Journal of the American Mosquito Control Association, 16(1):22–27, 2000

RELATIONSHIPS AMONG WEATHER, MOSQUITO ABUNDANCE, AND ENCEPHALITIS VIRUS ACTIVITY IN CALIFORNIA: KERN COUNTY 1990–98

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ABSTRACT. The summer abundance of *Culex tarsalis* in Kern County, California, during 1990–98 was related quantitatively to rainfall, snow depth and water content, and runoff of the Kern River. Total monthly rain that fell during winter, lagged by 4–6 months, explained only 13% of the variability in the number of host-seeking females collected per trap night per month during summer. In contrast, regression analysis showed that river runoff 1 month earlier explained 67% of the variability in mosquito abundance. The water content of snowpack measured within the Kern River watershed during winter explained 70% of the variation in average mosquito abundance during the following summer. After being absent from Kern County since 1983, western equine encephalomyelitis virus (WEE) returned during the wet years of 1996–98 after the flow of the Kern River exceeded 150,000 acre-ft (450 hectare-meters) per month. Water content of snow in the Sierra Nevada during winter provided an excellent early warning of vernal river runoff, mosquito abundance, and enzootic WEE activity levels on the floor of the San Joaquin Valley.

KEY WORDS *Culex tarsalis* abundance, western equine encephalomyelitis virus, surveillance, snowpack, river runoff, California

INTRODUCTION

In California, western equine encephalomyelitis virus (WEE) and St. Louis encephalitis virus (SLE) are maintained in nature in an enzootic cycle involving several bird taxa and the primary mosquito vector, *Culex tarsalis* Coquillett (Reeves 1990a). Transmission to humans and equines is tangential to this primary cycle and frequently occurs after specific weather conditions allow virus amplification (Reeves 1990b). Weather affects transmission primarily by altering the quality and quantity of mosquito larval habitats, and this generally results in changes in adult female abundance. The intensity of enzootic activity and therefore the risk of human and equine infection are associated closely with vector abundance (Olson et al. 1979) and therefore the interaction between weather and mosquito population size. Historically, the intensity of WEE activity in Kern County, California, was related to snowpack depth in the Sierra Nevada, vernal temperature, and Kern River runoff (Reeves and Hammon 1962). However, these associations were described qualitatively over a relatively short time period using mosquito population estimates measured by resting counts, a sampling method no longer used by mosquito control agencies. Runoff of the Kern River also has been modified extensively by the 1953 completion of the 11,200-acre (4,536-ha) Isabella Dam, which now regulates the flow of the Kern River onto the valley floor.

The overall objectives of the present research were to identify weather variables associated with changes in mosquito abundance and to develop a predictive model to help forecast mosquito-borne encephalitis virus transmission in California. Ultimately, if the factors driving virus transmission can be identified and quantified, initiating intervention measures may be possible before virus amplification exceeds thresholds necessary for human involvement. The present paper focuses on Kern County, because populations of host-seeking *Cx. tarsalis* have been monitored systematically by the Kern Mosquito and Vector Control District (MVCD) using Centers for Disease Control (CDC)-style traps since 1990 (Meyer 1991). These data allowed us to test the hypothesis of Reeves and Hammon (1962) that winter snowpack in the Sierra Nevada can be used to predict mosquito abundance and enzootic WEE activity during the following summer.

MATERIALS AND METHODS

Mosquito abundance data were obtained from the Kern MVCD and included both New Jersey and CDC trap data. The CDC-style traps (Sudia and Chamberlain 1962) baited with dry ice were operated without lights on alternate weeks at the same 24 permanent locations on the floor of the San Joaquin Valley from April through October each year from 1990 to 1998. New Jersey light traps (Mulhern 1942) were operated for 2 consecutive nights per week at 12–33 locations from April through October.

Precipitation, Kern River runoff, and snow depth and water content data were obtained from the California Department of Water Resources web page. Precipitation and impaired river runoff were mea-

