Origin of Stream Flows at the Wildlands-Urban Interface, Santa Monica Mountains, California, U.S.A

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Key Terms: ***Hydrogeology, Geochemistry, Urban Geology, Land-Use Planning***

ABSTRACT

1 **The Santa Monica Mountains of southern California have undergone moderate urbanization since 1960. Just a few decades ago, many of the riverine systems in the Santa Monica Mountains were intermittent, but they are now perennial. The transition to perennial streams has led many policy makers to conclude that urban runoff from landscape watering accounts for continuous flows during the lengthy dry season. The transition to perennial flows allows expansion of habitat for exotic and harmful species, raising arguments for controls on urban runoff during the dry season. Most communities in the Santa Monica Mountains depend entirely on State Project water imported from northern California. Stable isotopes of oxygen and hydrogen show that imported water is isotopically distinct from local precipitation, providing a useful tool for tagging source flows in Santa Monica Mountain streams. In this investigation, we perform a detailed analysis of dry weather flows in one of the Santa Monica Mountain's major streams, Las Virgenes Creek. We also present results of reconnaissance surveys of several other creeks. Las Virgenes Creek accumulates most of its initial flow along an urban part of its stream reach. Chloride and sulfate scatter plots indicate that Las Virgenes Creek is dominantly fed along the urban stream reach by locally sourced, groundwater base flow. Oxygen and deuterium isotopes show that Las Virgenes Creek and other creeks in the Santa Monica Mountains contain small percentages of imported waters (less than 10 percent), indicating little urban runoff during dry weather flows. The data suggest that perennial flow in urban streams results from the removal of riparian vegetation and deepening of channels rather than from urban runoff.**

INTRODUCTION

The Santa Monica Mountains National Recreation Area (SMMNRA) covers a gross area of 620.2 km^2 with various land-use designations, including urban, residential, commercial, agricultural, parks, and natural preserves (National Park Service, 2007) (Figure 1). Local precipitation, groundwater base flow, runoff of imported water (State Project water imported from northern California), and recycled water (treated municipal wastewater) derived from imported water are all potential water inputs to SMMNRA watersheds, including the Malibu Creek watershed.

Historically, the Mediterranean climate of the Santa Monica Mountains caused many local streams to flow intermittently (Wood, 1913). Recently, some of these historically intermittent streams have begun to flow perennially (National Parks Conservation Association, 2008). This uncharacteristic continuous flow has often been attributed to inputs of imported water from dry weather urban runoff (City of Calabasas, 2006, 2007; National Parks Conservation Association, 2008; and LVMWD, 2010).

The current continuity of flow is of concern as a potential means of contaminant transport and as a possible facilitator for more extensive spread of exotic, invasive species such as the New Zealand mud snail. New Zealand mud snails (*Potamopyrgus antipodarum*) were found in Malibu Creek in 2006. These snails consume most of the food resources available in the areas that they have inhabited, resulting in reduction of native mollusks and insects and leading to a decline in fish species (National Parks Conservation Association, 2008). Other aquatic invaders include bullfrogs (*Rana catesbeianna*) and the red-eared slider turtle (*Trachemys scripta*). Bullfrogs invade Santa Monica stream habitat and

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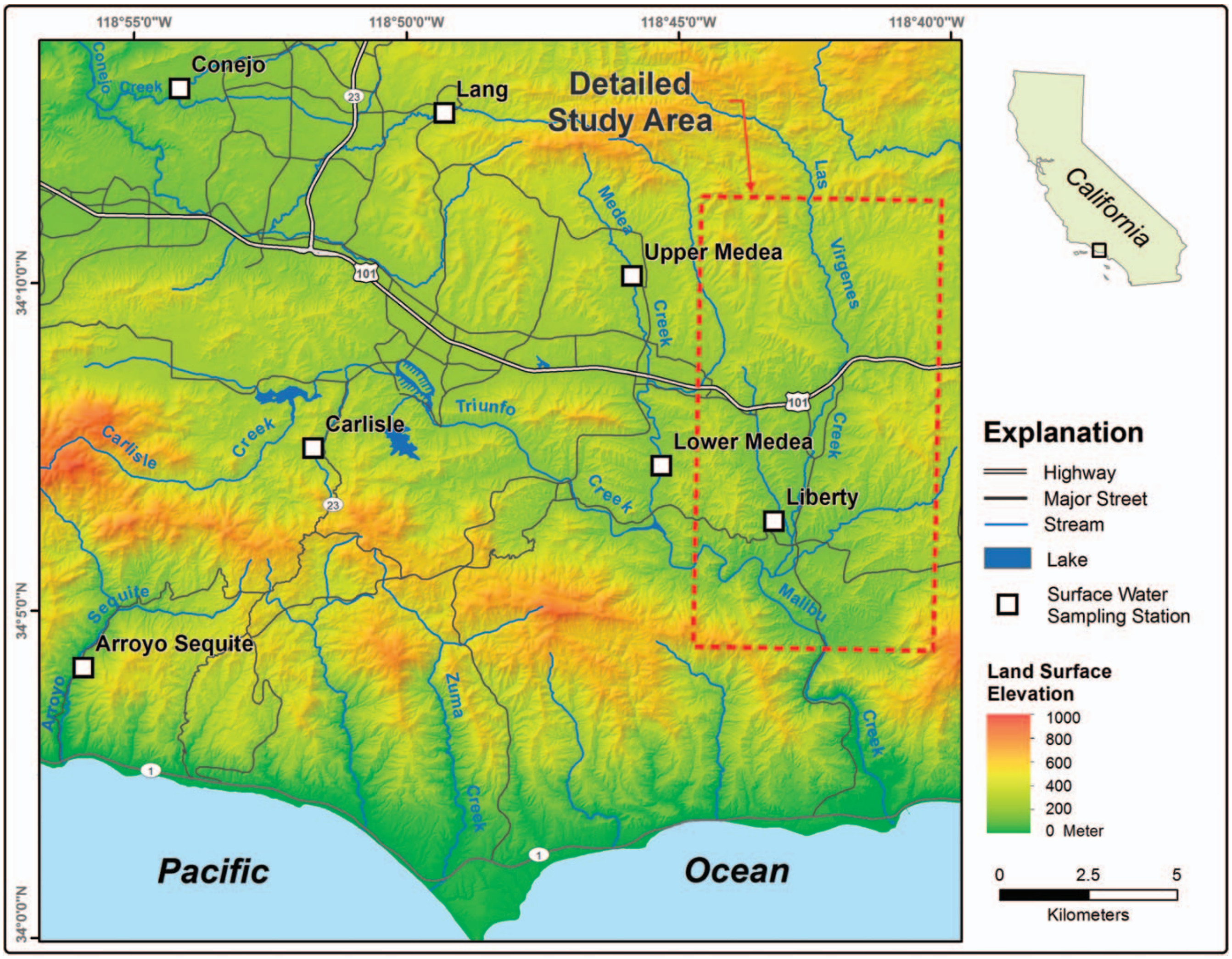

Figure 1. Santa Monica Mountains study area, showing detailed sub-study area in Las Virgenes Creek watershed and sample locations for one-time surface-water reconnaisance sampling.

outcompete native species for resources while preying upon native amphibians. The red-eared slider turtle eats insects and their larvae, bird eggs and chicks (National Parks Conservation Association, 2008). A continuously wetted channel allows these invaders to proliferate and expand into the habitat of species that are well adapted to the natural intermittency and drying cycles of streams in the Santa Monica Mountains. Thus, continuous wetting has impacted the ecology of these streams (National Parks Conservation Association, 2008).

There are also some streams in the SMMNRA that exceed mandated total maximum daily loads for nutrients, trace elements, and other pollutants (U.S. Environmental Protection Agency 2003a, 2003b; City of Calabasas, 2007). Several creeks in the Santa Monica Mountains are listed as impaired under the Clean Water Act, Section 303(d). Policy makers and others have suggested that urban runoff may be a major source of contamination of creeks and streams during dry weather (City of Calabasas, 2006, 2007; National Parks Conservation Association, 2008; and LVMWD, 2010). Most of the information on the transition from intermittent to perennial streams is anecdotal. From a regulatory perspective, identification of source flows is critical to understanding whether continuous flow in SMMNRA streams is a natural phenomenon or an artifact of urban development. Determining whether the source of the added flow is natural or anthropogenic may influence whether certain practices regarding urban runoff and irrigation should be implemented (Law et al., 2004; Milesi et al., 2005). By comparing the geochemical and isotopic signatures of source waters in SMMNRA streams, this study aims to ascertain the relative contributions of source flows.

