Hydrology of Vernal Pools on Non-Volcanic Soils in the Sacramento Valley

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Abstract. The hydrology of vernal pools near Mather Air Force Base in Sacramento County was investigated to assess the relative importance of direct precipitation, overland flow, and subsurface flow on the water level regime of vernal pools located on a Redding-Red Bluff soil complex, and to determine if constructed pools affected the hydrology of naturally-occurring pools. Studies included direct continuous measurements of vernal pool water levels and volumes, precipitation, evaporation, and groundwater levels. Lateral subsurface flow rates were studied using a bromide tracer. An upland watershed model was developed to estimate overland and subsurface flow under different combinations of soil depths and slopes over a range of rainfall regimes. The site's moderate to deep upland soils and the light to modest rainfall intensities, during the study period resulted in little overland flow, but the model predicts it can occur during periods of intense rainfall. In most years, overland flow contributions are probably limited to periods when pools are already full, so that overland flow is excess to the pool. In 1990, direct precipitation was the primary source of water in the pools, especially during the early winter. Using a direct precipitation-evaporation model, direct precipitation was found to be capable of filling the pools beyond capacity during most years. Although watershed contributions might be considered minor from a volumetric perspective, water exchange between the pool and surrounding upland plays a major role in controlling water level relationships, and subsurface inflows tend to dampen water level fluctuations during the late winter and early spring. This dampening may affect pool vegetative composition and play a role in the life cycle of biota in the pool and adjacent uplands.

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Introduction

The seasonal hydrology of vernal pools provides for a unique environment, which supports plants and invertebrates specifically adapted to a regime of winter inundation, followed by an extended period when the pool soils are dry. Although there has been much interest in identifying the occurrence and distribution of these species, there has been little work done in studying their physical habitat characteristics (Holland and Danes, 1990). There has been virtually no research-level studies of vernal pool hydrology by qualified hydrologists (Hanes et al., 1990) in spite of the importance of pool and watershed physical characteristics in providing the habitat necessary for these species to survive.

Conversion of land use from seasonal grazing to residential or commercial development has resulted in the widespread loss of vernal pools throughout California. Such development can truncate watersheds which supply runoff to downslope pools. Existing regulations under the Federal Clean Water Act currently require that developers mitigate for the loss of vernal pools through the construction of new pools. Such mitigation typically takes place within areas where there are existing vernal pools. The result is an increase in wetland density, and a reduction in the ratio of watershed area to pool area. The effect of such reductions in available contributing area have raised concerns. To what extent are vernal pools dependent upon runoff contributions from their watershed, and how would the water level regime of a pool be affected by reductions in its watershed size or by construction of new pools.

Investigations of vernal pool hydrology were conducted during the 1989-1991 water years (October 1 to September 30) on a 1,225-acre undeveloped parcel in east-central Sacramento County, California (Figure 1). The parcel is located approximately 14 miles west of downtown Sacramento. It was owned by The Sammis Company which funded the studies in order to guide subdivision development planning for the parcel. The overall objective of the project was to assess the importance of contributing area in maintaining the hydrologic character of existing vernal pools so as to avoid any development-related impacts.

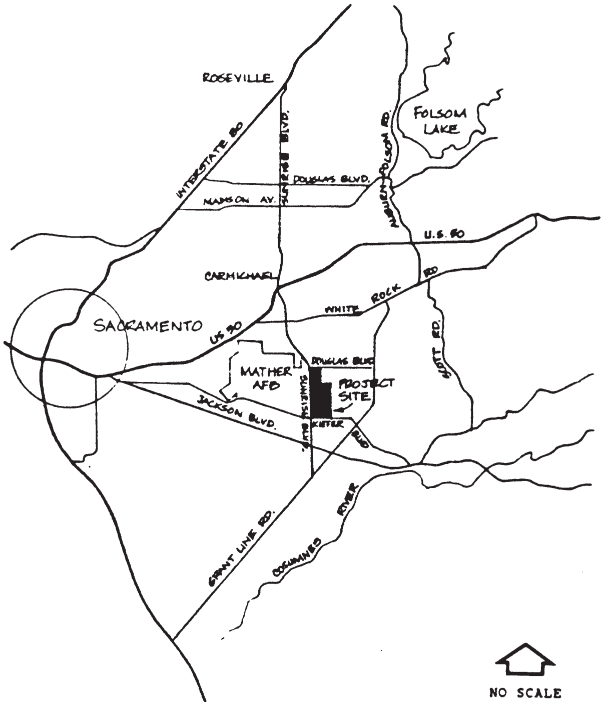

FIGURE 1. Study site location.

A number of separate studies were undertaken to investigate the relative importance of direct precipitation, and watershed runoff in the form of surface or subsurface flow, in the water level regime of "headwater," or "isolated" pools, i.e., pools that do not receive concentrated surface water inflows from channels or swales. These studies included:

1. Water balance analysis and development of a direct precipitation-ET model.
2. Pool water conductivity monitoring.
4. Analysis of conditions conducive to the generation of overland flow
3. Groundwater observations.
4. Analysis of water level changes during individual storms.
5. Examination of subsurface lateral flow rates through upland soils.
6. Development of an upland watershed model to assess watershed contributions

Isolated pools are the most likely to be impacted by watershed truncation (reduction of the pool's contributing area) or through the construction of new pools in upslope, tributary positions, because they are entirely dependent on incident precipitation and inflows originating from the pool's own watershed. Through these multiple lines of investigation, some general conclusions could be made regarding the hydrology of the vernal pools on the site.

STUDY SITE DESCRIPTION

Climate at the site is typical of the Sacramento Valley, with a cool, rainy period from November through April, followed by an extended drought from May through October. The site is believed to receive approximately the same rainfall as Sacramento, where the mean annual precipitation is 18.1 inches (National Oceanic and Atmospheric Administration National Climatic Data Center database). Mean annual potential evapotranspiration is estimated to be 51.9 inches (University of California, 1987). Based upon mean monthly precipitation and potential evapotranspiration, precipitation exceeds potential evapotranspiration for the period of November through February. The net of precipitation minus potential evapotranspiration during this period is 6.6 inches, indicating that there is typically 6.6 inches of "water excess" available for soil moisture recharge, percolation to groundwater, or runoff. Storms during the rainy season are typically low to moderate intensity frontal-type storms.

