differences were considered statistically significant at an $\alpha < 0.05$ level. Data are presented as mean values ± one standard error of the mean (SEM).

Estimates of Hydrodynamics and Recharge

Recharge characteristics and hydrodynamics were elucidated using a combination of literature and field hydrogeologic investigation, and observation of subsurface water levels. Subsurface water levels were monitored during 2000 and 2001 using a combination of piezometers installed at the approximate center of each slope wetland and groundwater monitoring wells installed upslope and downslope of each wetland. Piezometers were installed at depths ranging from 71 to 90 cm (28 to 35 inches) below the surface, depending on the existing depth to groundwater and lower permeability beds. Water level and chemistry data were recorded monthly during the dry months, weekly during the rainy season, and daily immediately following precipitation. Data were recorded from each piezometer at approximately the same time of day in order to limit the effect of daily temperature and pH fluctuations.

Groundwater monitoring ranged in depth from 12.5 to 15.5 meters (41 to 51 feet) below ground surface and wells were drilled beyond the alluvium/bedrock interface. Standard drill logs describing the sediment encountered were recorded by the field geologists during installation of the wells. Wells were "developed" with a bailer by surging the screened interval and bailing water from the casing to remove drilling mud and fine sediment. Development of the wells was considered complete when the water bailed from the casing appeared clear and free of obvious sediment. Pressure transducers and data loggers (Global Water WL-14) were installed in order to measure daily depth to groundwater.

RESULTS

General Description of Slope Wetlands

Twenty slope wetlands were identified and mapped within the San Juan Creek Watershed. These 20 wetlands lie within two distinct geologic formations and 6 different soil series (Table 2). Eight of the slope wetlands fall within young bedrock landslides associated with the Cristianitos fault zone and various unnamed faults. These wetlands are likely supported by the fractured geology that is conducive to entry and persistent seepage of meteoric water. Two wetlands are directly associated with faults that may provide conduits or serve as barriers for subsurface water movement, resulting in daylighting of groundwater. Nine wetlands are mapped in alluvium and colluvium deposits adjacent to the Upper and Lower Santiago formations.

The slope wetlands in the study area vary from perennially saturated to those that are saturated only during the winter months. All of the wetlands generally support palustrine emergent plant community compositions that would be classified as either alkali meadow or freshwater seep.

Determination of Wetland Subclasses

The PCA based on the physical and chemical data resulted in four principal components (PCs), or eigenvectors, with associated eigenvalues greater than one. Together, the four PCs explained approximately 84% of the variance in the data set, with PC1 and PC2 accounting for approximately 69% of the total variance. The two-dimensional plot of scores from PC1 and PC2 reveals relationships among the slope wetlands with regard to their soil properties, thus providing criteria on which to base the assignment of the wetlands to subclasses (Figure 2). The ordination plot shows that the wetlands separate into two distinct groups along the PC1 axis, which primarily describes variation in soil half saturation percentage, cation concentrations, organic matter, total nitrogen, and phosphate concentration. The PC2, which describes pH, soil salinity, electroconductivity, and bulk density, further separates the remaining wetlands.

Backward stepwise discriminant analysis (DA) and hierarchical cluster analysis (HCA) both yielded results that corroborated those of the PCA. For the DA, the wetlands were assigned *a priori* to subclasses based on the output from the PCA. The results of the DA indicated that sodium concentration, electroconductivity, organic ash content, organic matter, soil half saturation percentage, and pH were the most important predictors of wetland class membership. The suitability of the discriminant functions generated by the DA for accurately assigning class membership was demonstrated by a success rate of 84 percent. That is, the DA-based class assignment matched the *a priori* assignment for 16 of the 19 wetlands included in the analysis. A tree

Table 2. Soil and geologic setting of slope wetlands. Soil series from USDA mapping, geologic setting as mapped by Morton (1975), and average slope and aspect measured in the field.

