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A GEOGRAPHICAL INFORMATION SYSTEM TO MANAGE MOSQUITO AND ARBOVIRUS SURVEILLANCE AND CONTROL DATA IN THE COACHELLA VALLEY OF CALIFORNIA

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ABSTRACT. A geographical information system was developed to monitor and analyze mosquito abundance and encephalitis virus activity in the Coachella Valley to facilitate mosquito control operations. Data layers include soil types, vegetation types, irrigation method, standpipes, larval occurrence, adult abundance, and viral transmission to sentinel chickens. Base maps are digitized aerial photographs, with data entry done through sections of the range/township system. The image resolution of a section is 100 ft^2 (9.3 m^2) per pixel. This system currently is operational and in use by the Coachella Valley Mosquito and Vector Control District for data management.

KEY WORDS Geographical information system, mosquito surveillance, mosquito-borne encephalitis, *Culex tarsalis,* Coachella Valley

INTRODUCTION

Geographical information systems (GISs), in combination with remote sensing, have provided innovative approaches to analyzing temporal and spatial problems in the ecology of vector mosquitoes and the pathogens they transmit. For example, in rural Africa, remotely sensed changes in vegetation associated with rainfall monitored dambo flooding, the emergence of vector mosquitoes, and the occurrence of Rift Valley fever virus (Linthicum et al. 1991, Pope et al. 1992). In Mexico, proximity analysis of remotely sensed vegetation types near rural villages mapped potential malaria vector larval habitats and successfully predicted adult abundance and the risk of malaria transmission (Rejmankova et al. 1995, Beck et al. 1997). In the Sacramento Valley of California, remote sensing and GIS plotted land use patterns and revealed the importance of the juxtaposition of irrigated pasture to rice fields in the production of populations of *Anopheles freeborni* Aitken (Wood et al. 1991a, 1991b). These approaches seemed well suited to extending our on-going studies on the spatial ecology of *Culex tarsalis* Coquillett and encephalitis viruses in the irrigated inland valleys of southeastern California.

Geographical information system technology also has emerged recently as a management tool in vector control programs because of the ability of GISs to store, visually analyze, and report data in spatial as well as temporal formats (Freier and Flannery 1998). Most vector control organizations have chosen off the shelf solutions such as MapInfo (MAPINFO, Troy, NY) or ARC/INFO (ESRI, Redlands, CA). However, these packages require considerable expertise and lack data entry interfaces specifically tailored to the needs of vector control organizations. For a system to be useful operationally, it should meet not only the reporting needs of management, but also allow mosquito control staff to retrieve historical survey information, display and map potential problem areas, and update databases with recent survey and control information.

In 1994, with the collaboration and support of the Coachella Valley Mosquito and Vector Control District (CVMVCD), we initiated development of a GIS to extend our on-going studies on the landscape ecology of western equine encephalomyelitis (WEE) and St. Louis encephalitis (SLE) viruses in the Coachella Valley of California (Reisen et al. 1995a, 1995b), and to provide the CVMVCD with a geographical database for managing their surveillance and control information. We developed our own software to provide flexibility of system design and simplicity of use for the CVMVCD staff. The current paper describes this new GIS software, its data sources and reporting capability, and utility in CVMVCD operations. Subsequent papers will focus on the spatial analysis of adult mosquito and arbovirus surveillance data.

MATERIALS AND METHODS

Study area description: The Coachella Valley lies within the borders of the CVMVCD in eastern Riverside County, extending northward from the Imperial County border to the Banning Gap. Physiographically, the valley is bordered to the west by the San Jacinto and Santa Rosa mountains, to the north and east by the San Bernardino Mountains and the Mecca Hills, and to the south by the Salton Sea (Fig. 1). Dominant land use changes from residential communities such as Palm Springs in the northwest, to irrigated vegetable and fruit agricul-