The study area consisted of undeveloped land which was utilized for seasonal grazing during the study period. The site topography is nearly level to gently rolling which is representative of Redding-Red Bluff soil complexes, which occupy nearly the entire site. Upland slopes vary between one to eight percent. Within vernal pools, a loamy horizon typically 6-8 inches thick overlies a duripan (hardpan). The thickness and continuity of the hardpan can vary considerably within the pool bottom. Upland soils are characteristically composed of a loamy surface horizon from 2-3 feet thick, overlying a claypan. The claypan thickness can vary from 4-24 inches. A duripan often underlies the claypan. Depth of the loamy surface horizon tends to increase in a gradient from vernal pool to upland ridgetop. The presence of either the duripan or claypan severely restricts the downward rate of water movement, and in this respect are equivalent features in that both are water-restricting horizons. During the winter, once soil moisture is recharged, additional infiltration initiates the formation of a seasonal, or perched, water table above the water-restricting horizon. Root pores and rodent burrows are common in the upland surface horizon. Soils along the broad watershed divides are often devoid of any water-restricting horizon. Upland vegetation is composed entirely of a very dense cover of annual grasses, with no exposed bare soil, except during the early winter prior to germination. The study site had a wide range in the size and depth of pools. Large, deep pools are relatively common, exceeding one acre with a maximum depth over one foot.

METHODS: DATA COLLECTION

Figure 2 shows the location of the experimental watershed complex within the study area. Two small adjacent watersheds (0.10 and 0.11 acres) were used in a "paired" watershed study to assess the effects of vernal pool construction on existing pool

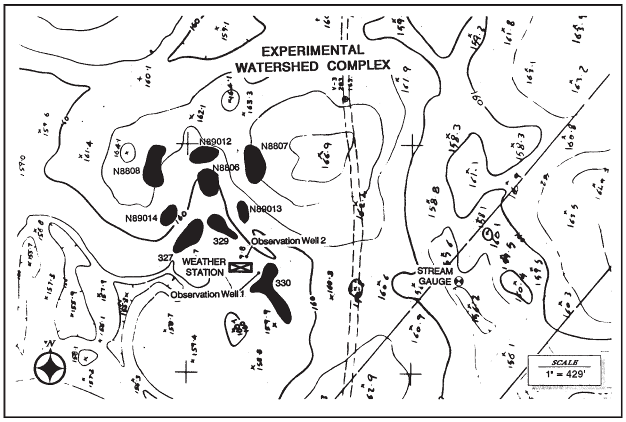

FIGURE 2. Experimental watershed complex.

hydrology. Pool 330's watershed served as a control, and the watershed of Pools 327-329 was treated by construction of three vernal pools in the fall of 1988 (N8806-08), followed by the construction of three additional pools in the fall of 1989 (N89012-14). These pools were constructed on a gentle slope and overflows from the pools pass into Pools 327-329. Pools typically had intervening undisturbed upland of less than 50 feet between pools.

Since Pool 329 is immediately adjacent to Pool 327, and flows directly into it, the two pools were treated as hydrologically indistinct. The aggregate characteristics of the two pools were used to compare pool and watershed attributes. The pools were similar in maximum depth (0.82 versus 0.89 ft.), pool area (74,660 versus 74,120 sq. ft.), and watershed area:pool area ratio (16.3:1 versus 14.4:1). Water levels were continuously measured in Pools 327, 330, N8806-N8808 using a combination of pressure transducers with a data logger, and float-type water level recorders mounted in a stilling well. Water levels were also continuously measured (pressure transducers) in two wells extending to the water-restricting horizon (claypan or hardpan) up-gradient of Pool 330. Water levels in Pools N89012-N89014 were measured weekly to twice-weekly. Precipitation was measured with a 0.01 inch electronic tipping bucket gage with a data logger. Evaporation was measured by monitoring the loss of water (adjusted for precipitation inputs) in a Class A evaporation pan. Water level in the evaporation pan was continuously measured with a pressure transducer and data logger. A combination V-notch weir was installed on a relatively large watershed adjacent to the experimental watershed to measure streamflow and compute water yield. This watershed was similar to the experimental watershed in all respects, except for size. Water level at the weir was recorded using a float-type continuous water level recorder. In situ conductivity measurements were made using a YSI salinity-conductivity-temperature meter. Topographic maps with 0.1 foot contour intervals of pools within the experimental watershed complex were prepared in order to compute pool water volume at any given water level.

METHODS: STUDY DESCRIPTIONS

Water Balance Analyses and Development of Direct Precipitation -ET Model

For a vernal pool, the volume of water (V) stored at any time is a function of the volume at some previous time and the inflow and outflow over the intervening period. Sources of inflow are precipitation (P), surface runoff (RO) associated with either channels or overland flow, and subsurface inflow (SUBIN). Water is lost through evapotranspiration, the sum of evaporation and transpiration (ET), surface outflow when the pool is full (SPILL), and subsurface movement into the pool sides (SUBOUT) or through the bottom (SEEP). The mathematical expression for this relationship is:

$$\text{V(NEW)} = \text{V(OLD)} + \text{P} + \text{RO} + \text{SUBIN} - \text{ET} - \text{SPILL} - \text{SUBOUT} - \text{SEEP}$$

V, P, and ET were measured directly in the field. Because the pools did not fill beyond the outlet elevation during 1990, SPILL can be dropped from the equation. The pools for which the water balance was performed are headwater pools, so that there is no channelized inflow, and RO consists only of overland flow. If the terms SUBIN, SUBOUT, RO (overland flow), and SEEP, which are all unknowns, are lumped in a residual term (RESID), the equation can be rewritten as follows:

$$\text{V(NEW)} = \text{V(OLD)} + \text{P} - \text{ET} + \text{RESID}$$

When RESID is zero, no water is exchanged between the pool and the surrounding watershed, i.e., the pool only receives water through precipitation and losses it through ET. The above equation was solved on a daily time step for Pools 327 and 330 assuming a zero RESID term. The result is a simplified model of daily pool volume referred to as the "direct precipitation-ET model." The resulting hydrograph of pool water volume through the rainy season shows how a pool would function if it neither received water from, nor delivered it to, a surrounding watershed. Differences between the observed and modeled hydrograph, therefore, show the influence of the watershed on the pool.

Although seepage (SEEP) cannot be measured directly, it can be indirectly estimated by comparing the loss in pool volume to that amount caused only by evaporation during periods between storms when 1) ET losses are minimal, 2) upland soils are at "field capacity" (Stephens, 1996), and 3) gravitational water within the upland soils is at a minimum. Performing this analysis for Pools 327 and 330 indicated that seepage losses for these pools are effectively zero. However, similar analyses at other vernal pool sites in the Sacramento Valley with different soils have shown that pools can exhibit relatively high rates of seepage loss, apparently because of weakly developed, or discontinuous hardpans underlying the pool bottom.

RESID is the difference in water volume between the observed and "predicted" (using the direct precipitation - ET model) water volumes at any date as displayed on a hydrograph. The net RESID for the season would be the sum of the daily RESID values. If the net RESID is positive, then, for the season as a whole, more water flowed into the pool from the watershed than was lost to the watershed from the pool. If the net RESID is negative, however, more incident precipitation in the pool was lost to the watershed, than watershed runoff entered the pool.