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Hydrography and Water Use

The Santa Monica Mountains form a 72-km-long, west-trending coastal range that drains south from the Simi Hills (Dibblee, 1982). Elevations are mostly between sea level and 600 m. The climate is Mediterranean, with the rainy season from December to April and the dry season for the remainder of the year. Average yearly rainfall is about 38 cm along the coast and 56 to 68.5 cm along inland ridges (Dale et al., 2009).

There are four major providers of imported water in the SMMNRA: Las Virgenes Municipal Water District (LVMWD), County of Los Angeles Department of Public Works Water District No. 29, Calleguas Municipal Water District, and Hidden Valley Municipal Water District (CDM, 2006). In the study area, the main water purveyor is LVMWD. All drinking water in the SMMNRA/LVMWD study area is imported due to a lack of native supply. Local aquifers are not prolific, and they are too saline to provide adequate supply for municipal and residential use. The California Aqueduct transports imported water from northern California to southern California. The water districts in the SMMNRA purchase the water from the Metropolitan Water District of southern California. By the time the imported water reaches the water districts, it has traveled over 710 km (LVMWD, 2008a, 2008b).

Sewage is treated by the LVMWD at the Tapia Water Reclamation Facility to produce recycled water. The recycled water is used for irrigating golf courses, public landscapes, and other parts of the study area. It contributes 20 percent of the water that the LVMWD provides to municipalities and other consumers (LVMWD, 2008c). It is therefore important to consider as a potential end-member water source.

Study Objectives

Las Virgenes Creek, a tributary to Malibu Creek, was investigated intensively in this study as a demonstration project to establish if dry weather creek flows consist primarily of urban runoff or locally sourced water (Figure 2). Dry weather flows are defined here as streams that are not receiving input directly from precipitation or storm runoff at the time they are sampled, including dry periods in the rainy season (at least 3 days after rain) as well as during the dry season. Data are also presented for a number of other creeks in the Santa Monica Mountains that were sampled on a one-time basis (Figure 1).

Several factors led to the selection of Las Virgenes Creek for demonstration analysis. There is only one perennial tributary flowing into Las Virgenes Creek along the 10 km stream reach we investigated ("unnamed tributary" in Figure 2). This fact reduces noise when studying isotopic variations and trends along the stream reach because tributary streams can create isotopic and hydrochemical variations where they join and mix with the main channel. A second and more important factor relates to the geographic setting. The head waters of Las Virgenes Creek begin in undeveloped wildlands before flowing into a concrete-lined, channelized segment for 5 km through a developed part of the City of Calabasas, which includes several commercial, residential, and industrial areas (Figure 3). After leaving Calabasas, the creek flows through natural open space before its confluence with Liberty Creek at White Oak Farm (Figure 2).

Overview and Geologic Setting of Las Virgenes Creek

Las Virgenes Creek is the largest tributary to Malibu Creek, the second-largest stream flowing into Santa Monica Bay (CDM, 2006). Several water-quality monitoring programs have reported that water quality is impacted as it flows through the City of Calabasas, and the creek is listed as impaired under the Clean Water Act, Section 303(d) (City of Calabasas, 2007). Impairments include nitrate, selenium, and organic enrichment. This creates speculation that these impairments may be due to urban runoff (City of Calabasas, 2006, 2007; National Parks Conservation Association, 2008; and LVMWD, 2010).

The urbanization of Las Virgenes Creek watershed occurred in two stages. Most of the urban area above the 101 Freeway was already developed to present levels by 1976 (Figure 2). By 1994, most of the areas below the 101 Freeway were built out to present density (Owens, 2001). Additional development has taken place sporadically in a few areas since 1994. The area studied in Las Virgenes Creek extends for 10 km from the natural wildlands of Ahmanson Ranch, through urbanized Calabasas, to the natural open space of White Oak Farm (Figure 2). Ahmanson Ranch and White Oak Farm are now state park properties used for outdoor recreation.

Along the first part of this stream reach, Las Virgenes Creek flows across the Modelo Formation and its eroded alluvial valley fill products (Figure 4). The Modelo Formation is a white punky diatomaceous-rich mudstone/turbidite complex of Miocene age (Rumelhart and Ingersoll, 1997). Further downstream, Las Virgenes Creek flows across outcrop of the Tertiary volcanic and intrusive rocks of the Conejo Formation (Figure 4). The Conejo Formation

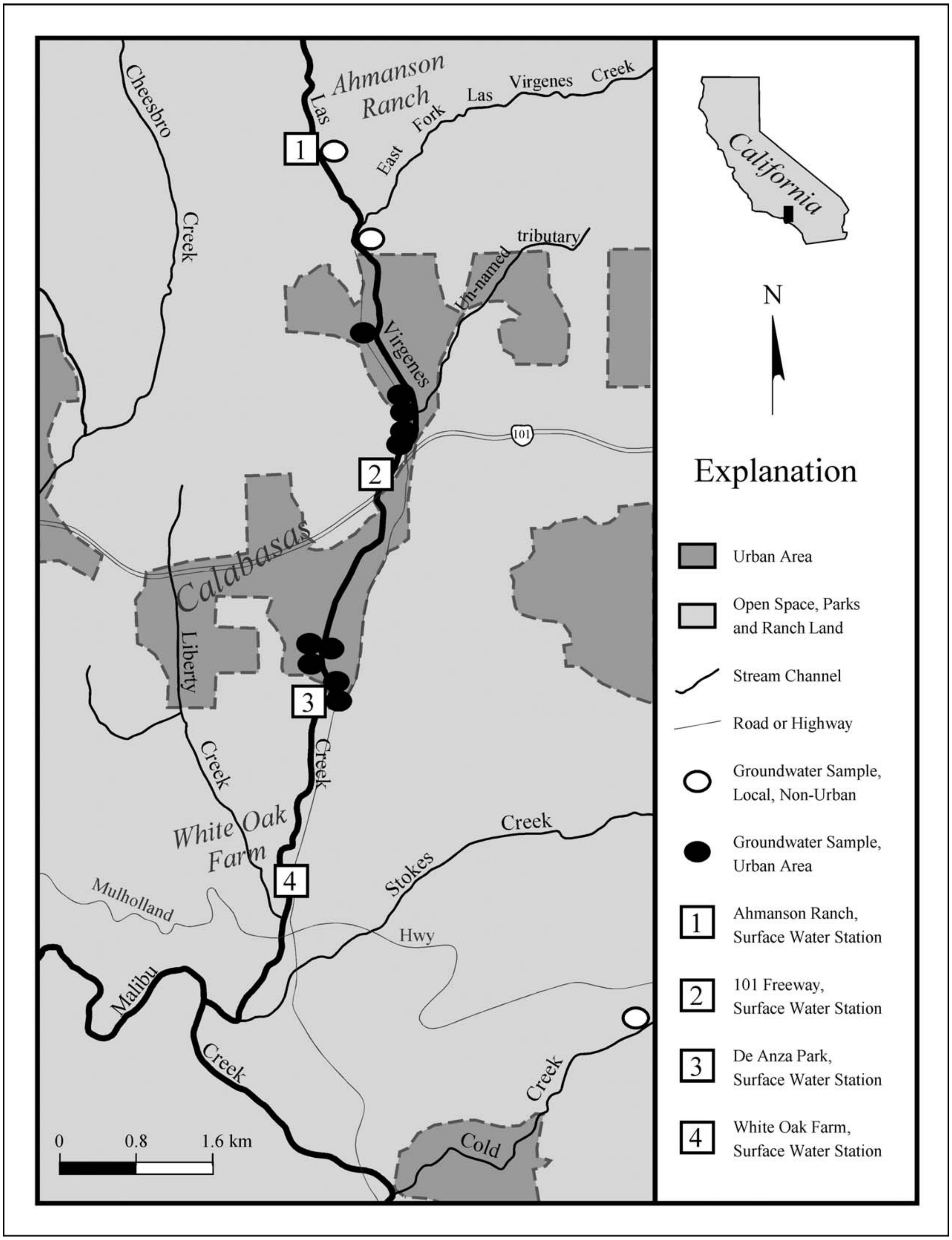

Figure 2. Intensive study region along Las Virgenes Creek, showing surface-water and groundwater sampling locations, urban areas, and open space.