Wetland	Soil Series	Geologic Setting	Aspect	Average Slope
1	Capistrano Sandy Loam (Entic Haploxerolls) 2 to 9% slopes	Alluvium/Colluvium	SW	21.30°
2	Capistrano Sandy Loam (Entic Haploxerolls) 2 to 9% Slopes	Alluvium/Colluvium	W	17.25°
3	Capistrano Sandy Loam (Entic Haploxerolls) 2 to 9% Slopes	Alluvium/Colluvium	SW	25.70°
4	Botella Clay Loam (Pachic Argixerolls) 2 to 9% slopes	Alluvium/Colluvium	SW	26.00°
5	Botella Clay Loam (Pachic Argixerolls) 9 to 15% slopes	Bedrock Landslide	E	22.50°
6	Botella Clay Loam (Pachic Argixerolls) 2 to 9% slopes	Alluvium/Colluvium	W	15.30°
7	Botella Clay Loam (Pachic Argixerolls) 2 to 9% slopes	Alluvium/Colluvium	W	27.00°
8	Botella Clay Loam (Pachic Argixerolls) 2 to 9% slopes	Alluvium/Colluvium	NW	26.70°
9	Botella Clay Loam (Pachic Argixerolls) 2 to 9% slopes	Alluvium/Colluvium	W	17.00°
10	Capistrano Sandy Loam (Entic Haploxerolls) 2 to 9% slopes	Bedrock Landslide	E	26.70°
11	Soper Gravelly Loam (Typic Argixerolls) 15 to 30% slopes	Bedrock Landslide	NW	28.30°
12	Soper Gravelly Loam (Typic Argixerolls) 15 to 30% slopes	Bedrock Landslide	NW	25.50°
13	Soper Gravelly Loam (Typic Argixerolls) 15 to 30% slopes	Bedrock Landslide	NW	25.00°
14	Cieneba Sandy Loam (Typic Xerorthents) 15 to 30% slopes	Fault	SW	18.50°
15	Soper Gravelly Loam (Typic Argixerolls) 15 to 30% slopes	Bedrock Landslide	NW	25.30°
16	Capistrano Sandy Loam (Entic Haploxerolls) 2 to 9% slopes	Alluvium/Colluvium	W	11.30°
17	Cieneba Sandy Loam (Typic Xerorthents) 15 to 30% slopes	Alluvium/Colluvium	N	29.30°
18	Chino Silty Clay Loam (Aquic Haploxerolls) 0 to 2% slopes	Fault	W	8.30°
19	Soper Gravelly Loam (Typic Argixerolls) 15 to 30% slopes	Bedrock Landslide	N	15.30°
20	Soper Gravelly Loam (Typic Argixerolls) 15 to 30% slopes	Bedrock Landslide	N	17.30°

diagram from the HCA on the scores from PC1 contained two branches with exclusively "alluvial" wetlands (with the exception of one wetland, #14, which is associated with a fault). Similarly, all of the wetlands located in bedrock landslide deposits clustered together in a single branch, which also contained wetland 16 and wetland 18 (fault). Moreover, for the HCA run on PC2 scores, the two fault wetlands appeared together as a couplet, demonstrating that the fault wetlands are best distinguished from the other two subclasses by the soil chemistry variables most highly correlated with PC2 (Figure 3).

The groupings resulting from the PCA, DA, and HCA correspond well with differences in the geologic setting of the wetlands. The wetlands clustered in the group with lower PC1 scores (indicating lower cation concentrations and organic matter) are all located in alluvial or colluvial deposits. In contrast, wetlands in the other clusters, with the exception of Wetland 16, are located in bedrock landslides or are associated with faults. Two of the wetlands with the highest PC2 scores (indicating higher soil salinity and sodium adsorption rates) are directly associated with faults. Based on these results, the slope wetlands were assigned to one of three subclasses: wetlands located in alluvium/colluvium, wetlands located in bedrock landslide deposits, and wetlands located along faults.

Differences Between Wetland Subclasses

Differences based on physical properties

There were significant differences among the wetland subclasses in terms of the soil physical and chemical properties, as described by PC1, based on the results of the one-way ANOVA ($P < 0.0001$). The PC1 scores for "alluvium" wetlands differed significantly from those of both "bedrock" and "fault" wetlands; furthermore, the latter two subclasses were nearly significantly different from one another (Tukey-Kramer HSD test, $\alpha = 0.05$). There were no significant differences between the subclasses for PC2 or PC3 scores. These results indicate that the slope wetlands in alluvial and colluvial deposits, in general, tend to have significantly lower soil organic matter, total nitrogen, phosphate, and cation concentrations than wetlands in bedrock landslide formations and wetlands associated with faults.

Results of the ANOVAs on the individual variables revealed several differences between the wetland subclasses. Wetlands in alluvial/colluvial deposits had significantly lower (i.e., between 2.0- and 2.5-fold) concentrations of the cations, magnesium, and calcium than the other wetland subclasses,