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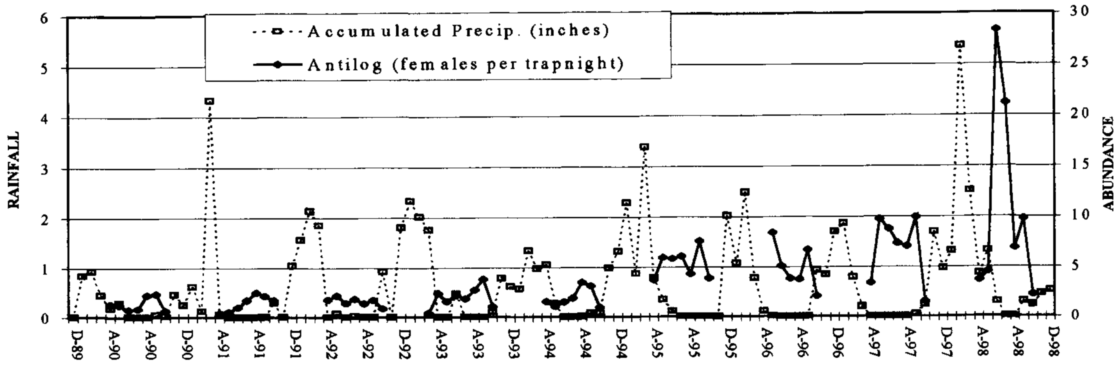

Fig. 1. Total monthly precipitation in inches and monthly geometric mean number of host-seeking females of *Culex tarsalis* per Centers for Disease Control-style trap baited with dry ice per night plotted as a function of time in months.

sured every month of the year. Impaired runoff measures actual river flow onto the San Joaquin Valley floor after removal by impoundments such as Lake Isabella and by canals for irrigation. Runoff data are measured in thousands of acre-feet (where 1,000 acre-ft ≈ 3 hectare-meters) and were collected at the Kern River just upstream from Bakersfield. Snow depth and water content, a measure of the amount of water accumulated in snow, were recorded monthly from February through May at Bighorn Plateau, a site in the Sierra Nevada near the headwaters of the North Fork of the Kern River.

Data on mosquito virus infection rates, sentinel chicken seroconversions, and equine and human encephalitis cases for the 1990–98 period in Kern County were provided by the California Department of Health Services and the University of California, Davis, as part of the California Encephalitis Virus Surveillance Program.

RESULTS AND DISCUSSION

Data were analyzed by regression to determine time series relationships among the weather parameters and mosquito abundance. No easily discernable relationship was detected between mosquito abundance measured by CDC traps and total monthly precipitation over the 9-year study period (Fig. 1); regression analysis indicated that precipitation, which falls mostly during winter, accounted for only 3% of the variability in female mosquito abundance during the following summer. Incorporating time lags of 1–3 months between precipitation and subsequent mosquito abundance did not improve the fit, whereas lags of 4–6 months accounted for ca. 13% of the variability in mosquito abundance during the subsequent summer season. Kern County lies in the rain shadow of the Coast Range and only limited winter rain falls on the valley floor (30-year normal total = 145 mm). However, these rains may be critical by providing surface-water oviposition sites for the overwintering *Cx. tarsalis* cohort that terminates diapause in mid-January (Bellamy and Reeves 1963) and before the initiation of vernal runoff from the snowpack. The relationships among winter rain, winter oviposition habitat, and abundance levels during the following summer were confounded by other effects on population dynamics, including temperature and subsequent water availability from runoff and agricultural irrigation.

In contrast to rainfall, strong relationships were found among snow depth, snow water content, river runoff, and mosquito abundance measured on the San Joaquin Valley floor (Fig. 2). Regression analysis indicated that the relationship between impaired runoff of the Kern River measured just upstream from Bakersfield and mosquito abundance was significant (df = 62, $P < 0.001$) and explained 56% of the variability among abundance of host-seeking mosquitoes measured by CDC traps (transformed by $\ln[y + 1]$ to normalize the data and control the variance). Incorporating a 1-month lag between runoff and subsequent mosquito abundance increased the R^2 value to 0.67; longer lag periods did not improve this relationship. The final model II regression function was highly significant ($y = 1.362 \pm 0.098 + 0.0105 \pm 0.0009x$, where $y = \ln[\text{females per trap night per month} + 1]$ lagged 1 month, x = runoff in total acre-feet, F = 124.3, df = 1,61, $P < 0.001$). Deviation analysis delineated the predictive value of river runoff for mosquito abundance (Fig. 3) and clearly showed that low runoff was associated with low *Cx. tarsalis* abundance and high runoff was associated with high abundance.

