We present a set of maps showing the distribution of oxygen and hydrogen isotope values, relative to the VSMOW standard, for the nation of Costa Rica. These maps utilize data from this study (51 new data points; 21 wells, 16 rivers, 14 springs) and data from previous workers (51 data points for rivers, Lachniet and Patterson, 2002; 13 data points for springs, Darling et al., 1989). Computer generated spherical kriging with a 12-point variable was used to produce interpolated isotope contours for each map. An altitude effect of 1.5 to 3 per mil was observed locally, with a superimposed decrease in $\delta^{18}O$ with decreasing latitude for low elevation locations. Additional work along the northern border with Nicaragua, in the northern Nicoya Peninsula, and the southern Cordillera de Talamanca will be required to produce a more complete map. Potential collaborators wishing to provide samples or data from these areas should contact the authors. This map will be updated as new data is added, and posted on the internet at http://wri.csusb.edu/.
INTRODUCTION

Stable isotope data for groundwater are important for understanding groundwater flow, surface-groundwater interaction, spring and groundwater recharge, and for interpretation of paleoclimate information. Oxygen and hydrogen isotope data for groundwater in Central America, and studies which examine stable isotope distribution in the tropics are scarce (e.g., Payne and Yurtsever, 1974; Darling et al., 1989; Salati et al., 1979; Gonfiantini et al., 1976; Longinelli and Edmond, 1983; Gat and Matsui, 1991; Njitchoua et al., 1999; Lachniet and Patterson, 2002; Lachniet and Patterson, 2006; Poveda et al., 2006). Studies in Costa Rica have focused dominantly upon water as a resource (e.g., Sanabria, 2001), surface waters (Lachniet and Patterson, 2002, Lachniet et al., 2007), or hydrothermally modified waters from volcanic aquifers (Darling et al., 1989; Pringle et al., 1990; Pringle, 1991; Genereux and Pringle, 1997; Birkle and Bundschuh, 2007). This lack of data for stable isotope distribution of groundwaters in Costa Rica has restricted their use in both groundwater and paleoclimate studies.

Precipitation

Limited stable isotope data on precipitation are available for Costa Rica (e.g., IAEA/WMO, 1998; Lachniet and Patterson, 2002). Shortcomings of these data include spatial bias to northwestern Costa Rica, limited temporal spread dominated by the period 1990-3, and limited accompanying data for temperature and precipitation amount. However, the data demonstrate that isotope values of precipitation yield a water line equation ($\delta D = 7.8 \times \delta^{18}O + 7.9$; Lachniet and Patterson, 2002) that is similar to the global meteoric water line ($\delta D = 8 \times \delta^{18}O + 10$; Craig, 1961), and that precipitation is seasonably variable (Lachniet and Patterson, 2002). Correlation of these data with elevation for the Caribbean slope and central highlands of Costa Rica indicates a $\delta^{18}O$ value decrease of $–1.9‰$ per kilometer of elevation (Lachniet and Patterson, 2002), which is comparable to values reported elsewhere in the tropics and North America (e.g., Payne and Yurtsever, 1974; Rozanski et al., 1993; Rose et al., 1996; Melchiorre et al., 1999).

Surface Waters

Stable isotope data for surface waters of Costa Rica are available in Darling et al. (1989), and Lachniet and Patterson (2002). The nine isotope analyses of river water presented in Darling et al. (1989) provide only generalized sampling locations (e.g., “Rio Seca”), and are from areas where volcanic-related hydrothermal activity may significantly modify waters. Of the 63 river and lake samples reported in Lachniet and Patterson (2002), 12 are from lakes or marshes where evaporative modification may have altered isotope values. Despite these shortcomings and limited coverage in some parts of Costa Rica, Lachniet and Patterson (2002) present reliable and detailed $\delta^{18}O$ and $\delta D$ maps of surface waters.

Volcanic Aquifers and Geothermal Waters

There is evidence that groundwater in portions of the Costa Rican Valle Central receive a significant quantity of recharge from a hydrothermally altered source, based upon positive $\delta^{18}O$ deviation from the local meteoric water line and deviation from local $\delta^{18}O$ vs. elevation relations (Darling et al., 1989). Additionally, geochemical studies suggest that some groundwater of the Costa Rican Caribbean slope contain locally significant quantities of geothermally modified waters (Pringle et al., 1990; Pringle, 1991; Genereux and Pringle, 1997). The isotope values of these modified waters are interpreted in this study as not representative of meteoric groundwater.
Objectives of this Study

We examine the $\delta^{18}O$ and $\delta D$ values of springs, wells, and gaining (baseflow-fed) rivers to produce maps that show the observed spatial distribution of stable isotope values for Costa Rican groundwater. We also examine the $\delta^{18}O$ vs. elevation gradient in both the Caribbean Monte Verde area and Pacific Osa Peninsula. The isotope values of meteoric water, surface runoff, shallow recharge springs, and geothermal waters are beyond the scope of this study and therefore not presented in this paper. These maps are intended to assist with future paleoclimate, volcanology, and hydrology studies in Costa Rica.