To account for the volume of water required to saturate pool bottom soils, which is a requisite condition before the pool can "pond" water, the direct precipitation-ET model was typically initiated with a negative water balance, equivalent to the volume of water required to saturate the pool bottom soils overlying the water-restricting horizon. Since sampling of the pool bottoms showed soil depths of 6-8 inches, an initial condition of -3.0 inches of water was assumed (based on an effective pore space of approximately 40 percent). A simple, widely used relationship was used to adjust the ET loss when the pool bottom had not yet reached field capacity (Zahner, 1967)

A water balance analysis using the direct precipitation-ET model was also conducted to assess the importance of direct precipitation during normal and wet years, when the pools could be expected to spill. Because climatic data on-site was limited, precipitation data from Sacramento, and evaporation data from Folsom dam (the climatic stations closest to the site with this type of data), were used to run the model. The data were adjusted slightly to better represent climatic inputs on-site.

Pool Water Conductivity Monitoring

Water that has had little to no contact with soil will reliably have very low conductivity, due to the lack of salts which can conduct a current. In contrast, water that has a long residence time in the soil will generally have much higher levels of conductivity (Hem, 1970). Water entering a pool as subsurface lateral flow through the soil is expected to have higher conductivity than precipitation. During the spring, a trend in increasing conductivity in pools is expected because of concentration of the salts due to evaporation. To assess seasonal trends, conductivity in Pools 327 and 330, and the two adjacent wells was measured eight times during the 1990 rainy season. Precipitation was 74 percent of average in Sacramento during November-April (National Oceanic and Atmospheric Administration National Climatic Data Center database).

Overland Flow Analyses

Overland flow was not directly measured, however, frequent monitoring activities during storms provided the opportunity to document its occurrence. Its potential for occurrence was analyzed by evaluating on-site precipitation intensity data, observations (soil pits) of average upland soil depth over a water-restricting horizon, and published literature on infiltration rates for rangeland in good condition.

Groundwater Observations

Two wells, located 12, and 47 feet from the edge of "control" Pool 330 extended to the top of the hardpan, which was less than four feet below the surface. Continuous water level measurements were made during the 1989-90 season, and periodic measurements were made in the 1990-91 seasons. Water levels in the pool and wells were plotted in order to identify when a hydraulic gradient existed toward the pool, i.e., when the water level in the well(s) exceeded the water level in the pool. This allowed for the identification of the specific periods during which subsurface lateral flow of groundwater to the pool could occur, and computation of the hydraulic gradient during these periods (flow through the soil is a function of the hydraulic gradient and soil properties). When the hydraulic gradient slopes away from the pool, i.e., when the water surface in the pool is higher than that in the uplands, water flows from the pool into the uplands.

Storm Analysis

Observation of 15-minute total precipitation and continuous water level measurement in Pools 327, 330, N89006 (referred to as Pool 6) and the wells allowed for observations of subtle water level changes during and after individual storms. Increases in water levels following the cessation of precipitation allowed for the identification of inflows into the pools attributable to the watershed (overland or subsurface lateral inflows).

Subsurface Flow Rate Plot Study

Although hydraulic gradient information was obtained through the groundwater observations at Pool 330, quantitative estimates of the rate of saturated subsurface flow are dependent upon estimating Darcy's "K" (Davis and Dewiest, 1966). Darcy's "K" is a function of soil properties which control the rate at which water is transmitted through the soil (texture, structure, presence and connectivity of macropores) is defined as the flow velocity with a hydraulic gradient of 1.0, while vertical flow occurs when the hydraulic gradient is infinite. As used in this paper, "hydraulic conductivity" is synonymous with Darcy's "K." Subsurface flow rate is the product of the hydraulic gradient and "K." Although "K" values are available in the literature for aquifers, none were available for undisturbed surface soils.

Three study plots, consisting of 20-foot wide parallel trenches excavated to the duripan and separated by 30 feet of undisturbed ground, were established on three different slopes near the experimental watershed. Excavation of numerous pits throughout the study area confirmed that soil conditions (depth, texture, and structure of the loamy horizon overlying the water-restricting layer) at the plots were representative of soils both within the experimental watershed and throughout the study area. Sheet-piling cutoff walls formed the sides of the plots. Water was supplied to the upper trench via a water tank and hoses once or twice each day in order to maintain the water level at a constant elevation. A single slug of a concentrated sodium bromide solution was mixed into the water in the upper trench. Bromide was used as a tracer because it is normally found in extremely low concentrations, has no adverse environmental effect, and has a very low affinity for adsorption by soil due to its large molecular size and valence of one.

Small observation wells were installed directly downslope at three foot intervals. Movement of bromide was tracked through daily conductivity measurements in the wells and the upper and lower trenches (sodium bromide is a salt), and through laboratory analysis of bromide concentrations from water samples taken from the lower trench in each of the three study plots.

Upland watershed model

The determination of Darcy's "K" via the use of the sodium bromide tracer in the field plot trials allowed for the development of an upland watershed model which was used to directly estimate watershed contributions to pools from overland and subsurface lateral flow. Recall that for the pool water balance analysis, such contributions were contained within the RESID term of the water balance.

The upland watershed model was designed to determine subsurface and overland flow water movement through a wedge-shaped slice of soil above the water-restricting horizon (Figure 3). The wedge represents a radial "unit-slice" of upland water shed extending out like a spoke from the margin of a circular pool at the hub. The width of the wedge at the downslope end was set at 1.5 feet, which represents 2.86 degrees of arc as measured from the center of a pool with a diameter of 60 feet. The wedge is divided into cells of equal length, and cells become progressively wider and increase in volume as distance from the hub increases.

The model operates on a unit time interval of one day. The required climatic data inputs are precipitation and ET. Inputs of water to each cell include precipitation and subsurface flow from the adjacent upstream cell. There must be free (gravitational) water within a cell after ET demand is met before any surface or subsurface outflow occurs. Outflow from the most downslope cell is assumed to enter the pool.

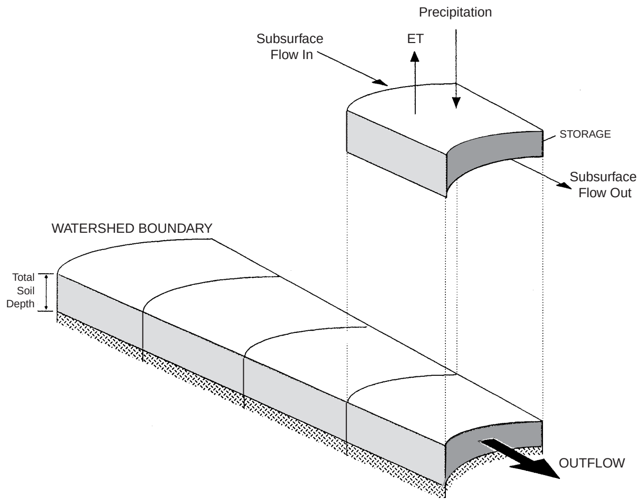

FIGURE 3. Upland watershed model.