Figure 3. Photographs showing the transition zone between open space and the lined section of Las Virgenes Creek (A) and a weephole in the lined section of Las Virgenes Creek (B).

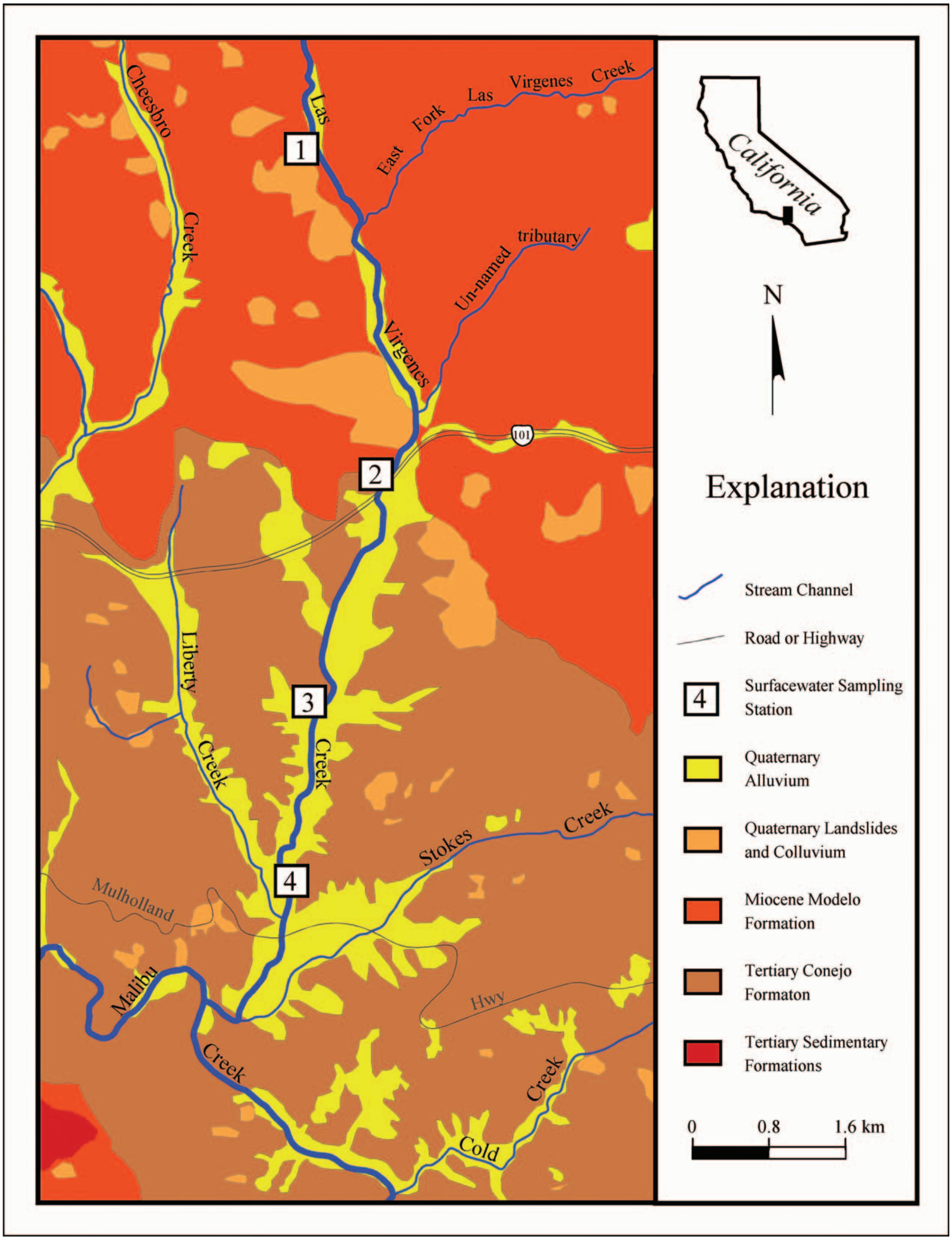

Figure 4. Geologic map for the intensive study region along Las Virgenes Creek (modified from Dibblee, 1992; Yerkes and Campbell, 1993; Yerkes and Showalter, 1993; and Integrated Water Resources, 2006).

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forms the core of the Santa Monica Mountains and underlies a large part of the Malibu Creek watershed (CDM, 2006). Overlying the bedrock formations, there are a series of recent alluvial units formed from the weathering of the regional formations. These include stream deposits, alluvial fan and floodplain deposits, dissected and older alluvial deposits, landslides, and colluviums (CDM, 2006). Stream deposits and floodplain deposits formed by Las Virgenes Creek are of interest to this study because they are in direct hydraulic contact with the creek (Figure 4).

METHODS

Field methods included sampling and measuring flow in surface water (creek flows, urban runoff), groundwater, tap water, and recycled water. Single grab samples were collected in streams at least 200 m below tributaries at locations where channel constrictions and other irregularities helped to ensure that stream water was well mixed. Samples were collected during dry weather conditions to assure that channel flows were not due to surface runoff of precipitation. Prior to collecting samples, Las Virgenes Creek and other creeks were reconnoitered to identify sampling locations for surface water and groundwater. Surface-water sampling stations were selected based on strategic location and accessibility. Groundwater sampling locations were identified during channel reconnaissance, including springs, seeps, and weep-holes in concrete-lined sections (Figures 2 and 3).

All water samples were collected in triple-rinsed polyethylene bottles. Aliquots were separated and preserved for various chemical analyses. Filtration was completed by passing samples through sample-rinsed 0.45 μm filters. Samples collected for analysis of a standard set of anions (chloride, bromide, fluoride, sulfate, and nitrate) were filtered and kept refrigerated below a temperature of 4 °C. For stable isotopes of hydrogen and oxygen in water, an unpreserved sample was collected in a 250 mL polyethylene bottle filled to the rim to ensure no headspace remained in the bottle.

Surface-water discharge measurements were made using a Marsh-McBirney Model 2000 flowmeter and top-setting wading rod following procedures of the U.S. Geological Survey (Buchanan and Somers, 1969; Turnipseed and Sauer, 2010). A straight stream reach characterized by a relatively symmetrical channel cross section and shallow depth of flow was chosen to make discharge measurements. In some cases, stream flow was channeled into an artificially narrow section using sand bags to constrict the width of flow. Based on field conditions and methodology, measured stream discharge was expected to be within 5 percent of the true stream discharge.

Laboratory analysis was performed according to Standard Methods (2005). Anion analysis was conducted by ion chromatography in the Hydrogeology Laboratory at the California State University–Los Angeles. Stable isotope measurements of water (δ^2H, and δ^{18}O) were made at the Laboratory of Isotope Geochemistry at the University of Arizona. The hydrogen and oxygen isotopic compositions of water were determined using a Finnigan Delta-S Isotope Ratio Mass Spectrometer (IRMS) following reduction with Cr (Gehre et al., 1996) and CO_2 equilibration (Craig, 1961a, 1961b). Results are expressed as δ^2H and δ^{18}O in per mil (‰) relative to the standard Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1978) with analytical precisions of 0.9‰ and 0.08‰, respectively.

Sampling of groundwater and channel flow in Las Virgenes Creek watershed was done initially in February 2007, followed by end-member sampling of tap water, urban runoff, and recycled water from February 2007 to April 2007. This was a record drought period in southern California, and little precipitation fell in the study area during these months (2.0 cm in February, 0.0 cm in March, 3.1 cm in April, 0.0 cm in May 2007). Though we do not have irrigation records, we assume urban irrigation was much higher than usual during this unusually dry period. Time-series sampling of two Las Virgenes Creek stations, tap water, and recycled water was subsequently carried out from February 2008 to April 2009. Only 34.5 cm of precipitation fell during this period, including 13.3 cm during February 2009 alone. One-time reconnaissance sampling of other creeks was done from October 2008 to December 2008. Precipitation was 0.02 cm during October 2008, 6.2 cm during November 2008, and 6.8 cm during December 2008. Most sampling was done at least 2 weeks after any rainfall event, and at least 3 days passed after rainfall before any sample was collected. When multiple stations were sampled in a stream, all samples in the stream were collected on the same day.