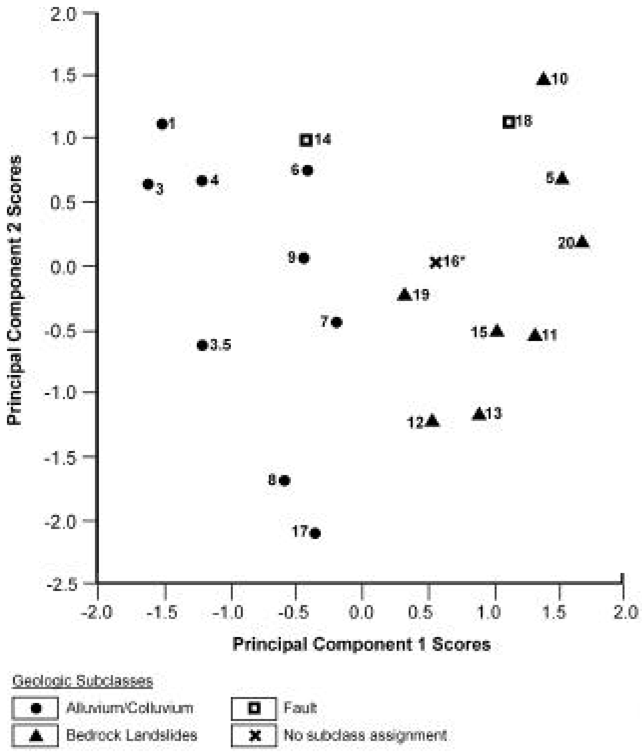

Figure 2. Results of the principal components analysis (PCA). Graph of PC1 versus PC2 showing three subclasses of slope wetlands. PC1, which represents cation and organic matter concentrations, separates wetlands in alluvial/ colluvial deposits from other subclasses. PC2, which represents soil salinity and electorconductivity, further separates bedrock landslide wetlands from those located along a fault. Wetland 16 was located in a mudflow deposit and exhibited hydrodynamics comparable to wetlands located in bedrock landslides.

as well as lower (i.e., between 2.3- and 2.5-fold) organic matter, as compared to bedrock wetlands. Conversely, estimated sodium adsorption ratio (eSAR) was significantly higher (2.4-fold) in the alluvial wetlands than in wetlands in bedrock landslides (Figure 4). In addition, potassium concentration was 4.75-fold higher in bedrock landslide wetlands than in alluvial/colluvial wetlands. Finally, mean eSAR was 2.6-fold higher in fault wetlands than in bedrock wetlands; however, this difference was not significant.

Differences based on biological properties

Shannon indices generated for the slope wetlands ranged between 0.97 and 2.23. A comparison of plant species diversity (H') among the wetland subclasses using a one-way ANCOVA (with transect length as a covariate) showed no significant differences between the wetlands based on geologic setting. Mean H' values (± SEM) for alluvial, bedrock, and fault subclasses were 1.61 ± 0.076, 1.51 ± 0.122, and 1.81 ± 0.42, respectively (Figure 5). A comparison of species evenness (J) among the wetlands using a one-way ANCOVA was also not significant. Mean J values (± SEM) for alluvial, bedrock, and fault subclasses were 0.71 ± 0.031, 0.67 ± 0.03, and 0.69 ± 0.06, respectively. Therefore, unlike previously discussed soil and water chemistry data, underlying geology does not appear to influence plant species diversity or evenness.

There were no significant differences among the three subclasses of wetlands in the hydrophilicity of the plant communities they support. Wetlands within the alluvial, fault, and bedrock landslide subclasses had average prevalence indices (± SEM) of 2.14 ± 0.106, 1.99 ± 0.275, and 1.91 ± 0.120, respectively. In contrast, wetlands within alluvial/colluvial deposits supported an average of 0.7 more obligate alkali species per wetland and 0.4 more facultative alkali species per wetland compared to the other two subclasses.

Hydrodynamics

Groundwater levels within the slope wetlands during the 2000-2001 monitoring period were typically within 30 cm (12 inches) of the surface. However, the pattern of seasonal fluctuations in the depth of shallow groundwater differed between the three wetland subclasses. In general, groundwater levels beneath wetlands in alluvium exhibited the most rapid and persistent response to precipitation compared to those in bedrock landslides or associated with faults. For example, following 2.97 cm (1.17 inches) of precipitation over a 3-d period, groundwater in the alluvial/colluvial wetlands rose to the surface within 4 d. In contrast, groundwater levels in the bedrock landslide and fault wetlands did not respond for 11 d and took several weeks to rise completely to the surface. Following the cessation of precipitation, the groundwater level beneath alluvial/colluvial wetlands remained near the surface for approximately 8 months. However, groundwater levels beneath bedrock landslide wetlands declined within approximately two months. Groundwater levels in wetlands associated with faults remained close to the surface for approximately eight months (comparable to the alluvial/colluvial wetlands), but exhibited more month-to-month fluctuation than the alluvial/colluvial wetlands (Figure 6). According to the California Depart-