The radial geometry of the model facilitates understanding of the flow convergence in vernal pool landscapes. In theory, subsurface flow from the larger upslope cells attempts to enter the downslope cell but the smaller volume of downslope cells results in a smaller total storage capacity. Because the smaller cells cannot transmit all the subsurface flow, overland flow is generated around the pool's margin.

Parameters of the upland watershed model include the slope, soil depth, field capacity per inch of soil depth, porosity, initial soil moisture, and an estimate of "K." Climatic data was the same used to drive the direct precipitation-ET model. A value for porosity was based on estimates from Rawls, Brakensiek, and Miller (1983), and Dunne and Leopold (1978). Soil depth to the duripan and slope were varied to assess the sensitivity of the model to changes in these parameters.

The model was run to compute the total outflow from a single slice for slopes of 1, 2, 4, and 6 percent; for soil depths of 2.0 and 2.75 feet; and for a range of dry to wet water years, from October 1 to June 1 for each year. Total seasonal precipitation of the years selected are shown in Table 1. It should be noted that the 1982 water year was one of the wettest ever recorded and represents watershed response during extremely wet and unrepresentative conditions.

Paired Watershed Study

The paired watershed study was conducted to estimate the effects of vernal pool construction within the watershed of Pool 327. The total area of the six constructed pools (Figure 2) was 9,860 square feet, or about 14 percent of the watershed. The edge of Pool N89014 was 30 feet from the edge of Pool 327. All pools except N8808 had water level regimes similar to those of natural vernal pools. Given the similarities of Pools 327 and

TABLE 1. Total seasonal precipitation.

Year	Precipitation (inches)
1977	6.4
1987	12.6
1975	18.5
1979	20.0
1973	26.1
1983	37.5

330, and the nearly identical characteristics of their watersheds, it was assumed that any significant change in the water level regime in Pool 327 could be identified as a deviation from the water level regime of Pool 330.

RESULTS

Water Balance Analyses

Figure 4 shows the predicted water volume in Pool 330 during 1990 using the direct precipitation-ET model, as well as the observed water volume. The actual pool water volume was much less than predicted. The cumulative RESID value for Pool 330 for the season was 754 cubic feet of water. However, the daily RESID showed an obvious trend in that it was negative early in the season, but then became slightly positive during, and several days following, the largest storm of the year on February 16, 1990.

The total loss in excess of ET between January 1 to February 16, 1990 was 4.46 area-inches (the volume of water equivalent to a depth of 4.46 inches over the pool surface). During the February 16 storm, RESID was positive in that the pool gained 263 cubic feet of water more than could be explained through direct precipitation.

Table 2 shows the results of the direct precipitation-ET model during average and wet years for Pools 327 and 330. The table gives the number of days when the computed pool volume exceeded the maximum pool volume, in which case the pool spills water and the volume is reset to the pool volume at the outlet elevation. The model was also run with the assumption that the pool sides were vertical and that precipitation could continue to accumulate in the pool (it was not allowed to spill). The "maximum ratio" given in the table is the largest computed ratio of total pool volume with no spillage over the measured pool volume at the outlet elevation. The results show that both of these natural headwater pools would spill for a minimum of 10 days (not necessarily consecutive) and that direct precipitation alone could fill the pools to at least 1.39 times their maximum volume. During moderately wet years, such as 1973, these pools would spill water for over 30 days and direct precipitation would fill the pools to approximately three times their total capacity.

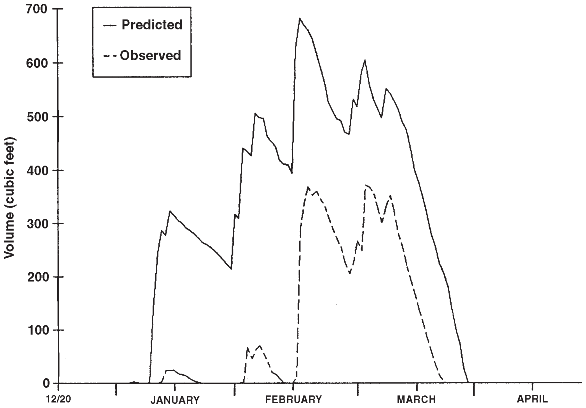

FIGURE 4. Comparison of observed versus predicted water volumes for the 1990 water year using a direct precipitation-ET model for pool 330.

Overland Flow Analyses

There are only three conditions under which overland flow can occur: 1) rate of precipitation exceeds the infiltration rate and surface detention storage is exceeded; 2) the soil column is completely saturated and the rate of precipitation exceeds the rate of percolation and/or net lateral subsurface flow out of the soil volume, and surface detention storage is exceeded; or, 3) converging topography and/or slope diminishment delivers more water into an area than can continue to be transmitted laterally, and/or vertically through the soil column, resulting in water exiting the soil column through the surface and becoming overland flow, once surface water detention storage capacity is exceeded. The first two conditions might be described as storm-dependent general overland flow, whereas the third is a special condition not dependent on precipitation.

During 1990, neither condition 1 or 2 was met. The maximum 15-minute rainfall intensity during the recorded 1990 storms was 0.3 inches/hour. Rangeland soils with good ground cover (typical of the conditions on-site), have final infiltration rates far in excess of this rate (Branson et al., 1981). As an example, Smith and Leopold (1942) reported wet infiltration rates (i.e., wet antecedent conditions) of 1.55 inches for 24 sites in New Mexico using a sprinkling infiltrometer. The Soil Conservation Service (1980) reports a permeability (final infiltration rate) for Redding soils, which are common on the site, at 0.6 to 2.0 inches per hour. Thus, there is no evidence to suggest that the first condition was met. The second condition was also not met. Continuous water level monitoring of the two wells in the Pool 330 watershed showed that the water level in the wells never rose to near the ground surface. At no time during 1990 were

TABLE 2. Direct precipitation-ET model results.

		Pool 327		Pool 330	
Year	Seasonal Precipitation (inches)	Days Spilled	Maximum Ratio	Days Spilled	Maximum Ratio
1975	18.5	11	1.52	10	1.39
1979	20.0	17	1.74	15	1.59
1973	26.1	35	3.05	34	2.79
1983	37.5	55	4.86	55	4.44

the upland soils saturated to the surface. Although condition 3 may have occurred, it is doubtful, given the fact that Well 1 was just 12 feet from the edge of Pool 330.