METHODS

Our river sampling focused upon sections believed to represent gaining, or groundwater base-flow fed rivers. Abrupt temperature change and/or upwelling flow indicative of significant localized base flow recharge were used as qualitative indicators for the identification of such sections. Water samples for isotope analysis were collected in a borosilicate glass bottle with a polyseal cap. Water samples were prepared for isotope analyses using the standard CO$_2$ equilibration method for oxygen isotopes (Epstein and Mayeda 1953), and by hydrogen gas equilibration for hydrogen isotopes (e.g., Horita, 1988). Isotope values were measured using an automated sample equilibrator interfaced with a Finnigan Delta Plus Advantage gas ratio mass spectrometer at California State University, San Bernardino. Results are reported in the usual d notation relative to Vienna Standard Mean Ocean Water (VSMOW) (Coplen 1995). Laboratory precision is ±0.08‰ for oxygen and ±1.2‰ for hydrogen isotope values, based on duplicate analyses of internal laboratory standards. Eight waters where both the $\delta^{18}O$ and $\delta D$ values plot significantly off the global meteoric water line (Craig, 1961), and possessing unusual chemistry such as extremely elevated TDS were assumed to be modified (e.g., anthropogenic, hydrothermal) and were not used in this study.

The isotope maps were generated using available data for groundwater, springs, and rivers with a significant groundwater base flow component. Interpolated contouring of this data using ARC-INFO Geographic Information Software was performed using spherical kriging, with a 12-point variable. This method and attendant conditions are described in McBratney and Webster (1986). Variance was calculated using the average variance of all point pairs within each interval of the cell size. This variogram is then automatically fit to the variance points using the Levenberg-Marquardt Method (Press et al., 1986) of nonlinear least squares approximation.

RESULTS AND DISCUSSION

We collected and analyzed water from 21 wells, 16 gaining rivers, and 14 springs at elevations ranging from 10 to 2994 meters above sea level (Figure 1, Table 1). Measured $\delta^{18}O$ values of waters range from –12.9 to –3.2‰ while $\delta D$ values range from –84 to –14‰.

This study also utilizes isotope data for 51 rivers presented in Lachniet and Patterson (2002). The degree of base flow at sampling points for these rivers could not be determined for many locations. However, the general consistency of these surface water data with our groundwater data, as plotted in Figure 4 suggests a significant degree of surface-groundwater interaction across Costa Rica. This is consistent with our observations that most rivers in Costa Rica, with the exception of some in semi-arid portions of the northwest, have significant base flow. Spatial and temporal concordance between our data and the data from Lachniet and Patterson (2002) also
Table 1. Sample locations and the $\delta^{18}O$ and $\delta^D$ (SMOW) values for meteoric waters of Costa Rica.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Sample Name</th>
<th>Sample Type</th>
<th>Sample Date</th>
<th>Northing</th>
<th>Westing</th>
<th>Elevation (meters)</th>
<th>$\delta^{18}O$ (VSMOW)</th>
<th>$\delta^D$ (VSMOW)</th>
</tr>
</thead>
</table>
Figure 1. Location of water samples used in this study.
Figure 1 (continued). Location of water samples used in this study.
suggest that these samples represent meteoric waters and not waters modified significantly by hydrothermal activity. For these reasons, we use the data from Lachniet and Patterson (2002) in our generation of the isotope value maps of Costa Rica.

We also utilize data for 13 springs from Darling et al. (1989). We omit the data for other additional springs which the authors of that study suggested contain modified geothermal waters, or which differ significantly from the global meteoric water line. The well isotope data from Darling et al. (1989) is not utilized, as specific well locations are not recorded.

**Distribution of $\delta^{18}O$ and $\delta^D$ Values**

Oxygen and hydrogen isotope data for a combined total of 115 unique ground and baseflow-fed surface water locations (Figure 1) from this study and other sources (Darling et al., 1989; Lachniet and Patterson, 2002) were compiled and contoured to show distribution across Costa Rica (Figures 2 and 3). Groundwater isotope values exhibit spatial variation with respect to elevation, similar to the effect observed for waters in other locations around the world (e.g., California, Melchiorre et al., 1999; Panama, Lachniet and Patterson, 2006). Additionally, low elevation coastal areas exhibit a correlation with latitude, with lower values generally to the south, and higher values to the north. As expected, the meteoric water line for groundwater of Costa Rica ($\delta^D = 7.7 \delta^{18}O + 11.1$; Figure 4) is quite close to the global meteoric water line ($\delta^D = 8 \delta^{18}O + 10$) of Craig (1961).

One significant anomaly occurs in the mapped $\delta^{18}O$ values of north central Costa Rica around Canas (Figure 2). In this area, there is an unexplained increase in $\delta^{18}O$ values. It is most likely that this unusual zone of higher $\delta^{18}O$ values is an artifact of low sample frequency in the area, and that the higher $\delta^{18}O$ values are connected to a similar coastal zone. Only additional sampling in this rugged and remote portion of Costa Rica will resolve this issue. No similar effect is observed for $\delta^D$ values, due to the resolution of the selected contour interval.