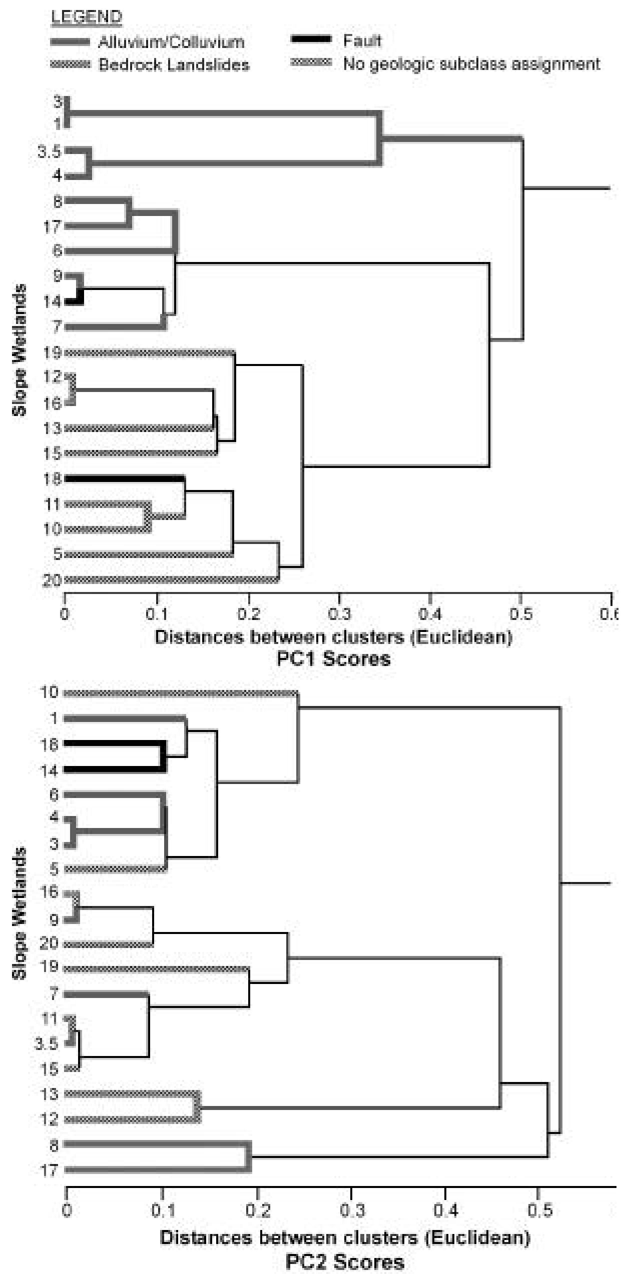

Figure 3. Results of the hierarchical cluster analysis (HCA). Dendrograms showing the relationships among slope wetlands based on PC1 scores (top) and PC2 scores (bottom). Note that PC1 results in clustering of alluvial/colluvial and bedrock landslide wetlands, while PC2 results in clustering of fault wetlands. In all cases, the cluster method is single-linkage (i.e., nearest neighbor).

ment of Water Resources (2001), the annual precipitation during the monitoring period was approximately 35 cm (14 inches), which is comparable to "average annual rainfall" over the period of record.

The patterns of fluctuation in groundwater-specific conductance (EC) (which is an indicator of subsurface water movement) for each wetland subclass were similar to those observed in the depth-to-groundwater data. Alluvial wetlands remained stable throughout the year; fault wetlands responded to precipitation rapidly and exhibited variations throughout the year; bedrock landslide wetlands exhibited increased EC values following precipitation that ultimately decline more rapidly than in wetlands located in alluvium/colluvium or associated with a fault. Annual mean EC values for the three wetland subclasses were 1265 ±73 μhos in alluvial/colluvial wetlands, 1222 ±128 μhos in bedrock landslide wetlands, and 2660 ±735 μhos in fault wetlands. As expected, groundwater EC levels decreased following precipitation and increased during periods of extended dry weather.

Seasonal changes in the depth and extent of shallow groundwater were reflected by changes in the extent and vigor of the perennial wetland plant species. Prior to the onset of the winter rains, many of the plants were either dormant or had been extensively cropped by cattle. However, following approximately 13 cm (5 inches) of rain in early spring 2000, most wetland plant species emerged and flowered. Within five months, many of the plant species in bedrock wetlands exhibited signs of stress, including abscission and chlorosis, while those in alluvial/colluvial wetlands remained vigorous for the remainder of the year (except where cropped by cattle).

DISCUSSION

Classification and Indicators of Function

Classification is an important initial step toward characterizing the mechanisms associated with wetland functions (Table 1). Because geologic setting influences the hydrodynamics, and the soil and groundwater chemistry of slope wetlands, it can be an important determinant (and indicator) of functional capacity and resiliency. This may be especially important when wetlands with similar morphologies have very different water (and biogeochemical) regimes (Cole *et al.* 2002). For example, differences in geologic setting and soil properties between the subclasses in this study were not reflected in the plant diversity or community composition. However, it is likely that several hydrologic and biogeochemical functions (such as water retention and groundwater export and retention and release of compounds) differed between subclasses based on their geologic setting.