During 1991, although the total seasonal precipitation was below-average, March was exceptionally wet in Sacramento (7.48 inches versus a mean of 2.66 inches) (National Oceanic and Atmospheric Administration National Climatic Center database). Observations of the study area during the last heavy rains for the season on March 26 indicated that there was shallow overland flow and surface detention storage on the sides of upland swales on March 26, 1991, but only during the most intense portions of the storm. Overland flow may have occurred during that period, although it is likely that condition 3 contributed significantly to its generation.

Subsurface Flow Rate Plot Study

The subsurface flow rate was computed by determining the peak conductivity or bromide concentration in the lower trench of each plot and dividing this total time by the total distance traveled, yielding an average rate per day. Figure 5 shows the conductivity of water in the downslope trench. The obvious peaks indicate, on a mass-weighted basis, the time required for the wave of bromide anions to travel through the soil between the upper and lower trenches. The hydraulic gradients were 4%, 7%, and 9% for Plots 1, 2, and 3 respectively. Plot 3, which had the steepest gradient, had the fastest flow rate and sharpest peak, as would be expected. The majority of the bromide took from 13 to 18 days to travel 30 feet downslope. However, some bromide reached the lower trenches within days, traveling very rapidly downslope. The bromide water sampling analysis, which was less intensive that the conductivity monitoring, approximates the results obtained using the conductivity measurements.

Based on the observed average subsurface flow velocity and measured average hydraulic gradients, an average Darcy's "K" of 30 feet/day was computed.

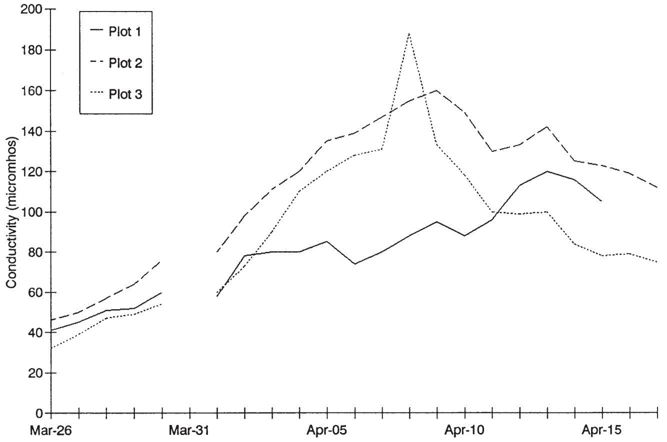

FIGURE 5. Conductivity of soil water in lower trench of subsurface flow plots.

Upland watershed model

Table 3 displays the modeled outflow from the upland radial slice for the indicated slopes and years (Table 1) for normal soil depth. Both the total computed subsurface and overland flow are shown. Also shown is the output for a 4% slope with a 2 foot soil depth to the water-restricting horizon. The data is arranged by water year in ascending order of total precipitation.

Paired Watershed Study

Figures 6 shows the hydrographs for control Pool 330 and treated Pool 327 for the 1989, 1990, and 1991 water years plotted as percent of their maximum capacity at the outlet elevation. The 1989 water year, although still below normal overall, was characterized by heavy precipitation in March (7 inches). This allowed the pools to fill to capacity. The 1990 water year was much drier and the pools filled to less than 35% of capacity. The 1991 water year was again dry, except for March when 10.9 inches of rain was recorded at the site. These heavy March rains caused all pools in the study area to spill.

Summary Results of Other Investigations

Conductivity of water in the wells was typically much higher than in the pools, which supports the hypothesis that direct precipitation is a dominant source of water in the pools. Conductivity levels in the pools were at a minimum early in the season and then generally increased over the remainder of the rainy season.

Figure 7 shows a diagrammatic cross-section of the well placement next to Pool 330. Water levels in Pool 330 during the 1990 water year exceed those in one or more of the wells during January when there was episodic partial filling, in March during the seasonal drying phase, and even briefly during Febru-

TABLE 3. Upland watershed model outflow for a unit slice for the years indicated.

Slope Length	Subsurface Flow / Overland Flow (cubic feet)					
	1977	1987	1975	1979	1973	1983
1% slope, normal soil depth (2.75 ft)						
25	0/0	0/0	0.2/0	3.3/0	39/0	73/0
50	0/0	0/0	0.2/0	4.4/0	61/12	92/54
100	0/0	0/0	0.2/0	5.5/0	122/44	141/248
200	0/0	0/0	0.2/0	5.5/0	135/89	141/871
2% slope, normal soil depth (2.75 ft)						
25	0/0	0/0	0.6/0	4.5/0	41/0	77/0
50	0/0	0/0	0.5/0	8.1/0	85/0	135/24
100	0/0	0/0	0.5/0	15/0	195/64	282/234
200	0/0	0/0	0.5/0	19/0	281/362	294/1109
4% slope, normal soil depth (2.75 ft)						
25	0/0	0/0	1.2/0	5.4/0	42/0	80/0
50	0/0	0/0	1.9/0	11/0	89/0	162/5
100	0/0	0/0	1.9/0	20/0	292/11	429/137
200	0/0	0/0	1.9/0	66/0	424/500	589/1176
6% slope, normal soil depth (2.75 ft)						
25	0/0	0/0	1.6/0	6.0/0	43/0	81/0
50	0/0	0/0	3.3/0	12/0	82/0	160/10
100	0/0	0/0	4.1/0	34/0	312/0	507/77
200	0/0	0/0	5.3/0	96/0	545/447	744/1109
4% slope, shallow soil depth (2.0 ft)						
25	0/0	0/0	1.3/0	18/0	*	*
50	0/0	0/0	26/0	36/1	*	*
100	0/0	0/0	54/0	78/2	*	*
200	0/0	0/0	167/34	207/148	*	*

* Model not run for these years.

ary following a major storm (Figure 8). Thus, there was a potential for water movement from the pool into the uplands predominantly early and late in the season. During most of February and early March water levels in the wells exceeded that in the pool, producing a hydraulic gradient toward the pool. This is the prerequisite condition for subsurface lateral inflows to occur. A maximum positive difference in water level of 0.8 feet occurred just after the February 16, 1990 storm. At that time, the maximum hydraulic gradient toward the Pool 330 at Well 1 was 0.067, and at Well 2 was 0.011. Once or twice weekly water level measurements during March, 1991, which was exceptionally wet, showed that while there was a hydraulic gradient toward the pool during the rainy period, the gradient reversed toward the upland 8-10 days following the cessation of rain on March 26, 1991.

