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Chemical tracing of interbasin groundwater transfer in the lowland rainforest of Costa Rica

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Abstract

Chemical data from several hundred surface water and groundwater samples collected mainly during baseflow over 4.5 years were used to detect and quantify the natural interbasin transfer of deep groundwater into watersheds at La Selva Biological Station, a research site in the lowland rainforest of Costa Rica. Most of the variability in major ion concentrations at La Selva can be explained by mixing of two chemically and hydrologically distinct waters: high-solute bedrock groundwater, and low-solute local water draining from hillslope soils within the study watersheds. Several lines of evidence indicate that high-solute bedrock groundwater represents subsurface interbasin transfer into the study site.

The fraction of water due to interbasin transfer (f_{water}) ranged from zero to about 0.49 for major streams at La Selva; f_{water} values were even higher (up to 0.84) for small riparian seeps and shallow groundwater near the Salto stream. The relative contribution of major ions by interbasin transfer was even more significant than of water itself. f_{water} values of 0.49 and 0.84 correspond to f_{Cl} values of 0.92 and 0.99, respectively (f_{Cl}, the fraction of dissolved chloride in a water sample that is due to interbasin transfer, is approximately equal to the fraction of all major ions contributed to the sample by interbasin transfer, given the observed linear correlation between Cl and other major ions). f_{water} and f_{Cl} of streams and riparian seeps varied on both long (monthly/seasonal) and short (storm event) time scales, in each case decreasing as conditions at La Selva became wetter. The high f_{water} values found in riparian groundwater and seeps indicate that local water and bedrock groundwater derived from interbasin transfer mix in the shallow subsurface at La Selva, not just in stream channels. With f_{water} values up to 0.84, it appears that some areas of riparian wetland may be maintained largely by interbasin transfer.

This large interbasin transfer significantly affects both terrestrial (e.g. wetland) and aquatic ecosystems. Results suggest the importance of a regional approach to land use planning in this and similar environments. Complete protection of lowland streams, wetlands, and ecosystems in this hydrogeologic setting requires protection of a deep interbasin groundwater system whose precise volume, boundaries, and recharge areas are presently unknown. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Groundwater; Watershed; Chemical tracer; Rainforest; Streamflow; Wetland

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1. Introduction

Much of our understanding of biogeochemical cycling is based on small watershed studies that have sought to quantify water and chemical budgets (e.g., Johnson and van Hook, 1989; Bruijnzeel, 1991; Likens and Bormann, 1995). Groundwater seepage into or out of small watersheds beneath topographic divides ('interbasin transfer') may be an important component of watershed budgets, but cannot be directly measured and is generally difficult to quantify. While considered a complicating problem to be avoided in small watershed studies, interbasin transfer is an expected, common feature of groundwater flow systems. Tóth's (1962, 1963) classic work demonstrated the likelihood of interbasin transfer through regional-scale groundwater systems beneath smaller, local systems.

We have previously presented geochemical evidence of interbasin groundwater and solute transfer into lowland rainforest watersheds in Costa Rica (Pringle et al., 1993; Genereux and Pringle, 1997). This transfer plays an important role in the hydrology, geochemistry, and ecology of lowland streams and watersheds (e.g., Pringle and Triska, 1991; Ramirez, 2000; Rosemond et al., 2001). In this paper, we expand on our previous work by analyzing a much larger body of chemical data in the context of a hydrogeochemical mixing model. We address four principal objectives: (1) to confirm and quantify the significant water and chemical inputs to our study area by interbasin groundwater transfer, based on chemical analyses of several hundred new surface water and groundwater samples collected over 4.5 years, mostly during baseflow, (2) to document the temporal (seasonal and storm event) and spatial variability of the interbasin transfer, and whether this variability is consistent with our conceptual hydrogeochemical model for the site, (3) to directly investigate riparian groundwater for chemical evidence of interbasin transfer and groundwater mixing in the subsurface, and (4) to assess the significance of results from objectives 1–3 for protection of water resources and ecosystems in this hydrogeologic setting.

2. Background

Evidence of interbasin transfer may be based on the water budget, that is, on the observation that stream discharge is significantly greater or less than the amount of rainfall minus evapotranspiration (ET) in a topographically delineated watershed. Direct measurement of the water budget can in principle quantify either a gain or loss in the watershed studied, but usually requires careful long-term measurements of stream discharge and ET (unless the interbasin transfer is large enough to be obvious from even approximate estimates of the other fluxes). Also, water budget evidence can show only a net gain or loss, not the actual rates of interbasin inseepage and/or outseepage (both could potentially occur for a watershed in a regional gradient). Chemical evidence of interbasin transfer need not take the form of a budget 'discrepancy'; it is often based on observation of stream or spring water that is chemically distinct (usually higher in solutes) from water draining hillslopes locally within a watershed. This type of chemical evidence can quantify only a positive interbasin transfer (gain of groundwater) into the study watershed (though clearly a gain on one watershed must indicate a loss from at least one other watershed in the region). Groundwater head data may also be used, but alone can only indicate the direction of interbasin transfer (through the direction of a hydraulic gradient beneath a topographic divide); estimation of the actual rate of transfer would require information on hydraulic conductivity and the cross-sectional area through which flow occurs.