Annual snow depth ($R^2 = 0.66$) and snow water content ($R^2 = 0.71$) measured in the Sierra Nevada within the Kern River watershed were related significantly (df = 7, $P < 0.001$) to total annual impaired runoff of the Kern River. The water content of maximum snowpack during winter explained 70% of the variability among the average number of *Cx. tarsalis* per CDC trap night during the subsequent summer (Fig. 4). The model II regression function was highly significant ($y = 0.881 \pm 0.306$

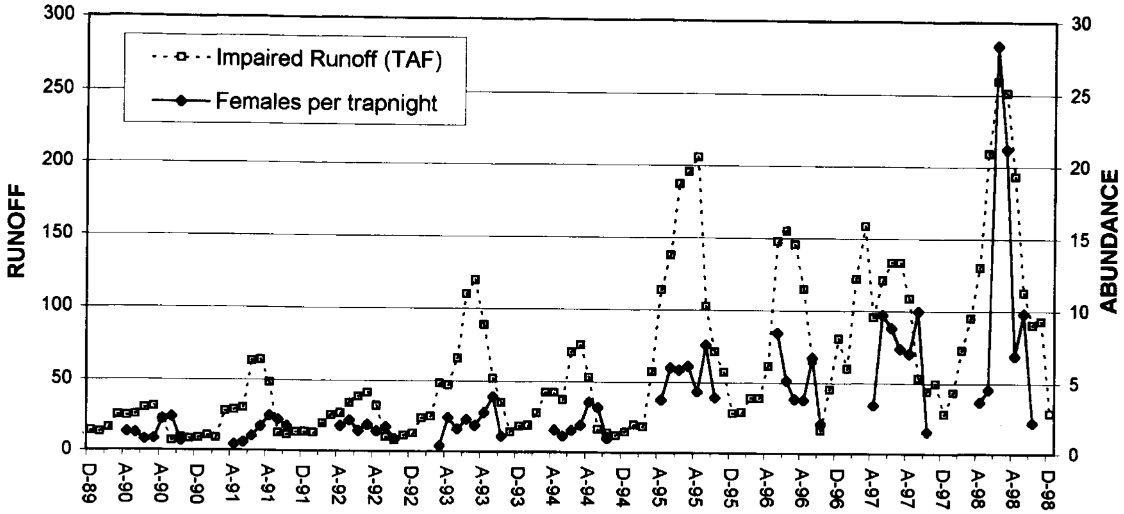

Fig. 2. Impaired runoff of the Kern River in thousands of acre-feet per month and the monthly geometric mean number of host-seeking females of *Culex tarsalis* measured by Centers for Disease Control-style traps baited with dry ice plotted as a function of time in months.