**Factors Controlling $\delta^{18}O$ and $\delta^D$ Values**

• Effect of Elevation Upon $\delta^{18}O$ Values

Examination of the relationship between $\delta^{18}O$ values and elevation at corresponding sampling sites (Figure 5) shows a correlation with $R=0.63$. Close examination reveals that deviations from this $\delta^{18}O$ vs. elevation trend result from two mechanisms. The first is local elevation effect which produces locally different $\delta^{18}O$ – elevation correlations with different Y-intercept and slope values. The second is a latitude-dependent effect for coastal sites at low elevation.

Local variation in orographic isotope fractionation of precipitation-derived groundwater is not unexpected. The Pacific coast has a wet season between May and October in the north and April to December in the south. The precipitation of the wet season is fed by thermal convection and onshore breezes. The Caribbean coast receives ample year-round precipitation due to northeasterly trade winds. (National Oceanic and Atmospheric Administration, 2008; Poveda et al., 2006). On the Pacific coast, data from the Osa peninsula defines a $\delta^{18}O$ decrease of 1.5‰ per 1000 meters of elevation increase (Figure 6a); on the Caribbean coast, the data from the Monteverde/Rio Peñas Blancas Valley defines a $\delta^{18}O$ decrease of 3.0‰ per 1000 meters of elevation increase (Figure 6b). The difference in intensity of elevation-induced fractionation between the two coasts is believed to be controlled by differences in the respective climate patterns and oceanic temperatures, with localized influence from baseflow recharge elevation and specific humidity (e.g., Gonfiantini
Figure 2. $\delta^{18}\text{O}(\text{VSMOW})$ values of groundwater in Costa Rica.
Figure 2 (continued). $\delta^{18}O$ (VSMOW) values of groundwater in Costa Rica.
Figure 3. δD(VSMOW) values of groundwater in Costa Rica.
Figure 3 (continued). $\delta^{18}D$(VSMOW) values of groundwater in Costa Rica.
These variations make it difficult to describe a generalized trend of $\delta^{18}O$ change with respect to elevation which would hold true for the entire nation of Costa Rica.

- **Effect of Latitude Upon $\delta^{18}O$ Values**

Groundwater samples from this study, with low elevations of <100 m above sea level, show strong correlation ($r=0.7$) between $\delta^{18}O$ and latitude, with an observed decrease in $\delta^{18}O$ with decreasing latitude (Figure 7). Correlation between $\delta^{18}O$ and latitude ($r=0.71$) was also observed for surface water samples in the neighboring nation of Panama (Lachniet and Patterson, 2006), though this study compared samples from all elevations. Our re-examination of the data for Panama from Lachniet and Patterson (2006) shows that for all samples <100 m above sea level there is actually a stronger correlation ($r=0.79$). Furthermore, the observed decrease in $\delta^{18}O$ with decreasing latitude for our Costa Rica data are of a similar slope and y-intercept as the Panama data.

![Figure 4. $\delta^{18}O$(VSMOW) vs. $\delta^D$(VSMOW) plot for samples used in this study.](image)

![Figure 5. $\delta^{18}O$(VSMOW) vs. elevation for samples used in this study.](image)
Other previous research has noted this type of effect in the humid tropics (e.g., Vuille and Werner, 2005, Lachniet et al., 2007). Our observed decrease in $\delta^{18}O$ with decreasing latitude is the inverse of the temperature-dependant latitude effect observed for the United States (Kendall and Coplen, 2001). It is believed that this latitude effect results from a trade wind signal, with increasing Rayleigh distillation as air masses traverse the isthmus (Lachniet et al., 2007). In Costa Rica, the trade wind vector is highly correlated with latitude (Hofmann et al., 1981), with the high mountains of the Cordillera de Talamanca superimposing a low $\delta^{18}O$ signature to vapor and precipitation in southern Costa Rica. This enhanced orographic distillation results in low $\delta^{18}O$ vapor being advected to the Pacific Coast (Lachniet et al., 2007). The paleoclimate record of stalagmites from the Panamanian isthmus also records this effect (Lachniet et al., 2007).

Figure 6. $\delta^{18}O$(VSMOW) vs. elevation for samples from a) the Osa Peninsula and b) Monteverde area.

Figure 7. $\delta^{18}O$(VSMOW) vs. latitude for samples with elevation <100m used in this study.
CONCLUSIONS

The new and historical isotopic data for groundwater of Costa Rica have been used to generate preliminary maps of $\delta^{18}O$ and $\delta D$ values across this nation. New data will be added in the future to this data set and these maps will be updated and re-posted in an on-line format at: http://wri.csusb.edu/. Though the isotopic compositions are predictably lower at higher elevations, quantification of this regionally-variable effect is only possible in localized, coastal-specific areas. For low elevation samples (<100m), a decrease in isotope values is observed with decreasing latitude.

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