RESULTS AND ANALYSIS

Stream Reconnaissance and Discharge in Las Virgenes Creek

Stream reconnaissance in February 2007 revealed a number of groundwater sampling points in Las Virgenes Creek, including springs, seeps, and weep-holes (Figures 2 and 3). Most of the groundwater sampling points were located along the urban reach,

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although a few springs were found in the undeveloped segments of Las Virgenes Creek above and below the City of Calabasas. The presence of many springs indicates that the water table is above stream stage and that gaining stream conditions exist.

Surface-water sampling stations selected for data collection included one station in the undeveloped area above Calabasas, two stations in the urban stream reach, and one station at White Oak Farm (Figure 2). Discharge rates increased from 0.0048 m^3/s at Las Virgenes Creek Station 1, to 0.035 m^3/s at De Anza Park Station 3, to 0.039 m^3/s at White Oak Farm Station 4. Most of the contribution to surface flows is derived along the urban stream reach. The East Fork of Las Virgenes Creek was not flowing into Las Virgenes Creek during the sampling period. The unnamed tributary contributed only 0.0019 m^3/s to surface flows at its confluence with Las Virgenes Creek; therefore, most of the flow in Las Virgenes Creek was derived directly from urban runoff and groundwater discharge. This sets up conditions favorable for the analysis of the proportional contribution of source flows in Las Virgenes Creek.

Standard Inorganic Constituents and Source Flows

Sulfate and chloride data proved to be the most useful anions in distinguishing among groundwater, surface water, tap water, and recycled water. Bromide was not as useful because bromide concentration did not vary significantly in end-member waters. Sulfate and chloride were conservative under the oxic to sub-oxic conditions usually observed in shallow groundwater and surface water in the study area, based on dissolved oxygen concentrations that usually ranged from 0.3 to 10 mg/L. Scatter plots of sulfate and chloride indicate that tap water, recycled water, and dry weather urban runoff were much more dilute than shallow groundwater feeding into Las Virgenes Creek (Figure 5). Groundwater had very high concentrations of sulfate, which is due to the dissolution of sulfur-bearing minerals, probably pyrite, in Modelo Formation strata and its weathered alluvial residuals. The saline signature of groundwater distinguishes it from imported tap water, recycled water, and urban runoff.

Surface water collected from Las Virgenes Creek plots mostly within the region defined by groundwater composition (Figure 5). One sample collected at the furthest upstream site at Ahmanson Ranch (Station 1) plots slightly outside the groundwater-defined region. This first sample at Las Virgenes Creek is located in open space where imported water is not used. It cannot have anything other than local groundwater base flow as its source. Surface water shows a gradual enrichment in sulfate from upstream (Station 1) to downstream (Station 4), matching general trends observed in groundwater. There may be a down-valley enrichment in sulfate in the Las Virgenes Creek aquifer due to mineral dissolution if groundwater moves axially down the alluvial valley before discharging into Las Virgenes Creek.

Despite accumulating flows in Las Virgenes Creek in the City of Calabasas, the sulfate/chloride scatter plots indicate that surface water is demonstrably from groundwater base flow and not from urban runoff (Figure 6). While the dominant source of flow is base flow, it is unknown the extent to which the groundwaters in the local aquifers that are connected to Las Virgenes Creek were derived from local precipitation versus percolation of imported water applied to urban landscapes (Figure 6). If imported water is recharging the aquifer, then a change from intermittent to perennial creek flow could simply be an artifact of increased recharge to shallow aquifers feeding into Las Virgenes Creek, due to use of imported water for irrigation of urban landscapes. Analysis of the composition of inorganic constituents is insufficient to differentiate recharge sources to the shallow aquifers. Other hydrogeologic tracers are needed to identify source waters replenishing shallow groundwater near Las Virgenes Creek.

Stable Isotopes Investigations—End-Member Waters, Surface Water, and Groundwater

The stable O-H isotopes of water described in this section help to determine the source of recharge to shallow groundwater and determine sources of water in Las Virgenes Creek. LVMWD tap water, recycled water, and local groundwater are reliable end members representing distinct water types (Figures 7 and 8). Previous studies have identified the stable O-H isotopic signatures of California State Project water imported to the Los Angeles Basin from northern California (USGS, 2003). By the time waters arrive at the Los Angeles Basin, State Project water ranges somewhat narrowly about a mean of $-9.5‰$ $\delta^{18}O$ and $-75‰$ δ^2H (USGS, 2003) (Figures 7 and 8).

State Project waters sampled in Las Virgenes Creek watershed plot within the range of isotopic signatures shown previously by the USGS (USGS, 2003) (Figures 7 and 8). Recycled water delivered by LVMWD ranges narrowly about a mean of $-8.3‰$ $\delta^{18}O$ and $-67‰$ δ^2H (Figures 7 and 8). Urban runoff samples plot within the range of tap water and recycled water, indicating little isotopic change after application of imported water to urban landscapes. Local groundwaters from three reference springs at or near Las Virgenes Creek had constant signatures of

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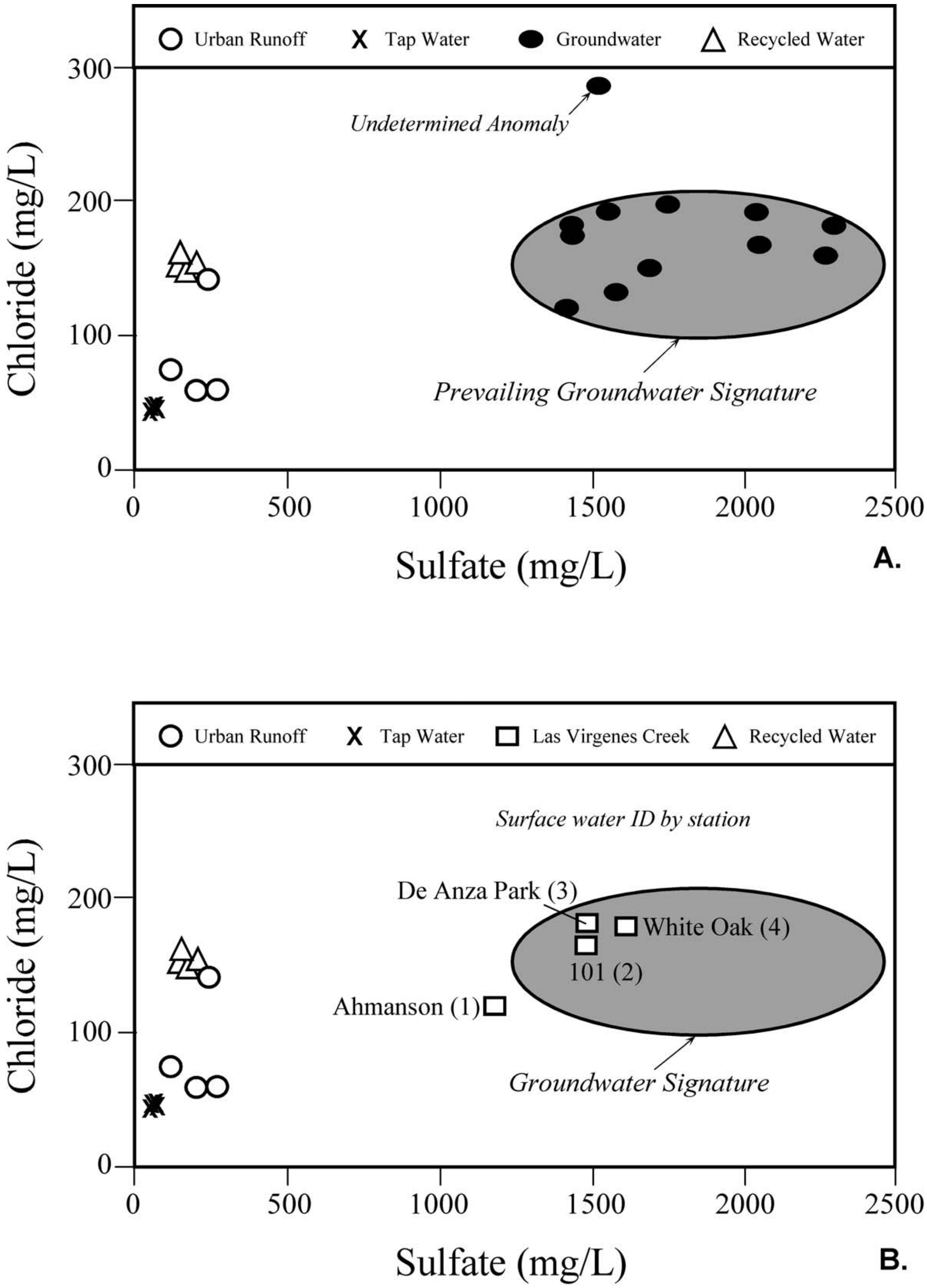