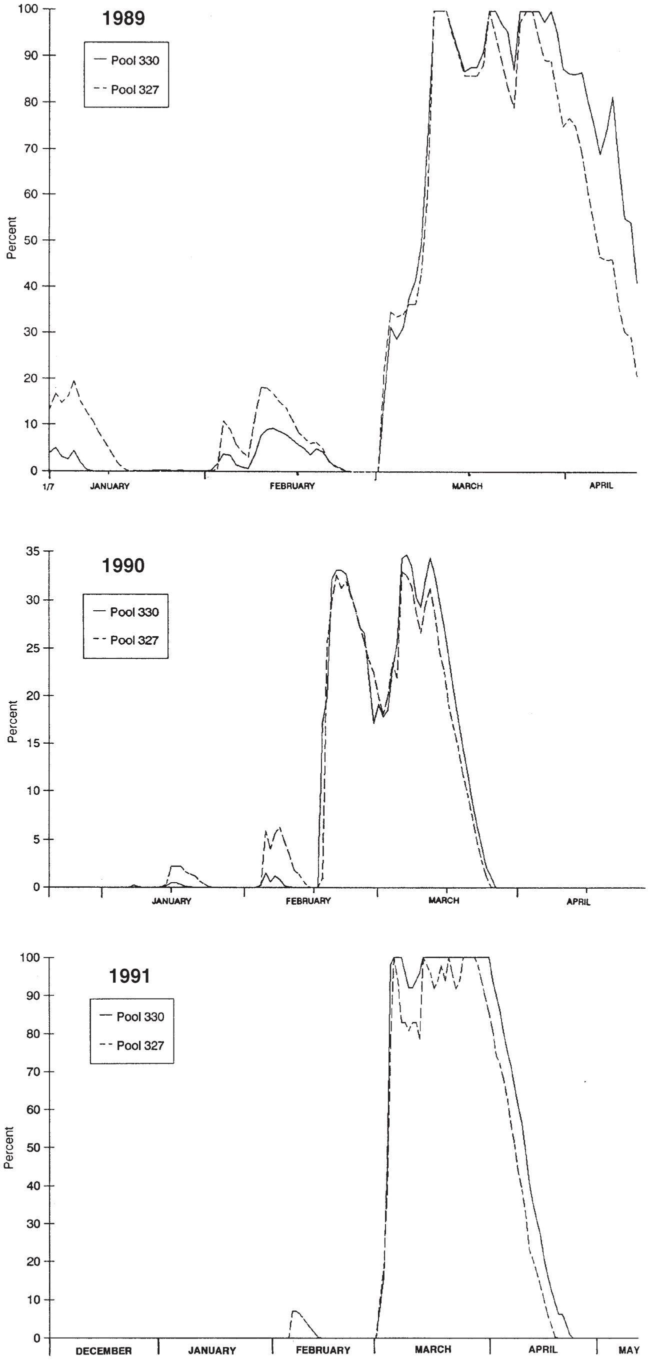

FIGURE 6. Comparison of pool volumes in Pool 327 (treated watershed) versus Pool 330 (control watershed), during the 1989, 1990 and 1991 water years.

Because of dry conditions during 1990, there were only three storms which occurred when upland soils were at or near field capacity, and therefore capable of delivering water to the pools.

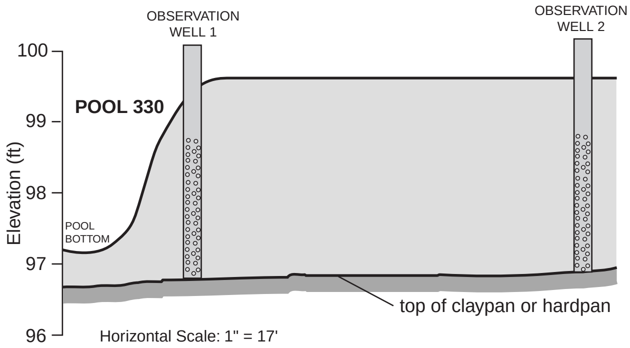

FIGURE 7. Diagrammatic cross-section through Pool 330 and observation wells.

Figure 9 shows the water levels in the continuously monitored pools and wells during and after the largest of these three storms (1.37 inches total precipitation). A slight upward gain of less than 0.1 feet is discernable in the water levels of the pools following the initial period of rainfall, up to hour 14. Pool 330, in particular, shows a slow progressive rise in water level that continues at the same rate up to 16 hours after the cessation of rainfall. The other pools show a more pronounced attenuation in the rate of rise in the pool water level.

DISCUSSION

The water balance analysis for Pool 330 for 1990 revealed that the pool never stored even the volumes of water that would be expected in the absence of any contributing watershed area, i.e., for 1990, the pool was a net loser of water to the watershed. Since there was no direct outflow, the loss of water to the watershed must have occurred through the movement of subsurface flow into the upland soils around the pool perimeter (SUBOUT in the water balance equation).

The results of the bromide tracer study are certainly not consistent with a hypothesis that water moves uniformly (slug flow) laterally above the water-restricting horizon. Although there was a clear peak in the conductivity readings in the downslope trench, it was also clear that limited amounts of water are rapidly transmitted through the soil, perhaps through a system of connected macropores. The presence of rodent burrows and high density of root pores certainly provides the setting for a limited amount of rapid transmission of water downslope. Most water, however, must flow through micro pores for at least some distance.

Laboratory-based estimates of "K" for non-sandy soils (Redding-Red Bluff soils are loams to clay loams) range from 0.01 to 1.0 feet/day (Morris and Johnson, 1967). The measured rate of 30 feet/day far exceeded any estimates available in the literature and suggests that undisturbed surface soils can transmit water at much higher rates than was previously thought possible.

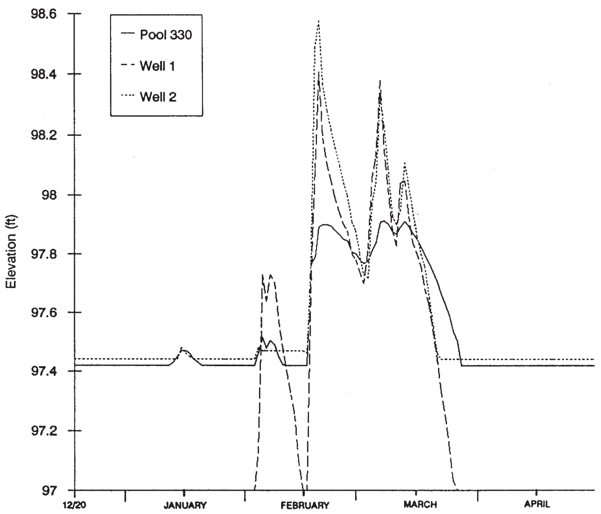

FIGURE 8. Water surface elevations (arbitrary datum) in Pool 330 and observation wells.

Development of the upland watershed model based upon the physical characteristics of the soil and topography found at the site show that subsurface flow of groundwater is quite sensitive to both slope and soil depth. Increasing slope and decreasing soil depth both tend to increase the total outflow. On nearly flat slopes with deep soils, most of the water can be held within the soil column. There is insufficient slope to force the water to move toward the pool; free water within the soil column is transpired before it can reach the pool.