Water budget and/or chemical data have been used to prove or suggest the possibility of interbasin groundwater transfer at small watersheds in Tennessee, USA (Luxmoore and Huff, 1989; Genereux et al., 1993a), Romania (Iurkiewicz et al., 1996), Malaysia (Kenworthy, 1971; Rahim and Yusop, 1986; Yusop, 1989), Brazil (Brinkmann, 1983, 1985), and Taiwan (Horng et al., 1985) (the Malaysia, Brazil, and Taiwan results are summarized by Bruijnzeel, 1991). In larger-scale investigations of regional flow systems, head data have been used to indicate interbasin transfer in Nevada (Winograd, 1962) and Texas (Darling et al., 1997), USA. Water budget considerations have also been used to demonstrate interbasin flow in Nevada (Eakin, 1966) and California (Thyne et al., 1999).

Chemical data have been particularly useful in studies of interbasin transfer in the western US.

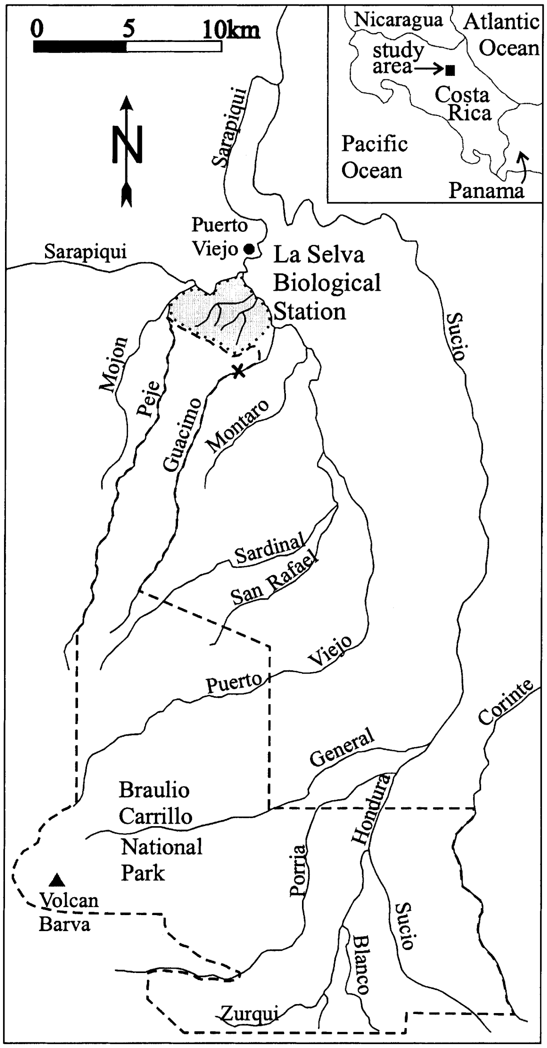

Fig. 1. Location of La Selva Biological Station (shaded area within the dotted line) in Costa Rica (after Pringle et al., 1990). La Selva sits at the northern end of Braulio Carrillo National Park; the dashed line shows the park boundary. Guacimo Spring is marked by the ' × ' about 1.5 km southeast of La Selva.

Walker and Krabbenhoft (1998) concluded that some of the stable isotope data from their study site in Wisconsin indicated interbasin transfer of shallow groundwater. Thyne et al. (1999) used chloride, sulfate, and deuterium data to detect interbasin transfer through fractured crystalline rock in southern California. Johannesson et al. (1995, 1997) used concentration data on rare earth elements to quantify interbasin groundwater transfer and mixing along the California–Nevada border. Naff et al. (1974) and Maxey (1968) used major element data from Nevada in a similar fashion. Maxey's paper shows spring waters ranging in concentration between high-solute waters of the 'regional flow system' and low-solute waters of the 'local flow system(s)'.

Our approach is similar to that of the geochemical studies listed above. We measured major ion concentrations in a large number of samples collected over a 4.5 year period, and interpret those data here in the framework of a geochemical mixing model. Most of the variation in concentration can be explained by mixing of two distinct components or end-members: high-solute 'bedrock groundwater' (deep groundwater that represents interbasin transfer into our study watersheds) and 'local water' (water that fell as precipitation on the study watersheds, and that resides in and drains from hillslope soils). We use the term bedrock groundwater to indicate that this water must have followed a relatively deep flowpath through bedrock prior to its discharge at the study site. In comparison, thick saprolite and alluvium at the study site suggest local water has little or no contact with bedrock.

The previous studies summarized above span a wide range of spatial scales, from small watershed studies (0.03–0.4 km^2) to investigations of larger groundwater systems in arid areas of western North America (up to roughly 20,000 km^2, with length scales of tens to a few hundred km). The scales associated with our study were toward the smaller end of this range: interbasin transfer into lowland watersheds of 0.46–1120 km^2 at the downslope end of a 30–35 km regional elevation gradient from the peaks of the Costa Rican Cordillera Central to the lowlands (an elevation gradient that most likely defines the length scale of the regional groundwater system responsible for the interbasin transfer).