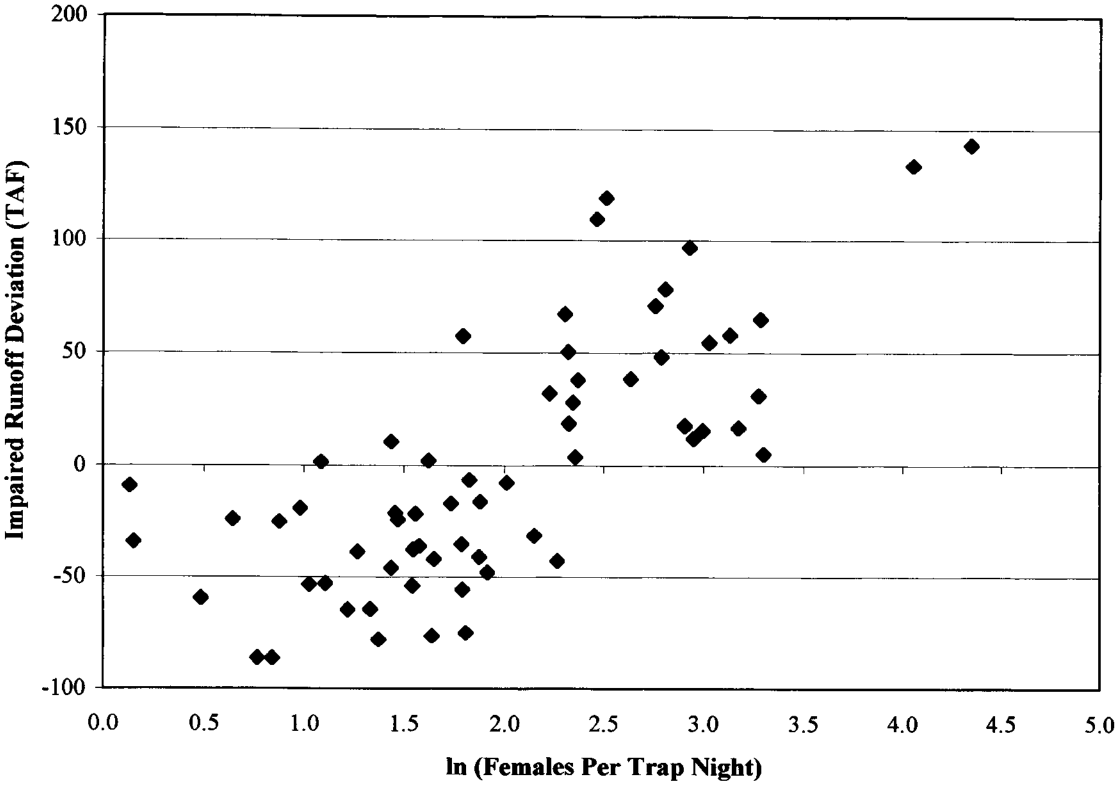

Fig. 3. Deviation analysis showing impaired runoff of the Kern River plotted as a function of the abundance of host-seeking *Culex tarsalis* transformed by ln(y + 1).

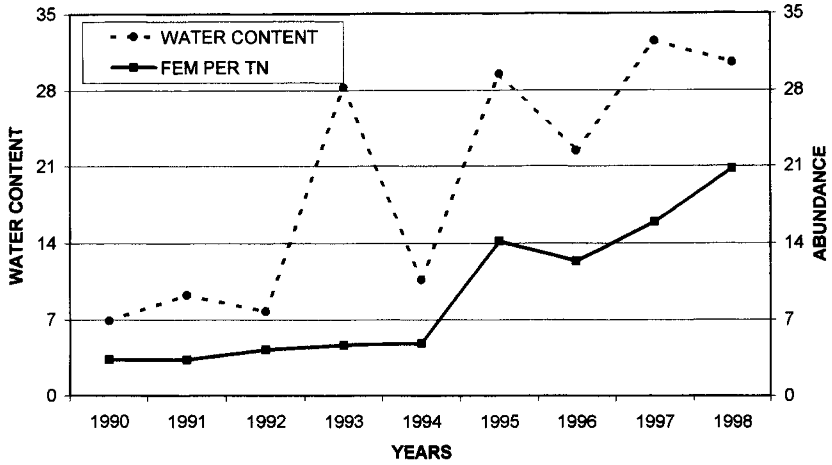

Fig. 4. Maximum water content of the snowpack in the Sierra Nevadas in inches measured at Bighorn Plateau and the geometric mean number of *Culex tarsalis* collected host-seeking per Centers for Disease Control trap night during the following summer plotted as a function of time in years.

+ 0.056 ± 0.014x, where y = average of *Cx. tarsalis* abundance transformed by ln[y + 1] during the following summer and x = maximum snow water content measured in inches at Bighorn Plateau, F = 16.78, df = 1,7, P = 0.005).

The relationship between mosquito abundance measured by New Jersey light traps and runoff of the Kern River (R^2 = 0.25, df = 61, $P < 0.001$) was not as strong as the relationship between CDC trap data and river runoff (R^2 = 0.67). The number of mosquitoes collected by New Jersey light traps was an order of magnitude less than the number collected by CDC traps and did not delineate seasonal abundance patterns as well as CDC traps, although these measurements were correlated significantly over time (R^2 = 0.44, df = 1,123, $P <$ 0.001). Correlation between these measurements of *Cx. tarsalis* abundance during 1990–98 (Fig. 5) delineated a general trend for increasing vector population abundance associated with increasing runoff of the Kern River. However, confounding factors such as competing illumination from street and security lighting (Reeves and Milby 1989) produced a gradually decreasing trend in New Jersey light trap abundance since 1980 (Fig. 5).

Although previously endemic (Reeves 1990a), WEE activity was not detected in Kern County from 1984 to 1995 (Reisen 1984, Reisen et al. 1990), a period that included 6 consecutive drought years. The summer of 1995 was the 1st time since 1983 that Kern River runoff exceeded 150,000 acre-ft (450 hectare-meters) per month and during