The percent marginal increase in total outflow from the soil slice decreases with increasing length of the slice. This is particularly apparent on gentle slopes and during years with average rainfall. The effect of a long distance to the pool is the same as a nearly flat slope. Flow rates are not rapid enough to deliver water to the pool prior to the rapid rise in evapotranspiration losses in the spring, such that water moving toward the pool is transpired before it can reach it. For example, on the 6% slope for the 1978 water year (an average year), doubling the length of the slice from 100 to 200 feet provides only an additional four cubic feet of outflow. Although not displayed here, the model was also run with a length of 150 feet and the total outflow was 18 cubic feet. Thus, as modeled, any additional contributing area more distant than 150 feet away from the pool does not materially affect pool water levels.

The results indicate that watershed contributions are negligible during dry years, and can, in fact, even be insignificant during some normal years, especially for more gentle slopes (see model results for 1975, Table 3). Shallower soils and steeper slopes yield higher watershed contributions.

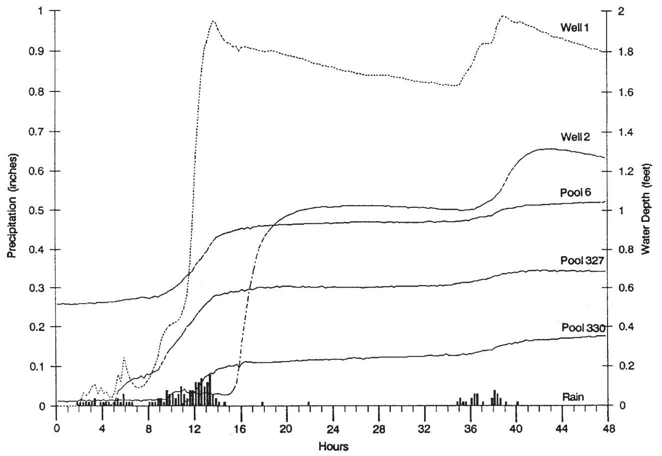

FIGURE 9. Water depths during the February 16, 1990 storm..

Modeled overland flow failed to occur during both dry and average years, but did occur abundantly during the wet years. Overland flow was greater on the more gentle slopes. This outcome is explained by the ability of soils on steeper slopes to transmit soil water at much higher rates, making more void space available to receive additional precipitation or subsurface flow from the upslope cell, and diminishing the amount of flow over the surface.

The paired watershed study showed that there was little overall difference between the water levels in Pool 327 and Pool 330. Pool 327 tended to pond water earlier in the season and gain slightly less water late in the season. Certainly, the tendency for Pool 327 to pond water earlier in the season would not be expected as a result of pool construction. The tendency for Pool 327 to gain less water than Pool 330 late in the season could be an impact of construction. However, the differences between the pools could reflect minor inherent differences in their watershed characteristics. Pool 330 has a watershed which is less steep than Pool 327's. As a result, there is more opportunity for water to move from the pool into the uplands through the soil early in the season, and also more opportunity to "recapture" this water later in the season as a positive hydraulic gradient forms toward the pool. Unfortunately, pre-construction monitoring of these pools was not conducted which weakens the ability to relate the minor differences in pool hydrology to either natural variation or pool construction. Overall, the water level regimes of the two pools were not substantially different. The addition of three more constructed vernal pools in the summer of 1989 did not materially modify the relative hydrologic performance of the two pools during either the 1990 or 1991 water years. Construction of six vernal pools, occupying a total of area of 14% of Pool 327's watershed did not induce a significant change in the hydrology of the pool.

Conductivity monitoring that revealed a trend for increasing conductivity in the pools over the course of the rainy season probably reflects the influence of inputs from subsurface inflows and the expected "concentration" effect associated with seasonal drying. Later in the season, Pool 330 had much higher conductivities than Pool 327 later in the season, which may reflect a greater exchange of water into and out of the surrounding uplands than occurs at Pool 327. This observation is consistent with Pool 330's tendency to fill later than Pool 327.

Continuous monitoring of precipitation and pool water levels (Figure 9) shows some water level increases in the pools occurring after the cessation of rainfall. These rises can only result from watershed-generated runoff. Because water levels in the wells rarely rose to more than a foot below the surface, and precipitation intensities were well below the probable minimum infiltration rate, it is likely that all watershed contributions were subsurface lateral flow. An exception may be the conversion of subsurface lateral flow to overland flow caused by decreasing slope and converging topography which may have occurred around the pool margin.

A significant characteristic of groundwater levels in the uplands at this site is their rapid decline following a storm (Figure 8). Although the data are limited, our analysis suggests that most of the water level decline that occurs after the first day or two following the end of the storm can be attributed to ET losses. Based on an analysis of water levels during individual storms, the amount of gravitational water in the soil was computed to be approximately 0.9 inches per foot of soil. Conversion of the measured water lost due to evaporation to an equivalent decline in saturated soil depth, approximates the observed water level declines within the wells.

CONCLUSIONS

Direct precipitation is by far the most important source of water to the vernal pools on the study site. Groundwater monitoring demonstrated that the hydraulic gradient sloped away from the pool initially, which caused direct precipitation to move laterally out into the upland soils at the pool margins. Low conductivities of pool water also indicate that it is largely associated with direct precipitation early in the season. During 1990, when the December-April total precipitation was approximately 61 percent of average, the pools were net losers of direct precipitation to the watershed. The pools would have been essentially devoid of any water in the absence of direct precipitation.

Significant watershed contributions rarely occur unless upland soils are fully recharged to the point where a perched groundwater table develops and a hydraulic gradient exists to move water laterally toward the pool. Based upon the upland watershed modeling results, this occurs only when seasonal precipitation is greater than, or perhaps slightly less, than average. Also, the timing and intensity of individual storms can play a significant role in controlling the hydraulic gradient toward pools and in the generation of overland flow. Although watershed contributions can generate sizeable volumes of inflow, generally during wet years, these contributions have little influence on the ability of the pool to fill. The water balance analysis for normal and wet years showed that the pools would commonly fill to overflowing from direct precipitation inputs alone. Thus, in some sense, volumetric watershed contributions can be considered excess to the pool. They tend to occur coincidentally when the pool is already full, or nearly so.

Investigations on this site indicate that overland flow is probably the least significant process in controlling vernal pool hydrology. General overland flow during storms is infrequent, and tends to occur during brief periods when upland soils are completely saturated, or nearly so, and pools are full, or nearly so. The conversion of subsurface flow to overland flow through slope diminishment and/or converging topography can be a common occurrence during and for a number of days after major storms. This inflow tends to be confined to a narrow band around the pool margin.