3. Study site

The Cordillera Central of Costa Rica is a northwest–southeast trending range of volcanic peaks associated with subduction of the Cocos plate as it moves to the northeast and beneath the Caribbean plate (e.g. Ludington et al., 1996). Our study site, La Selva Biological Station, sits northeast of the Cordillera

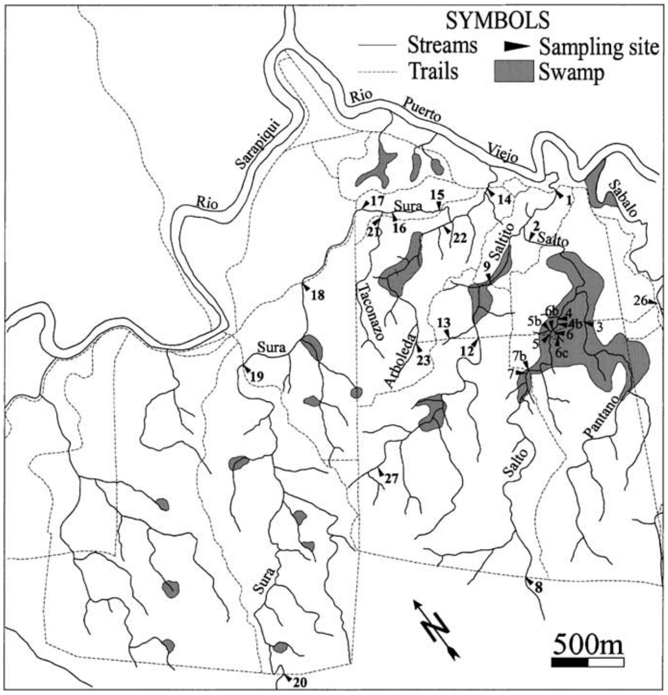

Fig. 2. La Selva Biological Station showing stream and riparian seep sampling locations.

Central, in the transitional zone between the steep foothills and the Caribbean coastal plain. La Selva is a 1536-ha research and education preserve owned and operated by the Organization for Tropical Studies (OTS); it forms the downslope end of a tract of primary rain forest that extends over 30 km to the south (Fig. 1), through Braulio Carrillo National Park and up the north slope of Volcan Barva (elevation 2906 m) and smaller nearby peaks (Pringle et al., 1990). Other large peaks in the region include Volcan Poas (about 15 km northwest of Barva) and Volcan Arenal (about 60 km northwest of Poas).

Volcanic/geothermal activity in the area is ongoing and more intense toward the northwest. A spring high in sulfuric acid emerges from the north slope of Barva at an elevation of about 2000 m, a strong indication of the presence of sulfur-rich volcanic fluids at depth (Pringle et al., 1993). The most recent eruption of lava at Poas was in 1953–1954; in 1989 the crater lake dried out and mud, sulfur, and ash were ejected (Pringle et al., 1993). Volcan Arenal has erupted frequently since 1968, with significant output of lava and pyroclastics (Pringle et al., 1993). This volcanic activity is an important influence on the geochemistry of natural waters in this area, including the groundwater which we believe represents inter-basin transfer into the lowland watersheds of La Selva from higher elevation recharge areas on and/or near Volcan Barva (Pringle et al., 1993; Genereux and Pringle, 1997).

Based on boulders, lithic fragments in soils, and limited outcrops in streams, Alvarado (1985) recognized three fairly distinct lavas in the bedrock at La Selva, most likely all Pleistocene. The oldest lava, the Taconazo andesite, was found at the surface only along the lower few hundred meters of the Taconazo stream and in a few other small areas accounting for about 1% of the total area of La Selva (streams are shown in Fig. 2). A lava flow of intermediate age, the Salto basaltic andesite, was found mainly in two broad bands, west of the Sura and along the Salto and Pantano streams, accounting for about half of the area of La Selva. Alvarado (1985) gives a radiometric date (1.2 million years) only for the youngest flow, the

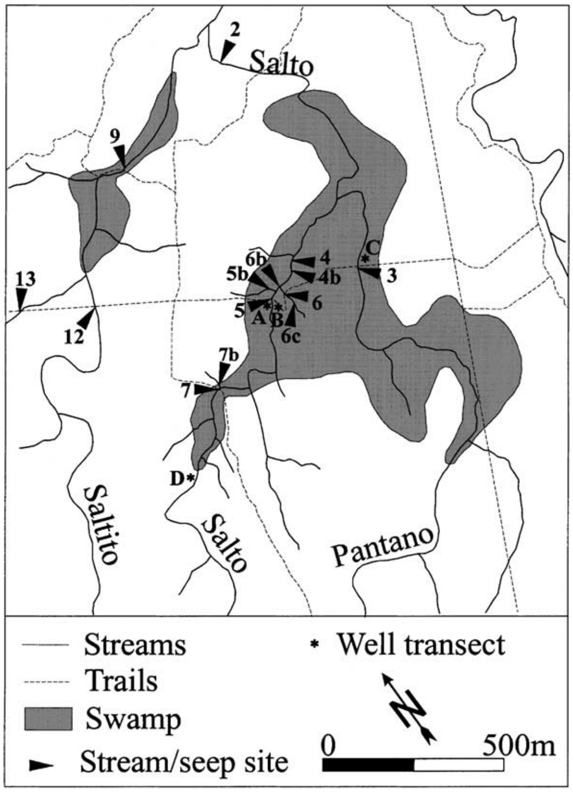

Fig. 3. Swampy area between the Salto and Pantano streams, with stream and seep sampling sites and groundwater well transects A–D.

Esquina andesite; this lava occurs in two broad bands, one running through the center of La Selva from the Saltito stream west to the Sura, and another southeast of the Pantano, between it and the Sabalo stream. One or all of these flows may underlie the younger surficial alluvium which covers the northern third of La Selva, along the Rio Sarapiqui and Rio Puerto Viejo.