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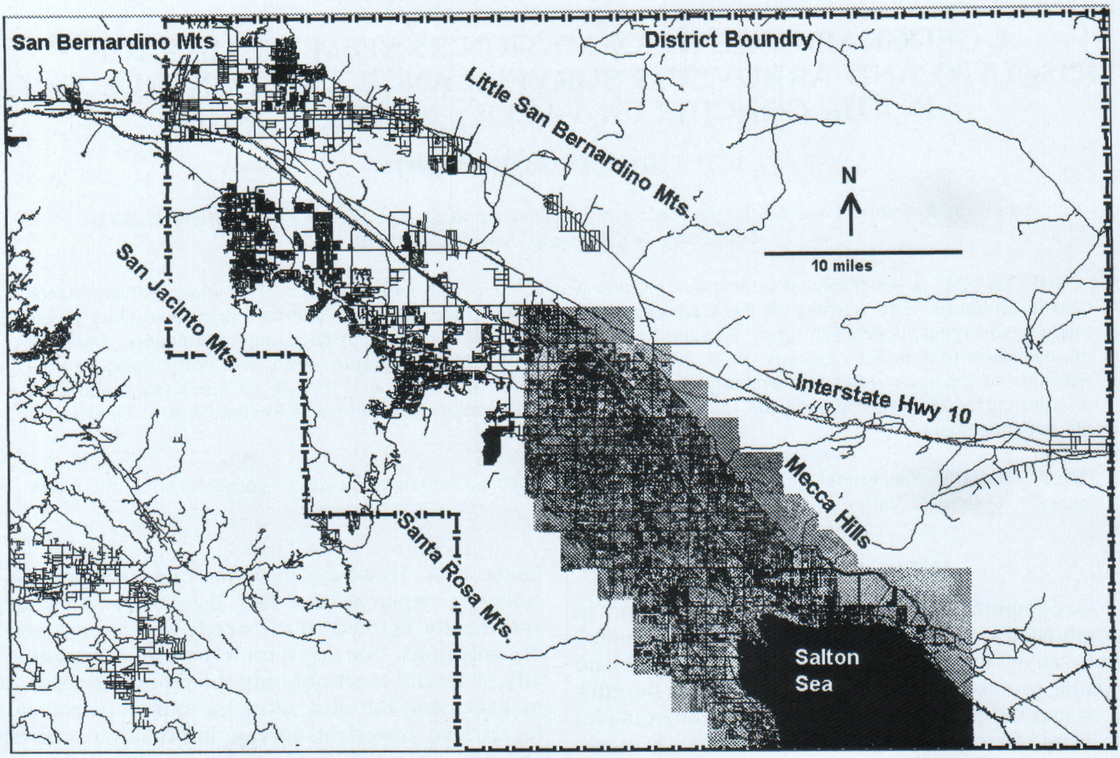

Fig. 1. Map of the Coachella Valley, Riverside County, California, showing the extent of the present geographical information system coverage.

ture, to fish farms, duck clubs, and wetlands along the Salton Sea in the southeast. Rainfall is infrequent, and all crops and landscaping require intensive irrigation.

Mosquito diversity and abundance increase progressively from the northwest to the southeast in association with changes in land use (Reisen et al. 1995b). In descending order of abundance, the species associated with urbanized habitats in the northwest are *Culex quinquefasciatus* Say, *Culex stigmatosoma* Dyar, and *Cx. tarsalis*. In contrast, rural areas in the southern valley have more diverse habitats and mosquito species. Habitats can be divided into managed and unmanaged and represent approximately 70,000 acres (28,350 ha) with a distinct temporal sequence of availability as larval habitats. Managed habitats include citrus, date, grape, and row crops as well as fish farms and duck ponds. Unmanaged habitats include salt- and freshwater marshes along the margin of the Salton Sea and occasional areas of undeveloped low desert flooded by infrequent rainfall. *Culex tarsalis, Culiseta inornata* (Williston), and *Anopheles franciscanus* McCracken exploit both managed and unmanaged habitats. *Aedes vexans* (Meigen), *Psorophora columbiae* (Dyar and Knab), and *Cx. quinquefasciatus* are found mostly in managed habitats, whereas *Aedes dorsalis* (Meigen), *Aedes taeniorhynchus* (Wiedemann), and *Culex erythrothorax* Dyar are found only in unmanaged habitats. Casual species such as *Culiseta incidens* (Thomson), *An. freeborni*, and *Culex thriambus* Dyar utilize habitats peripheral to the valley and rarely are found in adult traps.

GIS design: At the outset, the resolution of readily available satellite data was too coarse (10–30 m) to delineate many of the mosquito habitats in Coachella Valley. Therefore, the base map was derived from a series of color aerial photos of 1 in. = 4,000 ft scale, scanned at 300 dots per inch. Image processing and updating of the base maps was done with Adobe Photoshop LE (Adobe Systems Incorporated, Mountain View, CA). To conserve disk space and improve the speed of graphical functions, raster images were 8-bit, 256-color bitmaps. The range/township section image was selected as the geographical data unit and was cut and sized to match the dimensions of each section. The scale of this image on the monitor is 528 pixels per mile (1.61 km), which equates to 100 ft^2 (9.3 m^2) per pixel. This resolution allows for delineation of most physical features and can be displayed entirely on one screen in 800 × 600 super-VGA mode. Larval habitats, irrigation methods, irrigation valves (standpipes), and soil classification contours were entered as vector overlays on this image. Entry was done with a mouse by drawing over the section image or by transferring from maps using a digitizing tablet. Graphical data, including larval site outlines and habitat type boundaries, were stored in binary format. Surveillance data including adult abundance, larval presence and absence, treatment records, and virus transmission to sentinel chickens were entered from Windows dialog boxes and stored in Dbase IV format. This generic format allows these data to be imported by other applications, such as spreadsheets, for further examination and reporting.