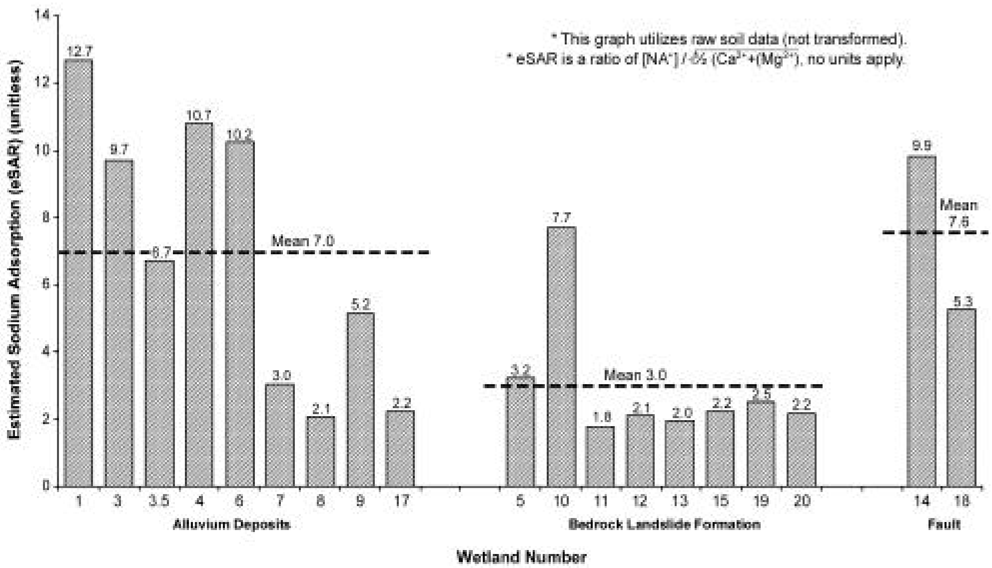

Figure 4. Comparison of estimated sodium adsorption ratio (eSAR) between subclasses. Bars show eSAR for each wetland plus the mean eSAR for each subclass. Bedrock landslide wetlands have significantly lower eSAR values than the other two subclasses. Wetland 16 was excluded from this analysis because its physical and geologic setting differs from the other wetlands subclasses.

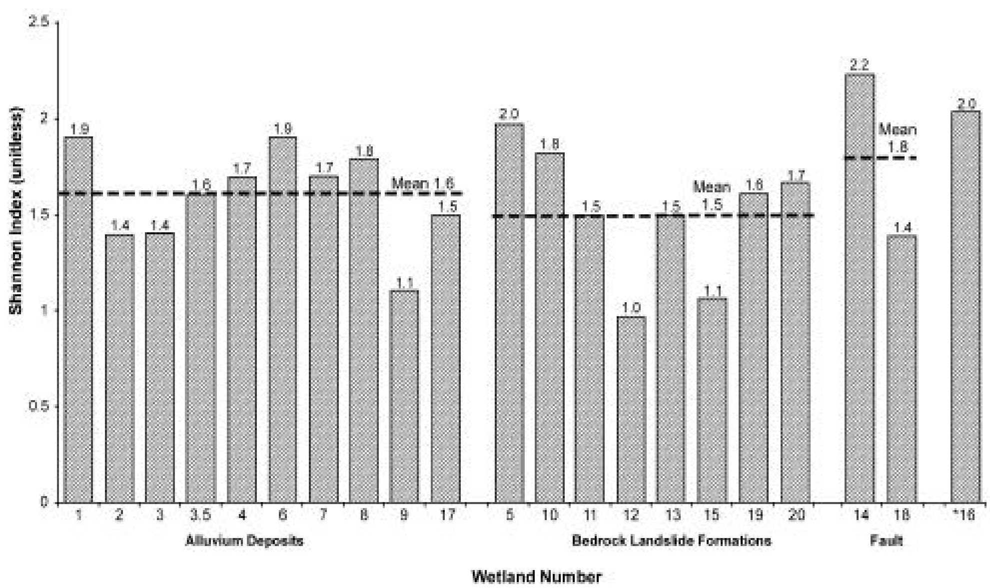

Figure 5. Comparison of plant species diversity between subclasses. Bars show the Shannon Index value for each wetland plus the mean Shannon Index for each subclass. There are no significant differences in plant species diversity between wetland subclasses. Wetland 16 was evaluated separately because of the ambiguity of its subclass membership.