The major soil orders at La Selva are Ultisols (45% of area; mainly Typic Tropohumults) and Inceptisols (55% of area; various suborders) (Sollins et al., 1994). Ultisols cover most of the area over the Salto and Esquina lava flows, with the exception of valley bottoms. Inceptisols are found in the valley bottoms and on the alluvium occupying the northern portion of La Selva. Small areas of Entisols (<0.5% of land area) are found near the Rio Sarapiqui. On most ridges a thick clayey saprolite several meters thick lies between the overlying soil (roughly 1 m in thickness) and the underlying bedrock.

Elevation at La Selva ranges between approximately 35 and 130 m (Sanford et al., 1994; Wood, 1999). From 1958 to 1997, annual precipitation at La Selva averaged 4200 mm (OTS, unpublished data; Sanford et al., 1994). February, March, and April are the driest months, averaging about 180 mm per month. Annually, ET accounts for about 47% of precipitation (Luvall, 1984). The Sura and Salto are the major streams draining La Selva, and were the subjects of our sampling, together with their tributaries and adjacent riparian groundwaters (Fig. 2). Topographically defined areas of the Sura and Salto watersheds are 120 and 1120 ha, respectively (based on IGNCR, 1985), though these areas are not an important control or influence on the interbasin groundwater transfer studied here. By definition, interbasin transfer cuts across (beneath) topographic watershed boundaries. We present watershed areas mainly to show that interbasin groundwater transfer in our study area affects lowland watersheds spanning a wide range of sizes, i.e., a factor of 24 between the areas of the Salto watershed (1120 ha) and the Arboleda watershed (46 ha) (the Arboleda lies within the Sura watershed). These watershed areas are within the very broad range of areas over which interbasin transfer has been investigated in prior work (Section 2).

4. Methods

We collected over 800 water samples for major ion analysis between August 1993 and March 1998. Results from three principal sample sets are presented here:

1. detailed dry season sampling (27 stream and riparian seep sites) in April 1994, March 1997, and March 1998;
2. monthly stream and riparian seep samples (nine sites), collected during August 1993–December 1997 (some of the 9 sites were sampled for only part of this 53 month period);
3. near-stream groundwater samples (25 wells), collected during October 1993–December 1994 (monthly), and March 1998.

In addition to the sites from which these samples were collected (Figs. 2 and 3), samples were also

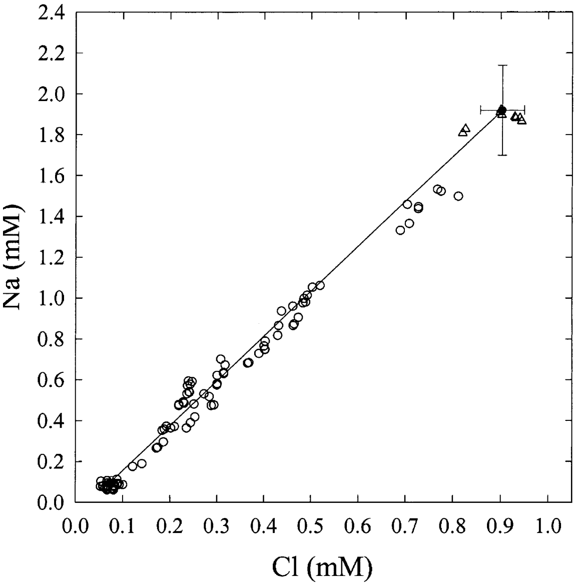

Fig. 4. Sodium concentration vs. chloride concentration in dry season water samples from La Selva, collected in April 1994, March 1997, and March 1998. Triangles represent bedrock groundwater samples collected during this period. The straight line connects the mean Na and Cl concentrations of the two end members, bedrock groundwater and local water, as given in Table 1. Error bars represent standard deviations about the means (Table 1); error bars on the low-solute local water are too small to be seen beneath the sample points.

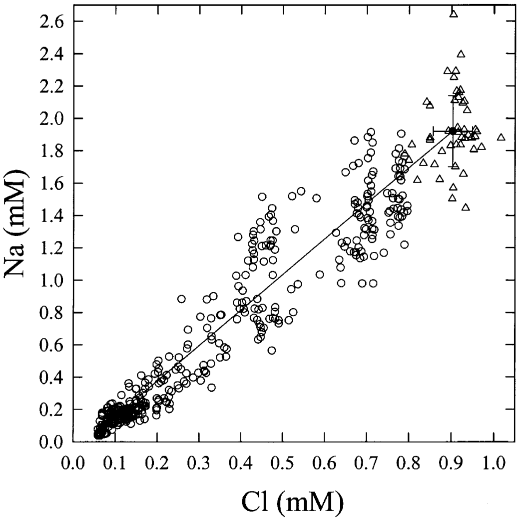

Fig. 5. Sodium concentration vs. chloride concentration in stream and seep samples from long-term sampling sites at La Selva, August 1993–December 1997. Triangles represent bedrock groundwater samples collected during this period. Straight line and errors bars are identical to those in Fig. 4.

taken monthly from Guacimo Spring, a large spring on the left (northwest) bank of the Guacimo River about 1.5 km southeast of the southeasternmost point on the La Selva boundary (Fig. 1). Each of our four well transects (Fig. 3) consisted of 2–3 clusters of wells, each cluster with 3–4 wells about 3 m apart. The wells were installed in 1987; Pringle and Triska (1991) report initial nutrient data for groundwater collected at the wells. Each transect had well clusters 3 and 10 m from the adjacent stream bank; in addition, transect 1 had a third cluster 16 m from the streambank. Wells were constructed of a 2-in. (5 cm) PVC pipe with slotted screen sections about 40 cm long at the bottom, installed in holes drilled with a gasoline-powered auger. Slots were about 0.13 mm in width. Most of the 25 wells sampled were 2.8–3.4 m deep (ground surface to bottom of screen), though 3 were 0.95 m deep. For sampling, wells were first pumped dry with a battery-powered peristaltic pump. Samples were collected with a plastic syringe and clear plastic tubing 1–2 days later, after the wells had refilled.