Georeferencing was accomplished using functions that converted Cartesian coordinates on the base map to decimal latitude and longitude relative to the northwest corner of each section. This allowed transfer of positions taken in the field with a Global Positioning System (GPS) to the map. The system currently is running on the CVMVCD local network. The execution (program) and data files are kept on the server and called from Pentium 200-MHz network stations with 15-in. and 17-in. multisync monitors.

Data acquisition and use: Eight data layers currently are contained within the system and are utilized in CVMVCD surveillance and control operations. These include the following:

1) Soils. Types and distribution were entered from a 1979 survey published by the U.S. Department of Agriculture Soil Conservation Service as vector images using the digitizing tablet (Fig. 2). Major soil types ranged from lacustrine deposits of silty clay located in low-lying areas along the north end of the Salton Sea to sands and coarse gravels in upland areas and the desert regions of the northwest. In combination with temperature, land use, and irrigation type, soil maps provide information on the duration of surface water persistence and therefore mosquito control requirements following irrigation or rainfall.

2) Vegetation. Habitat or vegetation types were categorized from aerial photos, confirmed through ground survey, traced over the base map images, and stored as vector images (Fig. 3). Major habitat types within our study area were categorized as salt marsh, salt desert, creosote desert, duck pond, row crop, grape, citrus, date, pasture, urban, and fish pond. These categories, in combination with weather and irrigation information, delineate mosquito larval habitats requiring periodic inspection and treatment. Historical databases of surveys indicate when and under what conditions which species of mosquitoes exploit each source. Changes in agriculture and land development can be modified on these images using Adobe Photoshop.

3) Irrigation. Methods were defined as drip, flood, or a combination of drip and flood. Drip irrigation can maintain pools of water suitable for

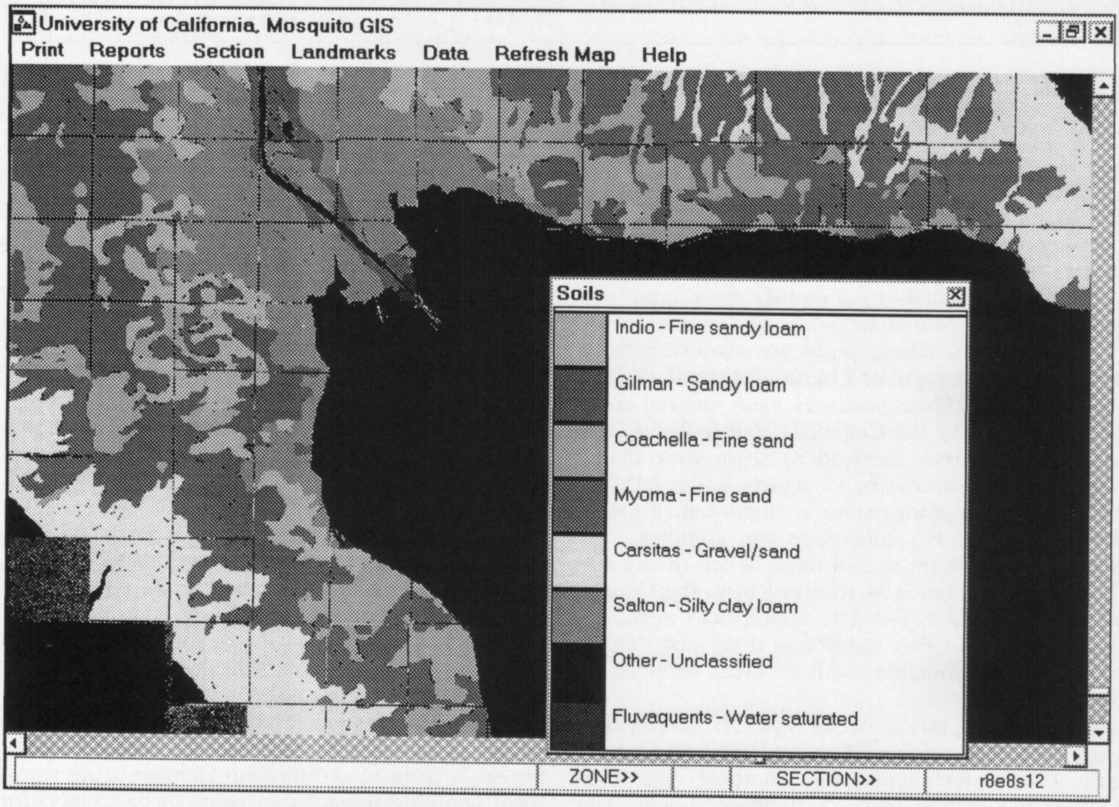

Fig. 2. Soil data entered from a 1979 U.S. Department of Agriculture soil survey.