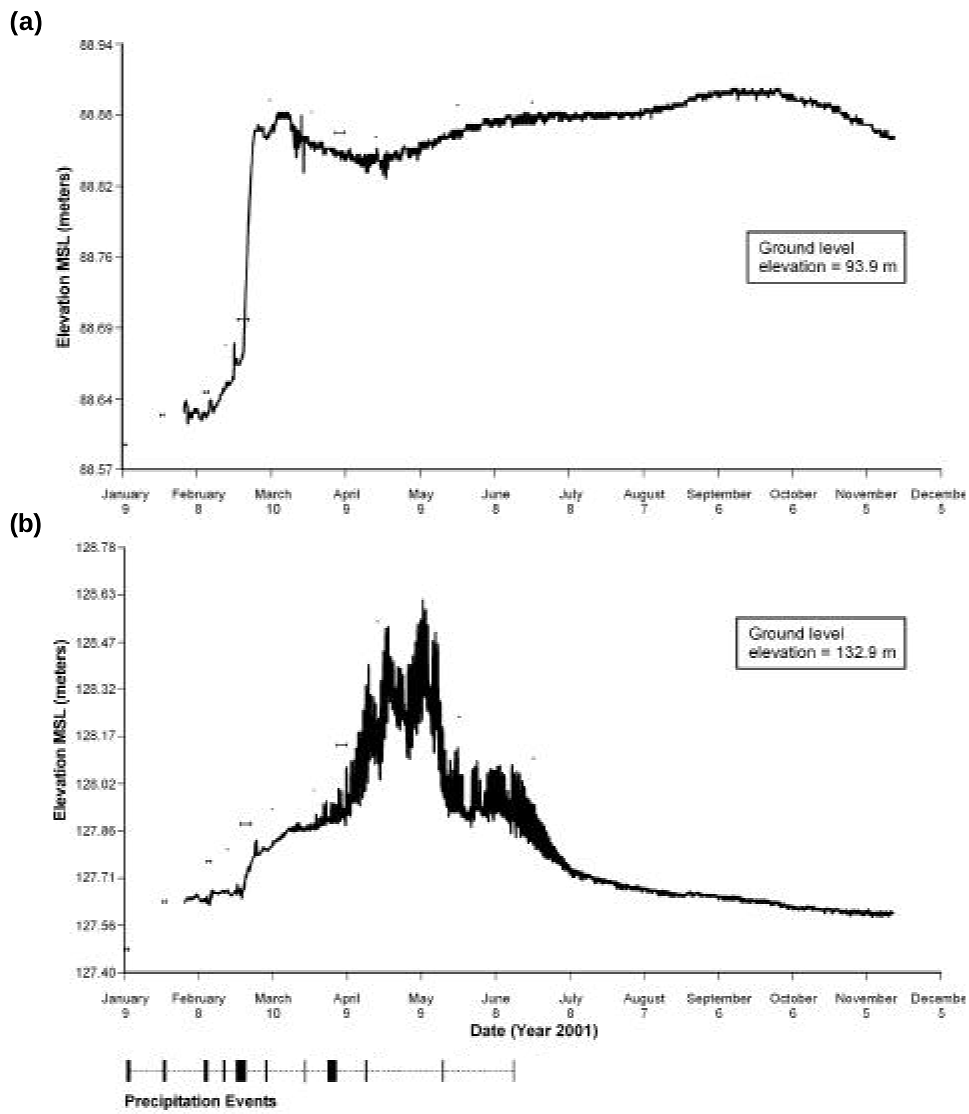

Figure 6. Subsurface water levels over time. Representative data collected over the course of one year from groundwater monitoring wells immediately adjacent to (a) an alluvial/colluvial slope wetland and (b) a bedrock landslide wetland. The solid bars across the bottom indicate rain events.

Estimated sodium adsorption ratio (eSAR) is an example of a physical parameter that may be used to indicate different functional capacity between wetlands. In this study, the slope wetlands located in alluvial/colluvial deposits tended to have lower soil organic matter and cation concentrations and higher eSAR and soil salinity than the slope wetlands located in bedrock landslide formations. These differences may result from the different-aged soils in alluvium versus bedrock landslides. Soils formed on old alluvial terraces are primarily young and underlain by recently deposited Alluvium (Qal) and Slopewash (Qsw). These recently weathered soils are high in alkaline cations released during the initial transition from rock to soil (Bohn *et al*. 1985). These cations include mainly sodium, magnesium, potassium, and calcium. Potassium and magnesium move more slowly through soil than do sodium and calcium, although small fractions of all four are retained by adsorption to negatively charged soil particles. The retention of the cations contributes to high soil sodium and eSAR. In contrast, the older, bedrock-landslide formations have mature, weathered soils from which much of their cations have been leached. Consequently, they have lower soil sodium and eSAR. Differences in soil salinity and eSAR may result in differences in biogeochemical functions. For example, because eSAR is inversely related to the ability of soil particles to adsorb ions, wetlands with lower eSAR may have a higher capacity to sequester certain elements and compounds (Table 1).