With few exceptions (Section 5.2.3), most samples were collected during baseflow conditions (where 'baseflow' is meant to indicate sampling not specifically focused on storm events). While there was no continuous stream gauging during the period of collection of the samples discussed here, the baseflow samples most likely represent a significant range of stream discharge conditions. Our continuous stream gauging at the Arboleda and Taconazo streams (tributaries to the Sura) during 1998–2001 shows that our weekly streamwater sampling during these years captured a significant range of discharges: approximately a factor of 10 between highest and lowest discharge at the Taconazo, and a factor of two at the Arboleda. The water samples discussed in this paper, collected during 1993–1998, most likely represent a similar, significant range of stream discharges.

All samples were collected in new, clean polyethylene bottles; samples were filtered to 0.45 μm, most in the field at the time of collection and others in the lab. Cation samples were preserved through addition of reagent-grade nitric acid after filtration. Samples were analyzed for dissolved Cl, SO_4, Na, K, Mg,

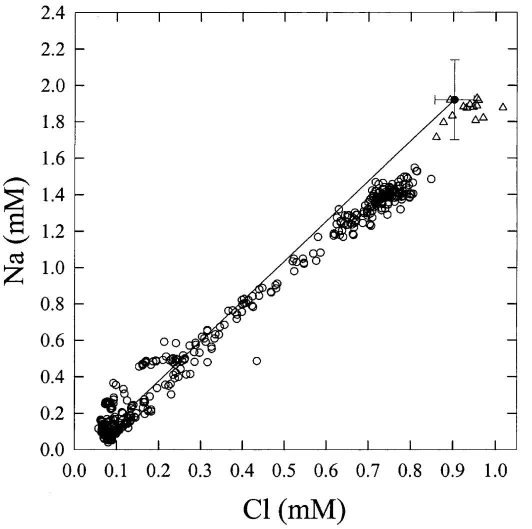

Fig. 6. Sodium concentration vs. chloride concentration in riparian groundwater samples from La Selva, October 1993–December 1994. Triangles represent bedrock groundwater samples collected during this period. Straight line and errors bars are identical to those in Fig. 4.

and Ca. Analyses were carried out by ion chromatography (EPA, 1993), with the exception of the cation analyses for the stream samples from August 1993 to December 1997 (these were done by atomic absorption spectrophotometry).

5. Results

5.1. Mixing lines

Na and Cl streamwater concentrations from the detailed dry season sampling in 1994, 1997, and 1998 fall along a well-defined mixing line between the high-solute water found at Guacimo Spring and low-solute water from small streams at higher elevation within La Selva (Fig. 4). Streamwater data from the long-term (8/93–12/97) sites plot along essentially the same line although scatter is generally larger than for the dry season samples and expands toward the high-solute end of the line (Fig. 5). The greater scatter in Fig. 5 can be explained by the greater variability in the bedrock groundwater end member (Guacimo Spring), itself a function of the greater variability in hydrologic conditions in this larger sample set that included both wet and dry seasons (as compared to samples from only the dry season shown in Fig. 4). Shallow groundwater samples from soil at La Selva (10/93–12/94) also fall along essentially the same mixing trend, though slightly below the mixing line at higher concentrations (Fig. 6). The most likely explanation for the slight deviation is that the bedrock groundwater end member was lower in Na during this 15 month period, compared to the long term 1993–1998 average on which the line in Figs. 4–6 is based (note that the triangles in Fig. 6 plot at or below the long term average Na concentration of bedrock groundwater, indicated by the solid dot with error bars).

We prepared 15 two-solute plots analogous to those in Figs. 4–6: Na, K, Mg, Ca, and SO_4 vs. Cl for each of the three major sample sets. Of the 15 plots, the only two showing greater scatter than Fig. 5 were the Ca and SO_4 plots for the shallow groundwater. We do not expect that mixing alone would be adequate to explain all variation in concentration, especially for nutrients such as Ca that are actively cycled in the relatively nutrient-poor tropical soils at La Selva.

Table 1
Mean concentration (Conc), and standard deviation (SD) and coefficient of variation (CV) of mean concentration, for six major ions in the two end-member waters of the geochemical mixing model

Solute	Local water (99 samples)			Bedrock groundwater (56 samples)		
	Conc (mM)	SD (mM)	CV (%)	Conc (mM)	SD (mM)	CV (%)
Na	0.094	0.032	34	1.92	0.22	11
K	0.016	0.006	38	0.226	0.012	5
Mg	0.054	0.027	50	1.56	0.11	7
Ca	0.036	0.019	53	0.725	0.098	14
Cl	0.072	0.009	13	0.903	0.046	5
SO_4	0.005	0.010	200	0.126	0.009	7

Table 2
Average dry season f_{water} and f_{Cl} values, based on samples from April 27–29, 1994, March 18–19, 1997, and March 10–13, 1998

Site	f_{water}	f_{Cl}
1	0.41	0.90
2	0.41	0.90
3	0.19	0.74
4	0.62	0.95
4B[a]	0.77	0.98
5	0.39	0.89
5B[a]	0.74	0.97
6[b]	0.62	0.95
6B[a]	0.84	0.99
6C[a]	0.79	0.98
7	0.36	0.88
7B[a]	0.14	0.67
8	0.01	0.11
9	0.24	0.80
12	0.21	0.77
13	0.015	0.16
14	0.27	0.82
15	0.19	0.75
16	0.18	0.74
17	0.16	0.70
18	0.19	0.75
19	0.0097	0.11
20	0.017	0.18
21	0.013	0.14
22	0.49	0.92
23	0.016	0.17
24	1.01	1.00

[a] 1998 samples only.