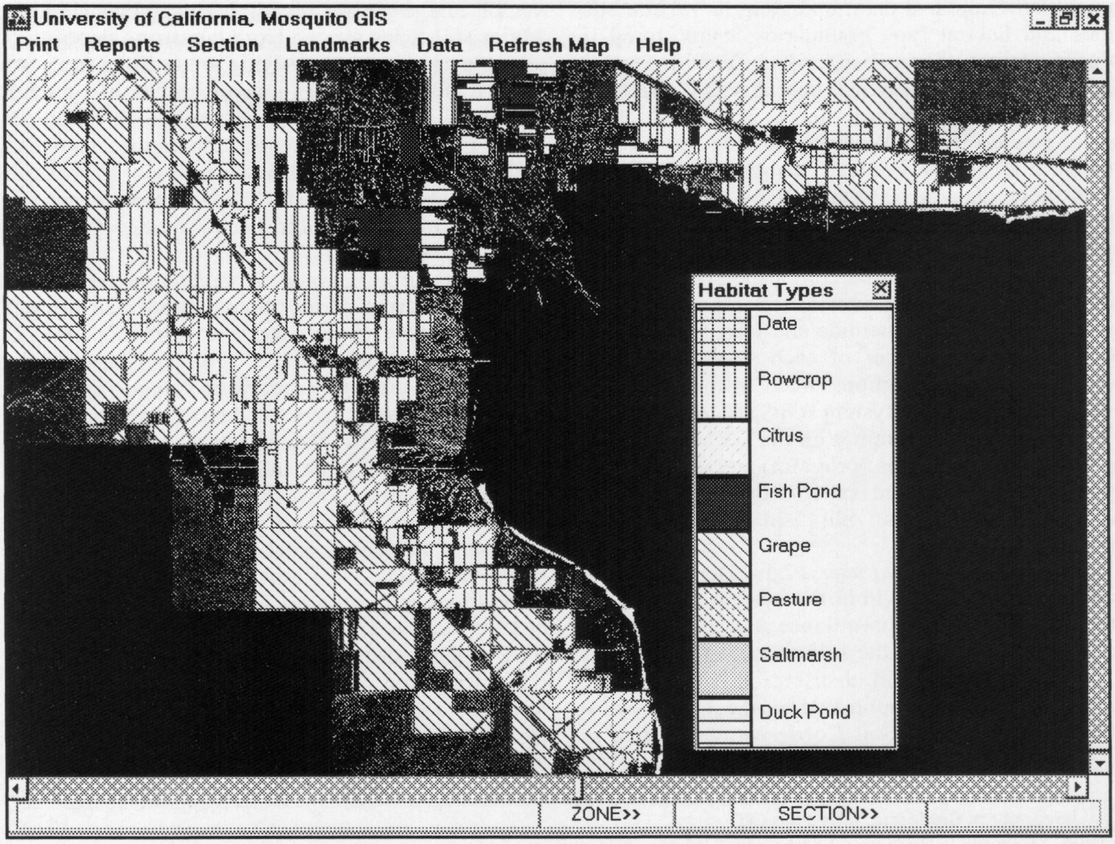

Fig. 3. Habitat vegetation categories defined from the aerial photographs and verified by ground survey. Undefined areas are undeveloped desert.

development of *Cx. tarsalis*, because drip systems are run continuously. Flood irrigation in crops such as date orchards results in large pools of short duration that are suitable for rapidly developing *Ae. vexans* and *Ps. columbiae*.

4) Standpipes. These pipes are associated with irrigation valves regulated by the Coachella Valley Water District. Their positions were entered from maps provided by the Coachella Valley Water District, and the areas serviced by them were determined by field surveys by Coachella Valley MVCD personnel. This information is important, because during summer *Ps. columbiae* can complete immature development in 3–4 days. When timely notification of irrigation is received from the Coachella Valley Water District, appropriate sites are flagged for immediate inspection if the distribution of this species coincides with the areas serviced by these valves.

5) Mosquito larval occurrence. In conjunction with each inspection and control operation, mosquito control technicians take multiple dips from each larval habitat using a standard dipper. The number and distribution of dip samples are determined by the type and size of the larval habitat and adhere to a protocol. Larval samples are transported to the laboratory for species identification, counting, and age-grading as small larvae, large larvae, and pupae. Habitats are sketched in the field onto section maps printed from the GIS, and then entered into the database and drawn as vector images. Habitat size is calculated from the sketch maps and stored with each sample. The status of past and active breeding sites can be displayed as color-coded maps to plan inspection and control operations (Fig. 4).