Figure 5. Chloride/sulfate scatter plot for urban runoff, tap water, recycled water, shallow groundwater (A), and surface water (B) collected in Las Virgenes Creek watershed. Surface water (Las Virgenes Creek samples identified by stations) plots primarily within the range of groundwater composition.

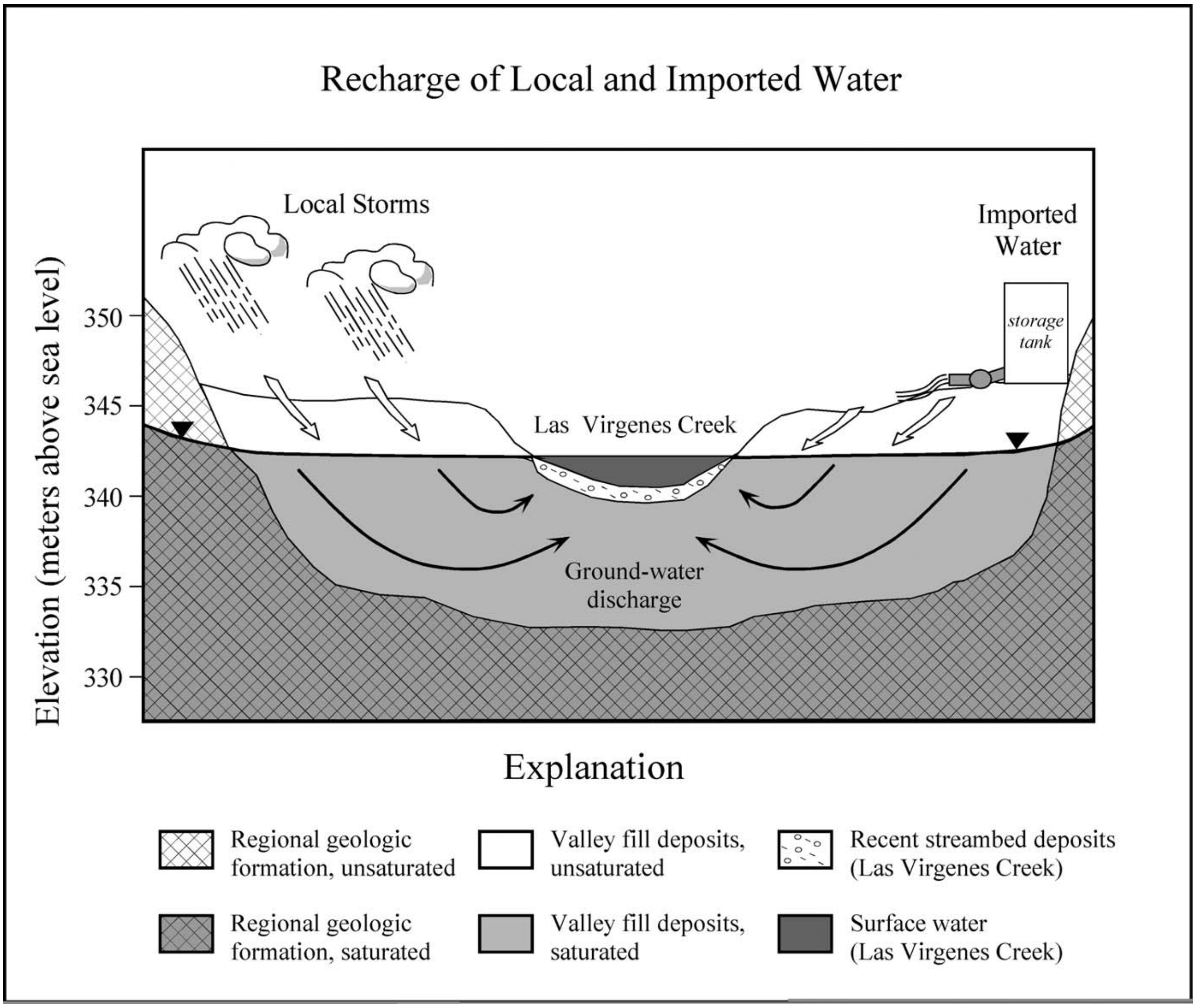

Figure 6. Conceptual diagram showing recharge by local precipitaton to shallow aquifers connected to Las Virgenes Creek. Shallow aquifers may also be recharged by imported water applied to urban landscapes or by exfiltration from leaky water and sewer pipes.

about −5.7‰ δ^{18}O and −43‰ δ^{2}H (Figures 7 and 8). Local isotopic values are consistent with mean isotopic values recorded for precipitation in the Los Angeles Basin (Rozanski et al., 1993; Clark and Fritz, 1997).

When the imported water data are plotted, the isotopic shift of recycled water along the mixing line between tap water and local reference water is interpreted to be due to the infiltration of shallow groundwater into sewer pipes through cracks and other openings in pipes, which occurs where sewer pipes penetrate the water table (Pettygrove and Asano, 1984; Ellis, 2001). A small amount of evaporation may have occurred at the sewage treatment plant, accounting for a smaller part of the isotopic shift between tap water and recycled water (Figures 7 and 8).

Groundwater samples collected at or below the developed reach of Las Virgenes Creek plot along the mixing line between imported waters (both tap water and recycled water) and local reference groundwater (Figure 7). We believe that tap water is a more reliable end member because it applies to the fractional contribution of imported water in the watershed due to controlled use of recycled water. Tap water runs off urban areas freely due to activities such as car washing and unintentional overspill from residential lawn watering. Greater care is taken by water districts and municipalities to ensure that recycled irrigation systems are less susceptible to