Hydrologic functions (such as ground and surface water interception) may also be dictated by the topography, geologic setting, and stratigraphy of slope wetlands (Richardson and Brinson 2001). The slope wetlands in our study area generally have distinct upper boundaries, which is characteristic of wetlands influenced mainly by stratigraphy (as opposed to topography). Because stratigraphic slope wetlands result from complex geologic and edaphic circumstances, elucidating the underlying geologic structure and resultant recharge mechanism is important to understanding/determining hydrologic function and to making effective decisions regarding protection and management of these wetlands.

Recharge Mechanisms

The three slope wetland subclasses identified in this study each exhibited different patterns of subsurface water fluctuation. Using the results of the hydrogeologic analysis and the groundwater monitoring, we were able to infer the probable recharge mechanism for each subclass. Slope wetlands mapped in alluvial/colluvial deposits exhibited groundwater levels that rose quickly following precipitation and stayed close to the surface for a prolonged period, indicating a persistent source of water. These wetlands are generally underlain by the Santiago sandstones, and geologic borings revealed a siltstone bed approximately 25 meters (80 feet) below the surface, with an overlying perched water table (Figure 7A). In addition, groundwater monitoring wells indicate persistent saturation in the underlying Santiago formation to much greater depths.

Using the piezometer and well data, and geologic borings, we infer that during wet periods, the primary recharge mechanism for the slope wetlands is likely water infiltrating through the ridges and slopes above the wetlands and migrating along the buried siltstone bed, discharging at the break in slope of the ground surface. During drier periods, the underlying Santiago formation acts as a reservoir by providing a sufficient volume of water to the wetland to sustain saturation over a prolonged period of time. The contribution of an extensive alluvial aquifer to the hydrologic support of these wetlands is further evidenced by the ion concentration in the groundwater, which indicates that there is likely some secondary recharge from water emanating from deep sandstones of the Santiago formation (Hecht 2001). The dual recharge from a shallow, perched water table and a deep, saturated aquifer provides a large, stable source of water to support this class of slope wetlands (Figure 7A).

In contrast to the alluvial/colluvial wetlands, subsurface water levels in bedrock landslide wetlands respond more slowly to precipitation, exhibit greater variation, and ultimately decline more quickly. These trends (along with analysis of groundwater chemistry) indicate that wetlands located in bedrock landslides are most likely recharged from sources with smaller volumes and greater year-to-year variability. The bedrock landslide deposits that support several of the slope wetlands in the study area originated primarily from the San Onofre Breccia (Figure 7B). The volume of water stored in landslide deposits is difficult to quantify, but is probably substantially less than the volume stored in alluvial aquifers (Hecht 2001). The well data and geologic borings suggest that for the bedrock landslide wetlands, recharge is predominantly from water seeping through the fractured landslide mass. However, high dry-season salinities and persistent, shallow subsurface water suggest that these wetlands may be receiving secondary recharge from the bedrock aquifers of the San Onofre Breccia, which underlies the landslide deposits. The high dry-season salinities likely reflect the mineralogy of the San Onofre formation, which contains a much higher percentage of Amphibole Group minerals (hornblende, tremolite, actinolite, glaucophane, crossite, etc.) than the Santiago sandstones (the Amphibole Group minerals contain between approximately 5% and 20% by weight of magnesium, which may account for the higher cation concentrations in the bedrock landslide wetlands as compared to those in alluvium/colluvium).

Wetlands located along faults have an intermediate level of variation in moisture regime compared to the other two wetland subclasses, indicating that their association with a fault may provide a conduit for water delivery to the wetland. Although the exact hydrologic support mechanism of wetlands located along faults is uncertain, there are two potential explanations for how the fault zone relates to the slope wetlands. First, the fault could be acting as a barrier to groundwater moving along less permeable, shaley interbeds of the upper Santiago or Sespe formations. Once intersected, this water is then conveyed to the surface by movement along the fault zone. Alternatively, subsurface water could be conveyed along slide planes and fault-zone beds