[b] 1994 and 1998 samples only.

SO_4 reduction clearly influences groundwater concentrations of SO_4; on a plot of SO_4 vs. Cl, samples plot throughout much of the triangular space below the mixing line, with many right along the Cl axis, at zero SO_4 concentration. With these exceptions for the effects of biogeochemical cycling, the overall findings strongly confirm the interpretation that most of the variability in major ion concentrations at La Selva can be explained as the result of mixing between two chemically distinct waters (Pringle and Triska, 1991; Genereux and Pringle, 1997; Wood et al., 1998): bedrock groundwater and lower-solute local water.

In addition, our groundwater data, in accord with earlier nitrogen and phosphorus data (Pringle and Triska, 1991), provide unambiguous evidence that this mixing occurs in a significant volume of the shallow subsurface at La Selva, not just in stream channels. Groundwater from all four transects shows significant contributions from bedrock groundwater. Some groundwater samples consisted of well over half bedrock groundwater, suggesting that some riparian and wetland groundwaters at La Selva are maintained largely by interbasin transfer.

5.2. Mixing calculations

5.2.1. Overview, end-member definitions

We carried out chemical mixing calculations to quantify the contribution of water and solutes from interbasin transfer (bedrock groundwater) to the waters sampled at La Selva. Following an approach well-known in hydrology (Hooper et al., 1990; Genereux et al., 1993b; Eshleman et al., 1993; Bazemore et al., 1994) and previously applied to a much smaller data set at La Selva (Genereux and Pringle, 1997), the fraction of water in a given water sample that was due to bedrock groundwater was computed as

$$f_{\mathrm{water}} = \frac{C_{\mathrm{S}} - C_{\mathrm{LW}}}{C_{\mathrm{BGW}} - C_{\mathrm{LW}}} \tag{1}$$

where C indicates solute concentration (in our case, all mixing calculations were based on Cl, the most conservative and least reactive of the major ions), and the subscripts S, LW, and BGW refer to the sample (shallow groundwater or water from a stream or riparian seep), local water, and bedrock groundwater, respectively. The approach of Genereux (1998) was used to estimate uncertainty in the Cl-based f_{water} values. 95% confidence intervals ranged from ±0.025 to ±0.1, small values due mainly to the large chemical difference between the two end members (a factor of about 13 in Cl concentration).

The fraction of the Cl in a water sample that was contributed to the sample by bedrock groundwater is

$$f_{\mathrm{Cl}} = \frac{f_{\mathrm{water}} C_{\mathrm{BGW}}}{C_{\mathrm{S}}} \tag{2}$$

The value of f_{Cl} quantifies the contribution of bedrock groundwater to the solute load of water samples collected at La Selva, in the same way that f_{water} indicates the contribution of water itself from the bedrock groundwater source. Analogous fractional contributions of other ions (e.g. f_{Mg}, f_{Na}, etc.) were also calculated and are, of course, similar to f_{Cl}, given the linear

Table 3
Average contributions of bedrock groundwater to riparian groundwater in four well transects at La Selva (Fig. 3), October 1993–December 1994. Each transect had two or three well clusters arrayed along a line normal to a nearby stream. The dry months (<200 mm precipitation per month) were January–April, 1994. The number of samples on which each f_{water} and f_{Cl} value is based is given as n. Distance between each well cluster and the adjacent streambank, and whether wells in the cluster were shallow (S, 0.95 m) or deep (D, 2.8–3.4 m), are indicated in the second column. The difference between the dry and wet month f_{water} averages for each well cluster is shown in the seventh column; the average difference (average of the values in the seventh column) is essentially zero (0.00083)

Transect	Distance (m), depth	Dry months		Wet months		Dry–wet	All months		
		f_{water}	n	f_{water}	n	f_{water}	f_{water}	f_{Cl}	n
A	3,D	0.75	8	0.76	18	−0.01	0.76	0.98	26
	10,S	0.036	2	0.082	7	−0.046	0.072	0.49	9
	10,D	0.23	4	0.21	8	0.02	0.22	0.78	12
	16,S	0.018	5	0.012	9	0.006	0.014	0.15	14
	16,D	0.000	10	−0.002	27	0.002	−0.001	0	37
B	3,S	0.83	4	0.80	11	0.03	0.81	0.98	15
	3,D	0.79	12	0.81	31	−0.02	0.81	0.98	43
	10,D	0.75	12	0.79	31	−0.04	0.77	0.98	43
C	3,D	0.26	8	0.27	22	−0.01	0.27	0.82	30
	10,D	0.025	5	0.018	19	0.007	0.020	0.20	24
D	3,D	0.37	12	0.30	33	0.07	0.32	0.86	45
	10,D	0.018	12	0.017	33	0.001	0.017	0.18	45

correlations between the other major ions and Cl. Thus, the f_{Cl} values reported here are indicative of the bedrock groundwater contributions to the major ion chemistry of La Selva waters in general (notwithstanding that the Ca and SO_4 concentrations of some La Selva waters have been modified by means other than mixing as discussed in Section 5.1).