6) Chemical control. Larval treatments are documented in the field on the source inspection data sheet (see 5 above) and entered either with the larval data or separately through an additional Windows dialog box. Comparing treatment records with area estimates allows immediate quality control on chemical application rates.

7) Mosquito adult abundance. Originally, populations of adults in the lower valley were monitored biweekly from March through October using a uniform sampling scheme consisting of 65 Centers for Disease Control and Prevention (CDC)-style traps

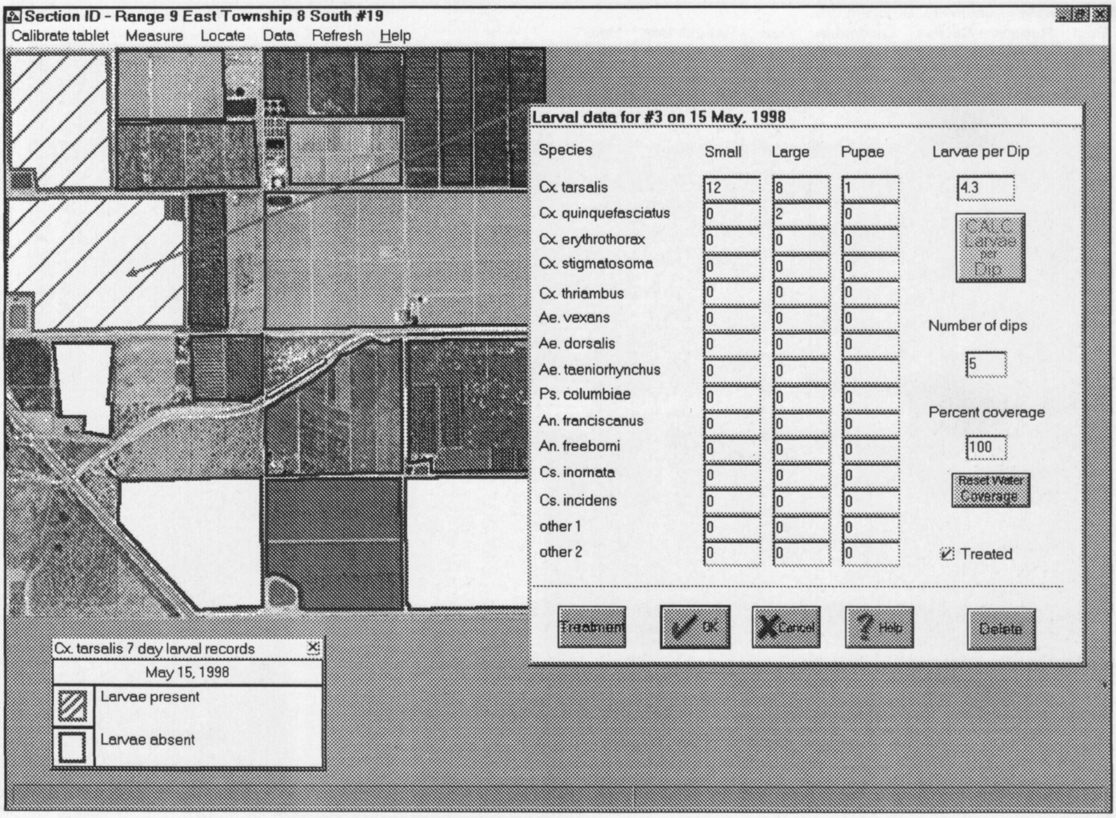

Fig. 4. Section image with larval sources and data dialog Window.

baited with dry ice and positioned at the intersect of section corners (Reisen and Lothrop 1999). In 1996 trap density was halved in the lower valley, and sampling was extended northward into the rest of the valley to augment the New Jersey light trap adult monitoring program. Conditional simulations indicated that this uniform scheme would adequately estimate abundance levels, delineate temporal patterns, and provide sufficient spatial sensitivity to detect control problems (Reisen and Lothrop 1999). Counts of females per trap night were transformed by $\ln(y + 1)$ and displayed spatially as a density of dots about each trap location (Fig. 5). Trap counts were considered to be representative of mosquito abundance within a 0.5-mi. (0.83-km) radius of each trap position, because mark–release–recapture studies estimated *Cx. tarsalis* emigration rates from focal sources to average about 1 km/day (Reisen and Lothrop 1995).