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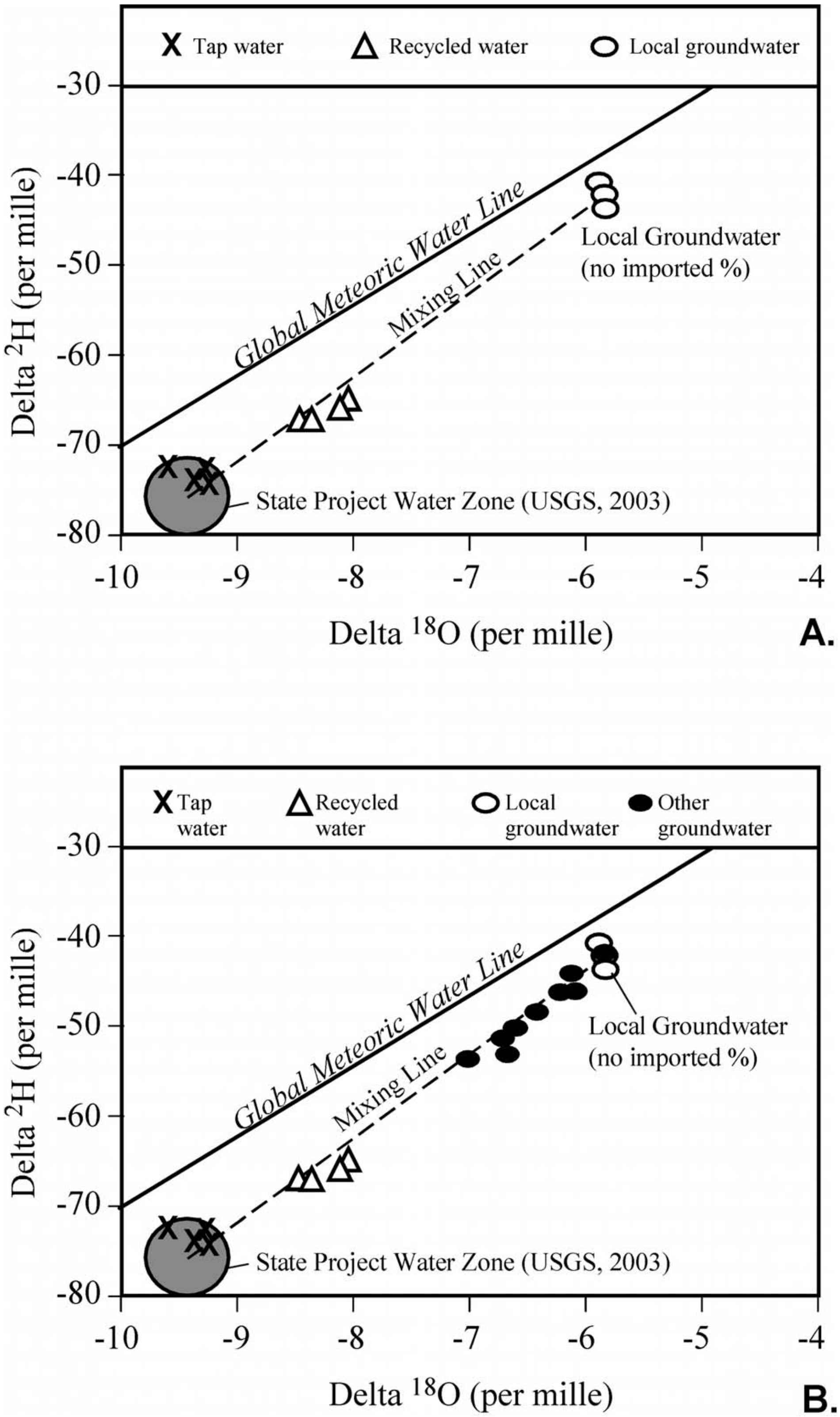

Figure 7. Stable isotope plot for tap water, recycled water, locally derived groundwater (A), and other groundwater (B) in Las Virgenes Creek watershed from 2007.

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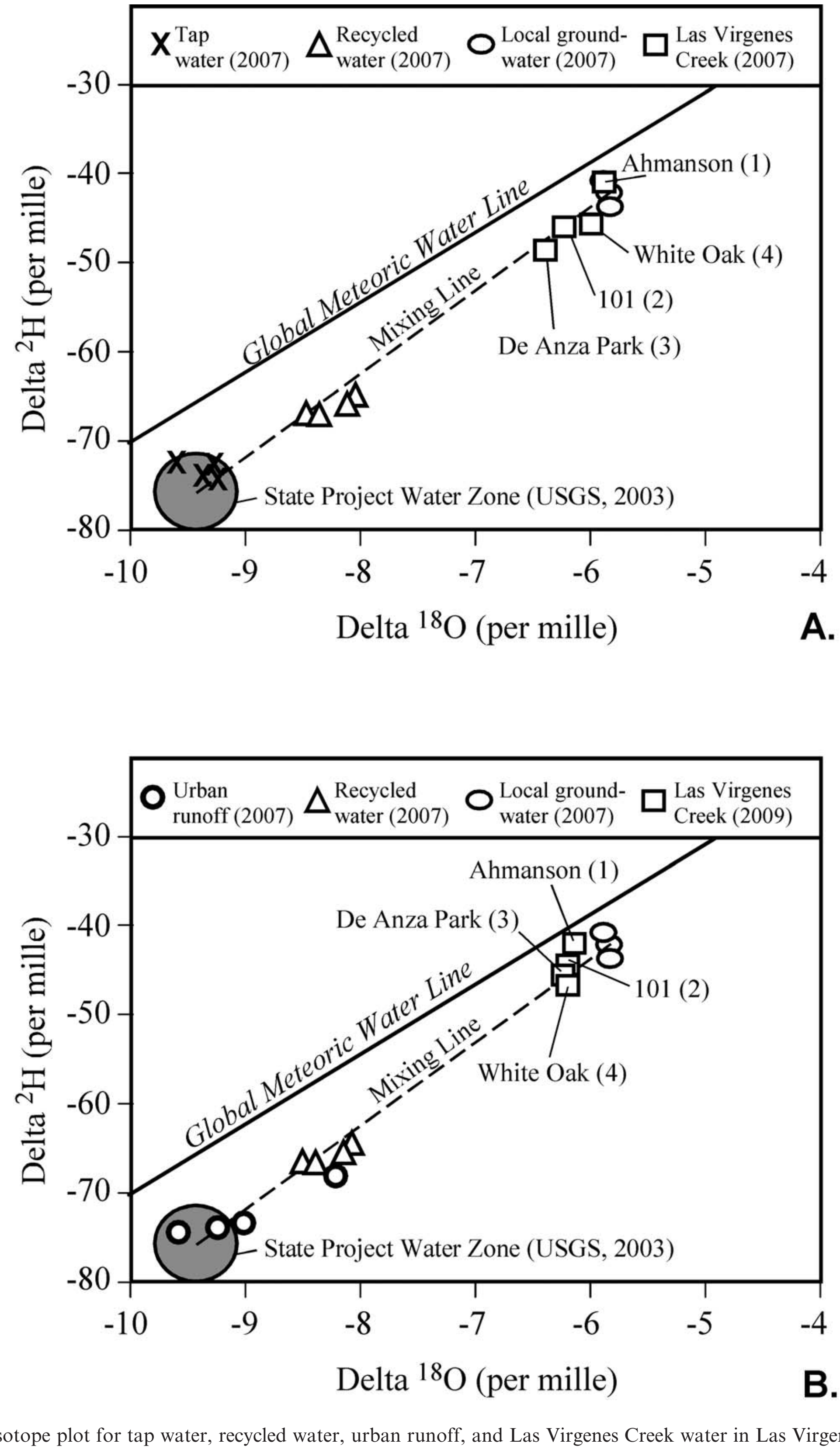

Figure 8. Stable isotope plot for tap water, recycled water, urban runoff, and Las Virgenes Creek water in Las Virgenes Creek watershed from 2007 (A), and repeat results for surface water sampled in Las Virgenes Creek in 2009 (B).

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runoff losses in urban catchments. Watering appurtenances for recycled water application are usually well maintained in California due to regulatory concerns about ecological impacts of emerging contaminants in recycled water.

Regardless of the source, tap or recycled waters, these results clearly establish that imported water is recharging the shallow aquifer connected to Las Virgenes Creek (Figure 7). The groundwater data are biased because most of the groundwater samples were collected from the urban reach of Las Virgenes Creek (Figures 2 and 3). Imported water is applied heavily in the city, so it is not surprising to see some imported water in shallow groundwater.

Shallow aquifers are clearly influenced by recharge from imported water in urban areas. Even so, data plotted for surface waters collected in February 2007 show that Las Virgenes Creek contains mostly locally derived water (Figure 8). The percentage of imported water increases slightly in Las Virgenes Creek between Ahmanson Ranch (Station 1) and De Anza Park (Station 3). De Anza Park is at the lower limit of the urban stream reach in Las Virgenes Creek (Figure 2). The percentage of imported water declines in the open space lands between De Anza Park and White Oak Farm (Station 4). These patterns indicate that Las Virgenes Creek was fed mostly by locally derived water during the 2007 sampling event, with no sample containing more than about 15 percent imported water (Figure 8).

Surface water was resampled in Las Virgenes Creek in late March 2009 to allow comparisons to results obtained in 2007 (Figure 8). Ahmanson Ranch (Station 1) showed a very minor shift and became isotopically lighter in 2009 (Figure 8). Ahmanson Ranch is a control station that is not fed by imported water. The shift at Ahmanson must reflect a natural shift of the isotopic signature of recharge waters and base flow, perhaps due to the "Pineapple Express" frontal systems that occasionally affect southern California (Hu, 2010). Other stations showed nominal changes of isotopic values at downstream stations since 2007; all stations contained a predominantly local water signature at and below the urban stream reach (Figure 8).