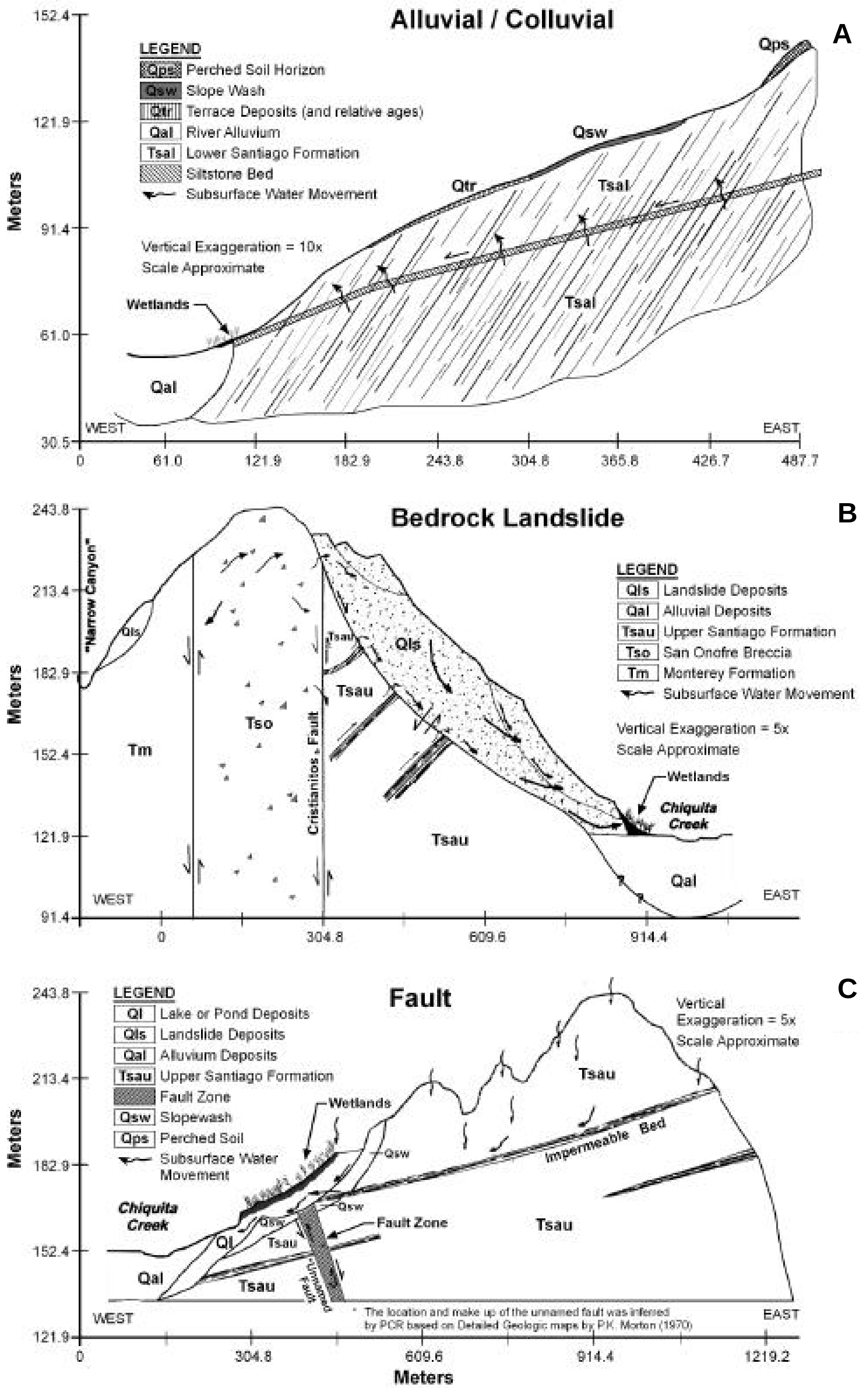

Figure 7. Inferred geologic setting and recharge mechanisms. Graphics show recharge mechanisms inferred from hydrogeologic investigations, boring logs, and groundwater monitoring for (A) alluvial/colluvial wetlands (B), bedrock landslide wetlands, and (C) fault wetlands.

within the underlying Santiago formation, and then discharged at the break in the slope where the less-permeable beds intercept the ground surface (Figure 7C). Either of these mechanisms would result in this class of wetlands having durations of inundation similar to wetlands found in alluvium/colluvium.

Hydrogeologic analysis revealed that the perennial hydrologic regime of slope wetlands can be associated with a variety of mechanisms driven by geologic setting. Understanding the geologic setting and hydrodynamics of the slope wetlands can provide a valuable perspective for making informed land-use decisions that will ensure long-term protection of these resources. Slope wetlands in alluvial/colluvial deposits are most likely supported by a large, extensive source of water, allowing for stable perennial discharge. In contrast, wetlands in bedrock landslide deposits are supported by a more proximate, confined, and lower volume water source. Wetlands associated with faults are most likely supported by persistent entry and seepage of meteoric water along fault zones (Morton 1974).

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