The first step in the mixing calculations was the definition of appropriate end-member solute concentrations, C_{BGW} and C_{LW}. Figs. 4–6 and other related plots show that samples from Guacimo Spring should be used to define C_{BGW}. We averaged solute concentrations from 56 samples to obtain C_{BGW} values: 47 samples collected during our monthly sampling program (October 1993–December 1997, with four months missed at random) and nine additional samples collected during the more detailed dry season sampling in 1994, 1997, and 1998. In defining C_{BGW}, we chose to average all Guacimo Spring data together rather than try to include minor temporal variation in

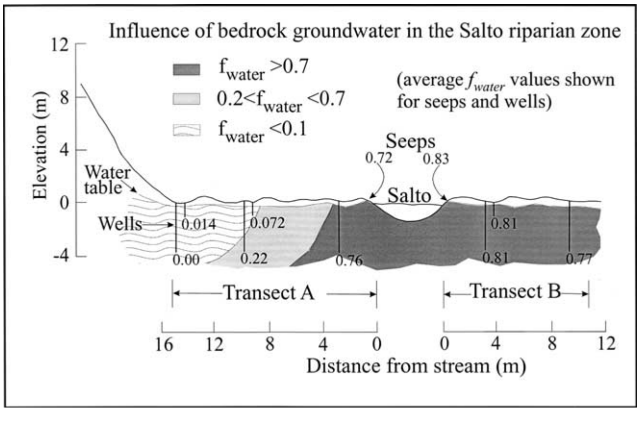

Fig. 7. Average f_{water} values in riparian groundwater along well transects A and B. f_{water} is lower toward the foot of the steep hillslope on the left side of the cross-section. (Pringle and Triska (1991) present phosphorus data for the same cross-section.)

Table 4
Average contributions of bedrock groundwater to stream and seep sampling sites at La Selva, August 1993–December 1997. Average monthly precipitation was 119 mm for the 15 dry months, 432 mm for the 38 wet months, and 344 mm for all 53 months. The number of samples on which each f_{water} and f_{Cl} value is based is given as *n*. The difference between the dry month and wet month f_{water} averages for each site is shown in the sixth column; the average difference was 0.045

Site	Dry months		Wet months		Dry–wet	All months		
	f_{water}	*n*	f_{water}	*n*	f_{water}	f_{water}	f_{Cl}	*n*
3	0.14	14	0.091	38	0.05	0.10	0.58	52
5	0.33	11	0.23	29	0.10	0.26	0.82	40
5B	0.74	10	0.70	28	0.04	0.72	0.97	38
6	0.84	11	0.83	29	0.01	0.83	0.98	40
9	0.16	11	0.11	30	0.05	0.12	0.63	41
22	0.46	11	0.41	29	0.05	0.42	0.90	40
26	0.034	11	0.021	29	0.013	0.024	0.24	40

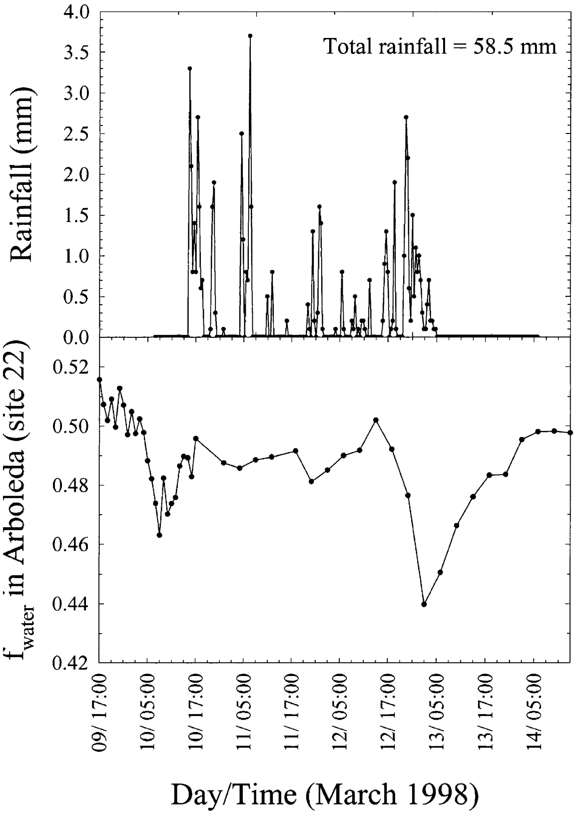

Fig. 8. Response of f_{water} in the Arboleda stream (sampling site 22) to a storm, March 1998. Total rainfall was 58.5 mm over about 3 days.

the analysis. For the six major ions, the coefficient of variation of the mean concentration for the 56 samples ranged from 0.05 for Cl and K to 0.14 for Ca (Table 1).

Our definition of C_{LW} was based on 99 samples with very low Cl concentration (average = 0.072 mM; Table 1), including (1) 53 groundwater samples collected during October 1993–December 1994, and March 1998, (2) 24 samples (replicate samples from 12 months) from site 27, the Saltito stream at relatively high elevation (100 m), collected during January–December 1997, and (3) 22 samples from several smaller, higher elevation streams (some ephemeral) at La Selva, collected in April 1994, March 1997, and March 1998.