8) Sentinel chickens. Enzootic virus transmission was monitored by 10 flocks of 10 sentinel chickens each that were bled biweekly from April through November. Flocks initially were positioned at every 3rd CO_2 trap site to provide uniform coverage of the southern valley; however, in 1996 some flocks were repositioned to ensure adequate surveillance at the towns of Mecca, Thermal, and Indio. Surveillance was concentrated in the southern valley, because previous studies indicated that enzootic transmission did not occur north of Indio, even during years of intense transmission at wetlands associated with the Salton Sea (Reisen et al. 1995a). Whole blood, collected onto filter paper strips from a lancet prick of the comb, was tested by indirect enzyme immunoassay for antibodies to WEE and SLE viruses (Reisen et al. 1993).

SYSTEM OPERATION

As a part of the surveillance and control program, technicians inspect newly created and historical sources, and follow up chemical treatments. A larval sample is taken in each case, and the source drawn in the field on 5-in. × 5-in. black and white printouts of the section. After the larval samples are processed in the laboratory, the section window is selected for each sample and new sources are drawn freehand from the field sheet or existing sources are selected and the data entered. If the source was treated, the amount and chemical is entered at this time.

Larval data are displayed on both the district and

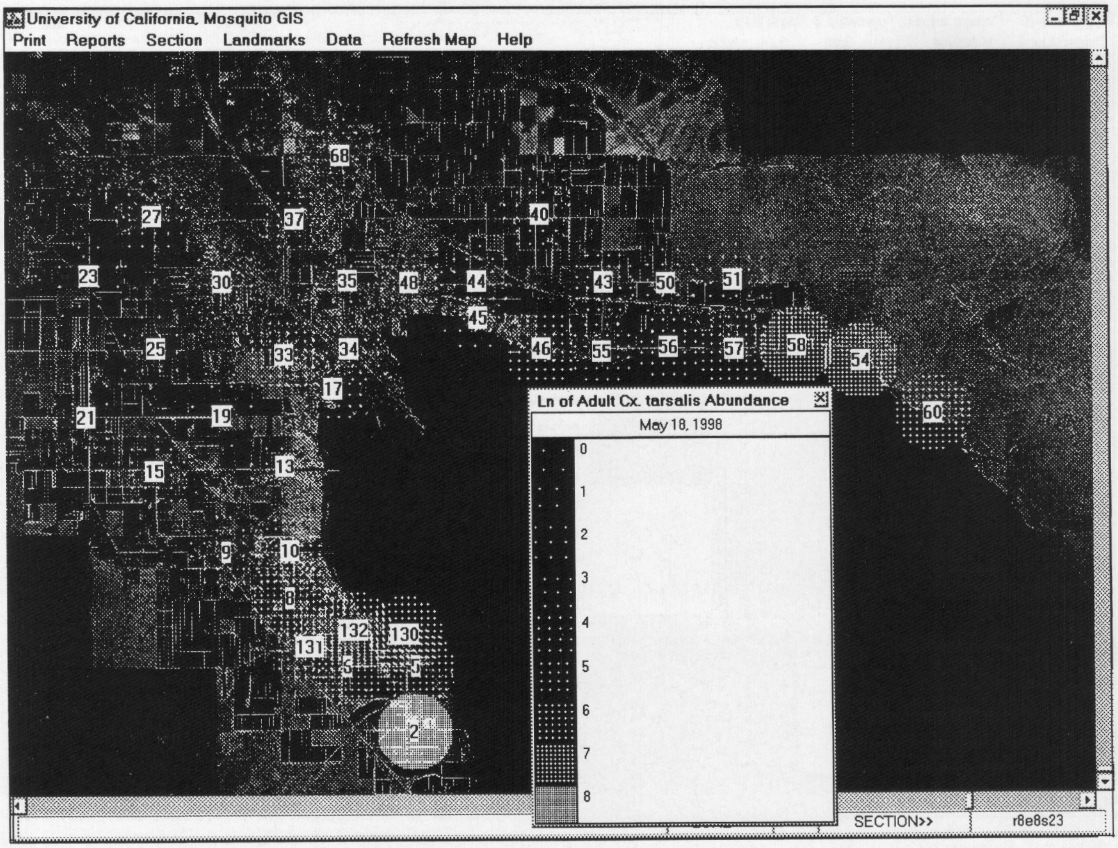

Fig. 5. Adult *Culex tarsalis* abundance depicted as dot densities around each trap is projected in a natural log scale. High dot density around traps 2, 54, and 58 denotes elevated *Cx. tarsalis* abundance.

section windows. On the district window, the larval samples for a 1-wk period appear as a series of red and blue symbols when a query is given for a particular species (Fig. 6). Red indicates positive and blue indicates negative samples. This display shows both inspection coverage and the occurrence of each species. Technicians use this information to check the thoroughness of surveillance in their work zone (designated geographical portion of the district). Potential larval habitat distribution also may be used as a predictive tool when data are displayed for a 1-month period surrounding the date selected from the previous season. This may be done for one or all mosquito species. When viewed on the section window, larval sampling activity is represented with white-filled, red and blue outlines of sources. Unsampled or inactive sources are outlined in blue only. Data for previously sampled sources may be viewed by double clicking on the source.