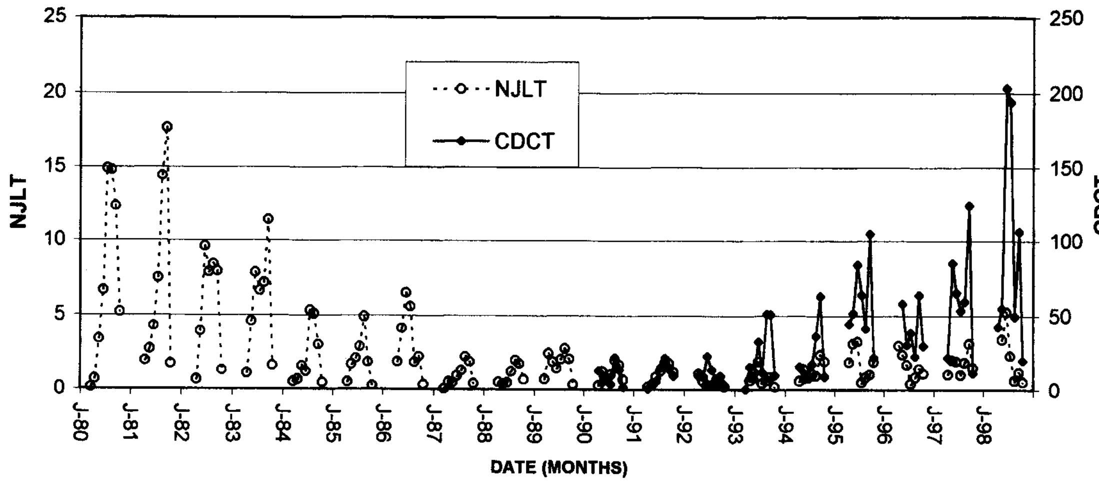

Fig. 5. Abundance of female *Culex tarsalis* measured by Centers for Disease Control-style traps baited with dry ice from 1990 to 1998 and by New Jersey light traps from 1980 to 1998 plotted as a function of time in months.

Table 1. Western equine encephalomyelitis virus (WEE) activity in Kern County, California, documented by surveillance conducted by the Kern Mosquito and Vector Control District and the University of California.

Method	Parameter	1990–95[1]	1996	1997	1998
Mosquito pools	Number tested	1,667	168	598	770
	WEE isolates	0	3	0	42
Chickens	Number of flocks	7–12	9	9	9
	Seroconversions	0	34	2	27

[1] Total number of pools and range of sentinel chicken flocks sampled each summer during 1990–95.

the subsequent autumn geometric mean *Cx. tarsalis* female abundance peaked at 7.6 per trap night. Interestingly, the following year, 34 sentinel chickens seroconverted in 6 of 9 flocks and 3 isolations were made from mosquito pools (Table 1). During 1996–98, Kern County experienced elevated snowpack, high runoff from the Kern River, and increased mosquito abundance (Fig. 2), and WEE activity was detected during all 3 years, albeit at an unexplained low level during 1997. In agreement, WEE has not been detected during 1999, a year when maximum snow water content was 38% and peak runoff of the Kern River was 30% of 1998 values. Despite elevated enzootic activity in close proximity to the city of Bakersfield, no human cases and only a single horse case were detected throughout this period, perhaps attesting to the successful mosquito control efforts of the Kern MVCD.

St. Louis encephalitis virus was not detected in the Central Valley of California during the 1990–98 study period, perhaps indicating that different ecological conditions were necessary for amplification. For example, the 1989 SLE outbreak that was centered in the Bakersfield area occurred during a period of prolonged drought during which the Kern River to the southwest of Bakersfield remained dry and runoff remained <56,000 acre-ft per month (Reisen et al. 1992).

In agreement with the previous conclusions of Reeves and Hammon (1962), snow water content during the winters of 1995, 1996, and 1997 was the greatest during the study period and resulted in increased runoff of the Kern River, increased abundance of *Cx. tarsalis* mosquitoes during the subsequent summer, and perhaps the reestablishment of WEE in Kern County. These quantifiable relationships among weather variables and mosquito abundance provide an important potential early warning of enzootic virus activity levels and therefore the risk of human and equine infection.

ACKNOWLEDGMENTS

We especially thank the Kern MVCD (Robert Quiring, manager; Richard Takahashi, entomologist) for providing mosquito abundance data. The Kern MVCD surveillance system was established by R. P. Meyer, the data were collected each summer by Boyd R. Hill, and the database was maintained by Sherry Sharp. The following MVCDs provided financial support: Butte, Coachella Valley, Contra Costa, Greater L.A., Marin–Sonoma, Northwest, Orange, Sacramento–Yolo, San Joaquin, and Sutter–Yuba. The Viral and Rickettsial Disease Laboratory, California Department of Health Services (DHS), and the Arbovirus Research Laboratory of the University of California at Berkeley and now at Davis tested mosquito pools and sentinel chicken specimens. Selected surveillance data summaries were provided by Lucia Hui and Stan Husted of the Vector Control Section, DHS. Bruce Eldridge, University of California, Davis, provided office space, logistical support, and helpful assistance during the protocol and manuscript preparation phases of this project. This research was funded, in part, by a subcontract of a grant from the National Aeronautics and Space Administration to Jonathan Day, University of Florida. Funds to defray publication costs were provided by the University of California Mosquito Research Program.

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