Although the watershed may have little influence on the pools from a volumetric perspective, the watershed does influence the water level regime of the pool, and the degree of influence probably becomes greater as the depth of upland soils increases. The exchange of water between the pool and the surrounding upland soils is an important process in delaying the onset of sustained inundation, in helping to maintain steady water levels during the period of sustained inundation, and in accelerating the seasonal drying of pools. The differential in soil depth to a water-restricting horizon between the pool bottom and the uplands (6-8 inches versus 2-3 feet) creates a much greater water recharge requirement in the upland soils to bring the entire soil column to field capacity. This creates the tendency early in the season for pool bottom soils to saturate quickly which causes the pool to pond water. This gives rise to a hydraulic gradient away from the pool that delays the onset of sustained inundation until sufficient rainfall has fallen to completely recharge the upland soils.

Once upland soils begin to develop a perched water table, the hydraulic gradient shifts toward the pool. This allows for subsurface inflows to the pool (which may be converted to overland flow at the pool margin). Although the rate of these inflows may be slow following a cessation of rainfall, they appear to be great enough to offset evaporative losses from the pool. Because the bulk of subsurface inflows occur when the pools are full or nearly so, they can cause the pool to remain full with a fairly constant water level for many days. These inflows tend to stabilize water levels near their maximum, and to delay the onset of drying in the spring. However, in late winter and early spring, ET rates rise substantially and rapid vegetative growth in the uplands quickly eliminates any residual perched water table. Thus, the hydraulic gradient once again shifts back toward the upland, and ponded water in the pool moves into the upland to replace water lost through transpiration.

Overall, the interaction with the uplands provides for a level of “inertia” in pool hydrology, i.e., it tends to delay, or “resist” the onset of sustained inundation, but once sustained inundation is achieved it tends to perpetuate it. These mechanisms which directly influence the water level regime may play important roles in the life cycles of some species of vernal pool vegetation and macroinvertebrates by acting as “triggers” alone, or in combination with other factors, such as shifts in water temperature or salt content. These may affect germination or reproduction. They may also lengthen the time period for such processes to occur. Some macroinvertebrates may depend on constant soil saturation around the pool perimeter as critical habitat during some phase of their life cycle. Certainly, it is easy to conceive that the resistance to late-season pool refilling may be an important mechanism in conserving macroinvertebrate eggs until suitable life-development conditions exist. Much research is needed to identify if, and to what extent, certain species may be dependent on the type of “buffered” water level regime which occurs in settings with moderate to deep upland soils.

The question of how much surrounding upland is required to withstand a material change in pool hydrology was partially answered at this site. The construction of six pools within the watershed of Pool 327, occupying an area of approximately 14% of the watershed had no apparent effect. There were minor differences in the water level regimes of the treated and control pools, but this could have been attributable to pre-existing differences in the pools. If there was a change induced by the construction, it was minor. Even though upland soils may be highly permeable, the actual rates of subsurface flow are still quite slow due to gentle slopes. For example, based on the measured “K” value of 30 ft/day, it would take 42 days for water to travel 50 feet to a pool if an hydraulic gradient of 0.04 could be constantly maintained over that extended length of time. At the study site, groundwater levels were observed to decline rapidly after storms, which limits both the saturated thickness (i.e., the volume of water moving) and the duration at which “steep” hydraulic gradients can be maintained. This is somewhat of an over-generalization because the tracer study demonstrated that limited amounts of water can be transmitted at rates far higher than the average rate. Overall, it appears that, after February during average years, most subsurface water enroute to the pool is transpired (or perhaps lost to vertical seepage) before it can reach the pool. Streamflow on the 60-acre watershed adjacent to the experimental watershed, ceased within 10 days following the end of the unusually heavy storms in late March, 1991. In that case, any subsurface flow originating at distances greater than it could travel in 10 days did not contribute to streamflow. Contributions may occur from greater distances during December and January when ET losses are at a minimum.

The relatively deep upland soils over a water-restricting horizon on this study site directly affect the hydrology of the vernal pools, which limits the findings of these investigations to sites with similar conditions. Certainly, it is reasonable to expect that the relative rate of occurrence of overland flow would increase, and the persistence of subsurface lateral flow would decrease, as the depth of upland soils decrease. Although the findings presented here are by no means exhaustive, they provide an adequate foundation for the design of efficient studies of the hydrology of vernal pools on different types of landscapes by qualified hydrologists. Successful "species-specific" vernal pool mitigation/protection must be based on research into the sensitivity of individual species to variations in vernal pool hydrologic regimes or changes to naturally-occurring hydrologic processes.

LITERATURE CITED

Branson F.A., G.F. Gifford, K.G. Renard, and R.F. Hadley. 1981. Rangeland Hydrology, Kendall/Hunt Publishing Company. Dubuque, Iowa. 340 pp.

Davis, S.N., and R.J. DeWiest. 1966. Hydrogeology. John Wiley & Sons. New York, NY. 463 pp.

Dunne, T., and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Company. San Francisco, CA. 818 pp.

Hanes, W.T., B. Hecht, and L.P. Stromberg. 1990. Water Relationships of Vernal Pools in the Sacramento Region, California, Pages 49-60 *in:* D.H. Ikeda and R.A. Schlising (Editors). Vernal Pool Plants – Their Habitat and Biology. Studies from the Herbarium, California State University, Chico, CA.

Hem, J.D. 1970. Study and Interpretation of the Chemical Characteristics of Natural Water. U.S. Geological Survey Water Supply Paper 1473.

Holland, R.F. and V.I. Danes. 1990. The Edaphic Factor in Vernal Pool Vegetation. Pages 31-48 *in:* D.H. Ikeda and R.A. Schlising (Editors). Vernal Pool Plants – Their Habitat and Biology. Studies from the Herbarium, California State University, Chico, CA.

Morris, D.A., and A.I. Johnson. 1967. U.S. Geological Survey Water-Supply Paper 1839-D.

Rawls, W.J., D.L. Brakensiek, and N. Miller. 1983. Green-Ampt Infiltration Parameters from Soils Data. Journal of Hydraulic Engineering 109(1):62-69.

Smith, H.L., and L.B. Leopold. 1942. Infiltration Studies in the Pecos River Watershed, New Mexico and Texas. Soil Science, Vol 53.

Stephens, D.B. 1996. Vadose Zone Hydrology. Lewis Publishers. New York, NY. 339 pp.

USDA Soil Conservation Service. 1980. Soil Survey of Placer County, California, Western Part. GPO 1980_273_056/10.

University of California. 1987. Determining Daily Reference Evapotranspiration (Eto), Cooperative Extension, Division of Agriculture and Natural Resources, Leaflet 21426.

Zahner, R. 1967. Refinement in empirical functions for realistic soil-moisture regimes under forest cover. Pages 261-272 *in:* W.E. Sopper and H.W. Lull (Editors). Forest Hydrology. Pergamon Press. New York, NY.