Adult abundance is displayed on the small-scale district map as a trap number surrounded by a 0.5-mi radius halo filled with a dot density configured for a natural log scale. The thoroughness of larval surveillance activities may be indicated by overlaying the larval distribution with adult abundance. If the adult abundance and distribution of a species are disjunct from larval records relative to the flight range, it strongly indicates that a source may have been overlooked or newly created and that additional surveillance is necessary.

The seroconversion rate for each sentinel chicken flock is calculated biweekly as the proportion of new seroconversions over the total susceptible hens and is displayed as a filled circle with an arithmetically scaled radius (Fig. 7). The combination of adult abundance, *Cx. tarsalis* virus infection rates, and sentinel seroconversions are used to focus adulticiding programs aimed at reducing the number of infective vectors and interrupting enzootic transmission.

Printed reports are produced using a utility program, which generates a filtered database query and formats output to a Window or printer. As new formats are desired, only the format template is edited and no additional coding is required. These reports presently include pesticide usage over time by chemical and habitat, and adult abundance at traps

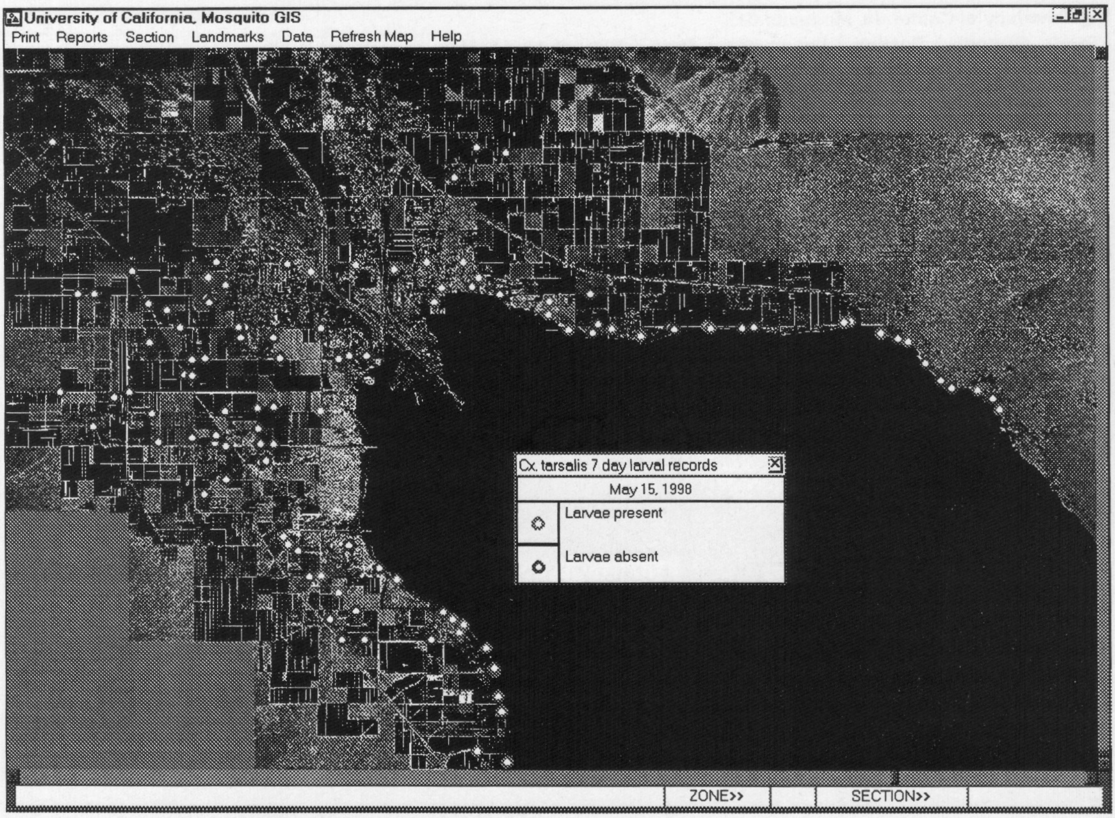

Fig. 6. Larval *Culex tarsalis* sources depicted as red (active) or blue (inactive) on the monitor.

exceeding a threshold response level adjusted according to season and virus activity.

IMPACT ON CVMVCD OPERATIONS

The principal benefit derived from integrating this GIS into CVMVCD operations has been an increased understanding of larval and adult distributions by both region and habitat. In addition, improved sampling methods have increased the level of control through better pre- and posttreatment inspections of larval sources. Technicians have been able to follow mosquito and arbovirus activity within their zone and surrounding zones and thereby improve surveillance schedules and focus control. Management has been able to spatially follow mosquito control success and failure and adjust control strategies.