Need for Further Study: Time-Series Analysis of Stable O-H Isotopes

The results presented thus far establish the following: (1) Surface-water discharge increases mostly along the urban stream reach (established from discharge measurements); (2) groundwater base flow, and not urban runoff, accounts for most of the dry weather flows in Las Virgenes Creek (established by chloride/sulfate data); (3) shallow aquifers connected to Las Virgenes Creek have been recharged in urban areas by some imported water (established by stable O-H isotopes); and (4) some imported water is detected in Las Virgenes Creek, but most of the flow in the creek comes from locally derived groundwater (established by stable O-H isotopes). These findings are limited because sampling was done during a limited interval of time. Further studies were needed to examine source flows to Las Virgenes Creek over a longer time period.

Additional work focused on analyzing seasonal effects and longer-term trends in isotopic signatures of Las Virgenes Creek. Creek samples were collected from February 2008 to April 2009. Samples were collected at Ahmanson Ranch (Station 1) and White Oak Farm (Station 4) to analyze the spatial difference in stream flows between the upper and lower limits of the study area. Recycled water and tap water were sampled concurrently.

Throughout this period, isotopic signatures of LVMWD tap water and recycled water continued to remain relatively constant and distinct (Figure 9). With few exceptions, creek samples from Ahmanson Ranch and White Oak Farm varied little over time. One noticeable anomaly occurred in late 2008, when the sample collected at White Oak Farm was isotopically heavier than the sample collected at Ahmanson Ranch. This anomaly was possibly due to mixing from inflow from an ephemeral tributary below Ahmanson Ranch (Figure 9). None of the samples collected from Las Virgenes Creek plots close to either tap water or recycled water. The isotopic signatures of samples from Ahmanson Ranch are only slightly heavier than those of samples from White Oak Farm. The slight depletion in Las Virgenes Creek's isotopic signature between Ahmanson Ranch and White Oak Farm may be attributed to the input of a small amount of imported water. Most input to Las Virgenes Creek comes from locally derived groundwater over time (Figures 6 and 9).

Regional Sampling

Reconnaissance sampling was carried out once in Santa Monica Mountain streams to determine the possible sources of water in streams over a broader area (Figure 1). Samples were collected from October 2008 to December 2008. A few minor rain events occurred during this period, but at least 3 days passed after a rainfall event before any samples were collected. All stations were selected within or below urban or developed stream reaches to increase the chance that imported water would be a source of stream flow.

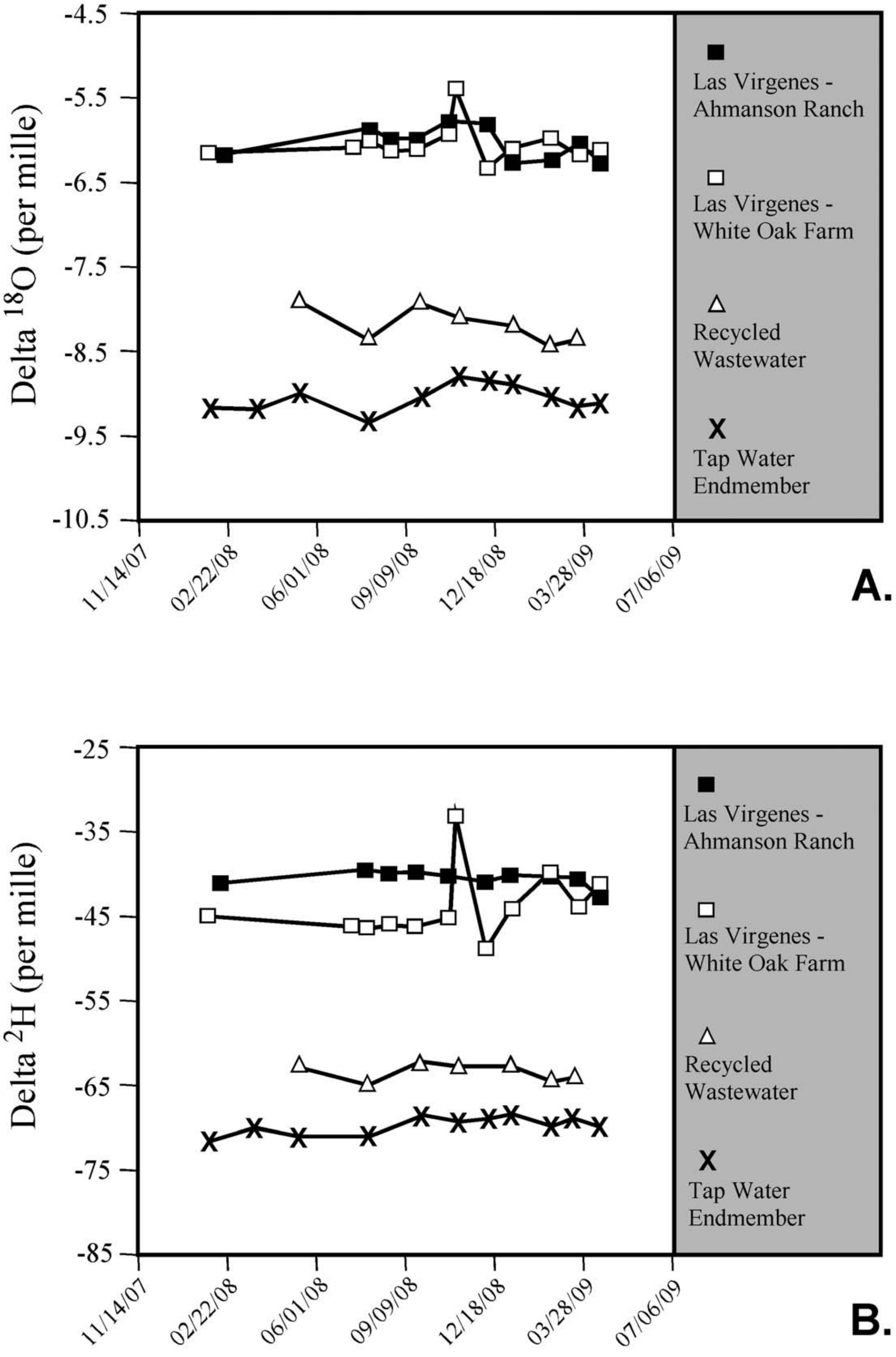

Figure 9. The $\delta^{18}O$ (A) and $\delta^{2}H$ (B) values of Las Virgenes Creek samples, tap water, and recycled water in time series from February 2008 through April 2009 showing similar isotopic values at upstream and downstream locations in the creek.

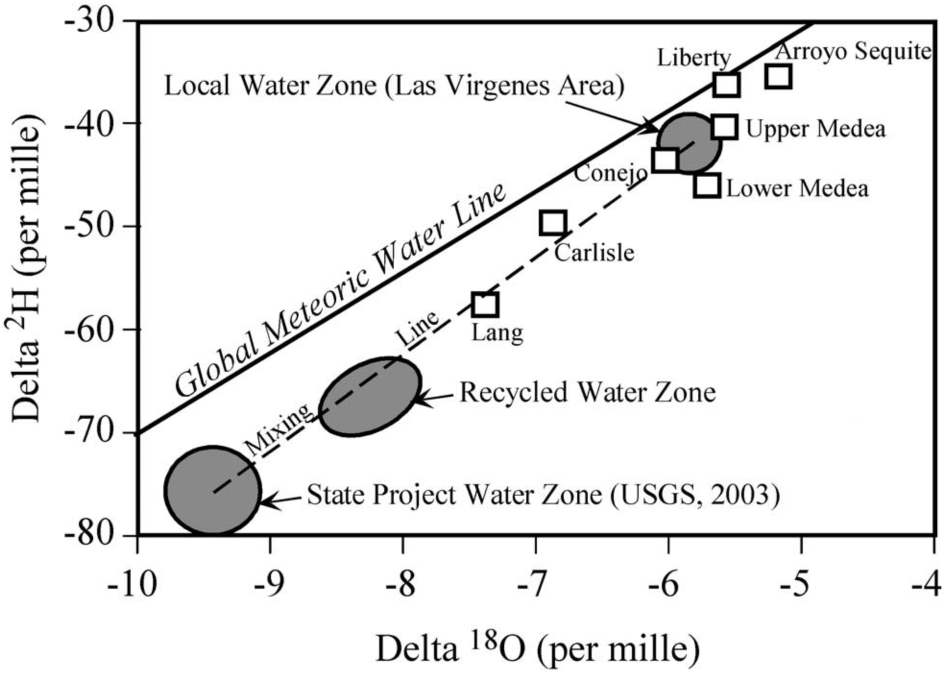

Figure 10. Stable isotope plot comparing data for other creeks in the Santa Monica Mountains with end-member waters detected in Las Virgenes Creek watershed (creek locations shown in Figure 1).