Other needed functions have become apparent as the system has come on-line. These planned upgrades will include the following:

1) Proximity searches. Factors possibly contributing to an adult abundance record will be determined by a proximity search based on the flight radius relevant to the species in question. The search will locate possible larval sources from databases of individual source histories. This search will be helpful when a technician is new to a zone and possibly has overlooked a source contributing to an adult trap collection or service request. In addition, a plot of larval habitat types associated with the species in question will be displayed.

2) Forecasting. Analysis of irrigation, vegetation, and soil thematic layers to predict mosquito larval production will be a useful adjunct, especially for rapidly developing species such as *Ps. columbiae*.

3) Animation. Using historical databases and analyses integrating the various thematic layers, it eventually will be possible to output images to the district map showing projected larval presence, adult abundance, and virus transmission during a selected time period from inputs of weather and cropping pattern data or forecasts.

As with all software, this program will continue to evolve to meet the changing needs of the CVMVCD. Eventually it may become necessary to have a dedicated database manager to handle data input, changes in habitat due to development or crop replacement, and archiving of older data. This system also may be configured for use by other vector control districts with largely rural mosquito

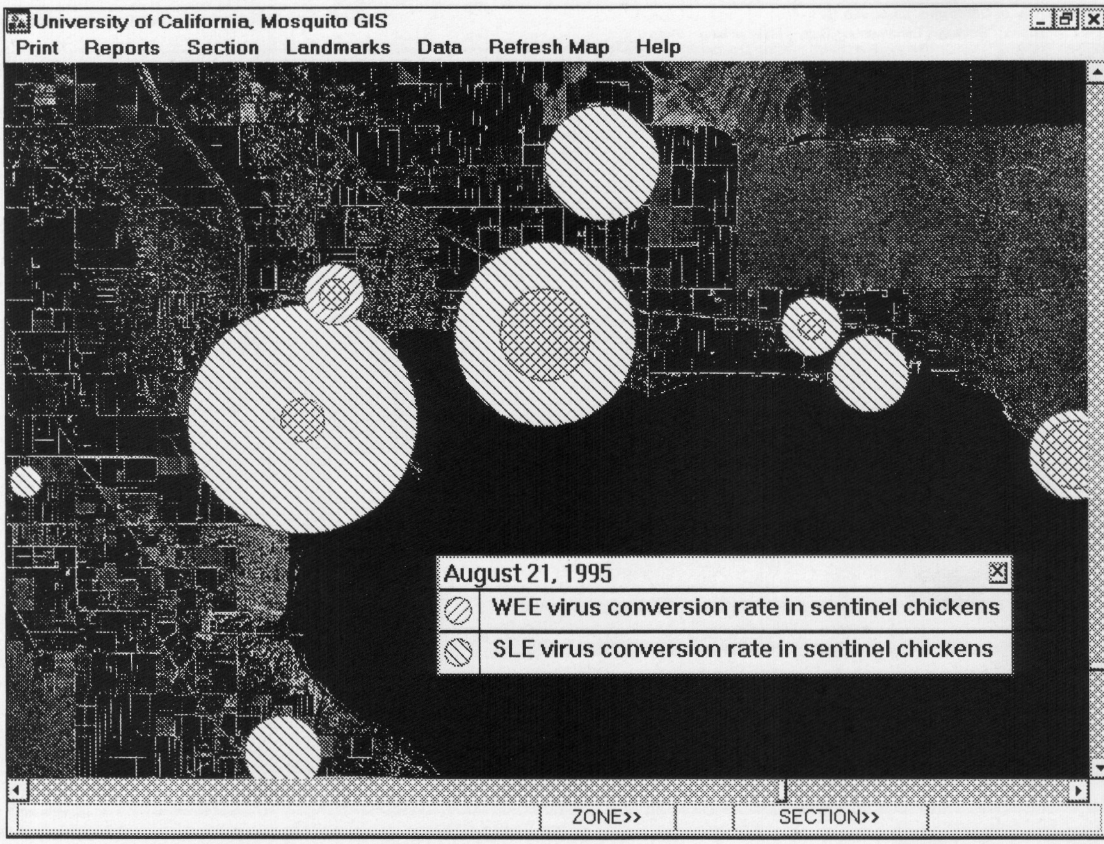

Fig. 7. Sentinel chicken seroconversion rates depicted as an expanding radius scaled from 0.1 to 0.8 (1–8 negative chickens seroconverting per biweekly period). St. Louis encephalitis and western equine encephalomyelitis viruses are displayed as different colors on the monitor.

sources. As mentioned, georeferencing is possible using a GPS where necessitated by terrain or lack of immediate landmarks.

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