Sampling was done in Carlisle Creek, Arroyo Sequite, Liberty Creek, Medea Creek, Conejo Creek, and Lang Creek (Figure 1). The origin of Carlisle Creek is a few hundred meters higher than Las Virgenes Creek. Arroyo Sequite is located coastward of the mountain ranges separating Las Virgenes Creek watershed from the Pacific Ocean and is a few hundred meters lower than Las Virgenes Creek. Liberty Creek, Medea Creek, Conejo Creek, and Lang Creek have sources at elevations close to those at Las Virgenes Creek. Proximal creeks at the same elevation might have local isotopic signatures that are similar to Las Virgenes Creek, while creeks at other elevations may have different local isotopic signatures due to fractionation processes associated with rainout at different altitudes (Mazor, 1991; Clark and Fritz, 1997). Recycled water is used in the Medea Creek and Liberty Creek drainages only. Drainage areas feeding the other creeks do not use recycled water in urban landscapes.

All samples except Arroyo Sequite, Carlisle Creek, and Lang Creek plot in regions that are characteristic of the locally derived water defined in Las Virgenes Creek (Figure 10). Little or no imported water appears at Arroyo Sequite. Arroyo Sequite is isotopically enriched relative to the other samples, probably due to its location in a coastward area of low elevation. Arroyo Sequite probably contains isotopically heavier water due to rainout of heavy water molecules during rising frontal systems passing over the coastal mountains toward Las Virgenes Creek (Clark et al., 1982).

Carlisle Creek is isotopically depleted relative to other samples. Carlisle Creek's source is at an elevation higher than Las Virgenes Creek, which increases the chances that this sample might be isotopically lighter due to prior rainout of heavier water molecules in precipitation that eventually fell in Carlisle Creek watershed (Mazor, 1991; Clark and Fritz, 1997). Aside from elevation effects, the lighter isotopic composition of Carlisle Creek could also result from imported water runoff. Lang Creek appears to show a clear component of imported water, approximately 50 percent (Figure 10).

Reconnaissance sampling in creeks and streams suggests that most other catchments in the Santa Monica Mountains, except Lang Creek, are fed predominantly by local water at a moment in time. These individual data points establish a launch point for further study. Spatial studies, for example, are needed to determine if isotopic changes in Santa Monica Mountain creeks occur at upstream and downstream sampling sites. Sampling in time may show variances in isotopic signatures seasonally, especially during the summer, when urban runoff might peak. Studies are also needed to determine the isotopic and hydrochemical signatures of groundwater seeps and springs feeding into other creeks. This

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information will help to determine if groundwater is recharged by local water primarily, or by infiltration of imported water.

DISCUSSION

Study results show that Las Virgenes Creek receives little urban runoff during dry weather conditions. The data suggest that other factors must account for the transition from intermittent to perennial flows. In most instances, stream water samples collected during this study have isotopic signatures nearer to those of locally derived groundwaters than of imported waters. On occasions where the isotopic signatures of stream samples are unusually light in contrast to local waters defined in Las Virgenes Creek, isotopically depleted precipitation at higher elevations can sometimes be an alternate explanation instead of input of imported water. Las Virgenes Creek flows through urban areas, which results in Las Virgenes Creek receiving some imported water, albeit a surprisingly small amount—usually less than 10 percent based on isotopic analysis.

Stable water isotopes and sulfate/chloride data do not support the hypothesis that the transition from intermittent to continuous flow results primarily from direct inputs of urban runoff to Las Virgenes Creek during dry weather conditions. For the most part, stream water samples do not have light isotopic signatures and dilute hydrochemical signatures, as imported waters do.

Alternative hypotheses must be considered. Continuous flow in Las Virgenes Creek may result from alteration of the channel for flood control and channel stabilization. Lining channels with concrete eliminates vegetation growth. The removal of riparian vegetation prevents plant uptake and evapotranspiration of water; riparian plants in fact acted as groundwater pumps until they were removed. To a great extent, loss by plant uptake may explain intermittent flows in pre-development times. Groundwater that formerly might have been consumed by riparian plants during the dry season seeps through cracks in the concrete lining of Las Virgenes Creek (Figure 3). In the absence of extensive riparian vegetation, groundwater base flow increases locally along urban channels and serves as the primary source of continuous flow rather than imported water runoff.

This study shows that shallow aquifers feeding Las Virgenes Creek are receiving recharge from imported water sources (Figure 6). It is unknown the extent to which this is from irrigation on urban landscapes or from leaky water pipes. Additional recharge from imported waters may increase hydraulic head in the shallow aquifer locally, driving more base flow into Las Virgenes Creek. At the time of this study, the data did not show much input of imported water to Las Virgenes Creek, but that could change with time. The urban areas along Las Virgenes Creek were developed only a few decades ago, and the hydrology and chemistry of the aquifer may still be evolving in response to the removal of native vegetation and recharge by imported water.

Few streams in the Santa Monica Mountains receive recycled water directly from sewage treatment plants, but there are a couple of exceptions. The largest treatment facility, the Tapia Wastewater Treatment Plant, treats about 38,000 m^3 (10 million gallons) of wastewater per day. Most of the water recycled at the plant is used to irrigate urban landscapes. Additional recycled water from the plant is discharged seasonally into Malibu Creek, as regulated by the Los Angeles Regional Water Quality Control Board. There is a spike in the amount of imported water in Malibu Creek when there are sewage outflows in the creek (Hu, 2010). In most of the streams in the Santa Monica Mountains, however, imported water comes only from residential and municipal watering of urban landscapes, and from ancillary flows such as from residential car washing and open fire hydrants.

CONCLUSIONS

This study provides key insights on source flows along a major urban corridor in the Santa Monica Mountains while raising doubt about perennial flows in streams as a result of additive flow due to urban runoff. Stream flows have increased more as a result of urban development through a combination of channelization, removal of riparian vegetation, and recharge of imported water. Critical policy questions will be raised if additional study shows similar results in other creeks. In particular, controls on urban runoff with on-site retention systems are not very likely to allow for the return to intermittent flows in streams. Restoring the urban stream to a vegetated riparian zone might return the stream to natural intermittent flow. Furthermore, suggestions that urban runoff is the main source of nutrient loading to Las Virgenes Creek are overstated. Concurrent studies have shown that nutrients in Las Virgenes Creek primarily originate from nitrate-laden groundwater base flow during dry weather conditions (Hibbs et al., 2009).

Further work is needed in several areas. Streams and creeks in the Santa Monica Mountains must be sampled more intensively for isotopes and hydrochemical parameters. Time-series analysis at a num-

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ber of spatial stations, combined with analysis of end-member waters of both local and imported sources, will provide abundant insights on source flows in streams and creeks. The importance of characterizing local end-member waters in individual creeks cannot be overemphasized, because elevation changes across the watersheds in the Santa Monica Mountains create differences in local isotopic signatures. A great deal of effort should be devoted to sampling stream-feeding groundwaters along wildlands and urban corridors alike. Urban runoff, tap water, and recycled water should be sampled concurrently with surface water and groundwater.

Once the data are collected and analyzed, it should be possible to provide interpretations and recommendations comparable to those provided for Las Virgenes Creek. Policy makers and managers will then be better equipped to evaluate and protect stream ecosystem health. Identification of source flows is a key factor from a regulatory perspective. Fortunately, the isotopic contrasts between imported and local waters in the Santa Monica Mountains provide a means by which we can understand flow in SMMNRA streams, as either a natural phenomenon or as an artifact of urban development.

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