5.2.2. Mixing results: f_{water} and f_{Cl}

The overall range of f_{water} and f_{Cl} values was the same in all three sample sets listed in Section 4: f_{water} ranged from zero to a high of about 0.84, f_{Cl} from zero to about 0.99. For the detailed dry season sampling, the value of f_{water} at each site differed by only a few percent among the April 1994, March 1997, and March 1998 samples. Discharge of bedrock groundwater seems to occur only at elevations below 45 m; all sampling sites at higher elevations (8, 13, 19, 20, 23) had f_{water} values of zero or near zero (Table 2). Results from site 27 (one of the sites in the long term stream sampling program, at an elevation of about 100 m) are also consistent with this pattern of low concentration at higher elevation. Discharge at the sampling points furthest downstream in the two largest streams, the Salto and the Sura, averaged 43% and 28% bedrock groundwater, respectively, during these dry season sampling periods; the associated f_{Cl} values were 0.90 and 0.83. Discharge of bedrock groundwater is clearly a major factor in water and solute budgets at La Selva. Chemical fluxes are even more sensitive than water fluxes to the interbasin transfer of bedrock groundwater; an f_{water} value of only 0.01 would lead to an f_{Cl} of over 0.11. The highest f_{water} values (0.74–0.84) occurred in four small riparian seeps, tiny rivulets flowing into the Salto from the swampy area between the Pantano and Salto streams.

The highest solute concentrations at small seeps in the swampy area near the Salto are similar to values found in some of the wells (Table 3). f_{water} values in groundwater were lower farther away from the Salto and Pantano stream channel (Fig. 7), indicating the increasing importance of low-solute local water closer to the foot of the steep hillslopes which bound the relatively flat riparian zone. In well transect B there is no significant decrease in f_{water} of groundwater between 3 and 10 m from the Salto stream, but there is also no nearby hillslope. The transect sits in the flat, swampy area between the Salto and Pantano streams; the nearest significant hillslope lies east of the Pantano stream, past well transect C.

SRP (soluble reactive phosphorus) concentrations in riparian groundwater from the same wells were also found to decrease with increasing distance from the stream channels during April–August 1987 (Pringle and Triska, 1991); previous work has established bedrock groundwater as the source of high SRP (e.g. Pringle et al., 1990, 1993). The general decrease in f_{water} of riparian groundwater closer to hillslopes is consistent with our conceptual mixing model (Pringle and Triska, 1991; Genereux and Pringle, 1997), that low-solute water draining from hillslopes at La Selva mixes with high-solute bedrock groundwater discharging to streams and riparian areas from below. The groundwater data provide conclusive proof that this mixing takes place in the riparian subsurface as well as in stream channels themselves, as previously suggested by Pringle and Triska (1991) based on nutrient data. Subsurface mixing of bedrock groundwater and local water near streams is also shown by water samples collected in March 1998 through minipiezometers 10–60 cm deep in the bed of the Salto stream, near stream sampling site 5; water from these piezometers had $f_{\mathrm{water}} = 0.82$, while the overlying streamwater had $f_{\mathrm{water}} = 0.41$.

Of the nine sites included in long-term sampling (August 1993–December 1997), data from two, Guacimo Spring and site 27 on the Saltito stream, were used in defining the chemical concentrations of bedrock groundwater and local water, respectively. Thus, their f_{water} values averaged 1 and zero, respectively. The remaining seven sites span a wide range of f_{water} values consistent with the spatial variability observed for the more intensive dry-season sampling. The Sabalo stream at site 26 shows little or no bedrock groundwater, while sites 5B and 6 (small seeps adjacent to the Salto stream) were roughly three-fourths bedrock groundwater (Table 4). Other sites had intermediate average f_{water} values.

5.2.3. Temporal variability

f_{water} values at La Selva show variability on both short (hourly) and long (seasonal) time scales. Short-term storm event sampling on the Arboleda (site 22) in March 1998 shows that f_{water} drops quickly in response to rainfall and recovers at a somewhat slower rate after rainfall (Fig. 8). This is consistent with our mixing model: a local source of low-solute water responds quickly to rainfall while a larger, regional source of high-solute bedrock groundwater does not.

There also seems to be a seasonal response of f_{water} values to rainfall, based on the long-term stream sites (Table 4). The 53 months from August 1993 through December 1997 were separated into 15 dry months (average rainfall = 119 mm per month, no month with more than 200 mm) and 38 wet months (average rainfall = 432 mm per month, no month with less than 200 mm). Each site had a slightly higher average f_{water} during the dry months; differences between wet and dry averages at the same site ranged from 0.01 to 0.10, and averaged about 0.05. Given that each water sample represents conditions only at the moment of collection, and samples were sometimes collected early in the month and sometimes late, there is scatter between the instantaneous chemical data and monthly rainfall totals. However, on average, f_{water} of stream and seep samples is slightly higher during drier months at La Selva. This is consistent with our mixing

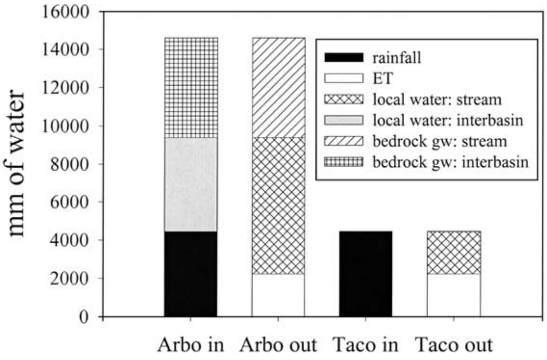

Fig. 9. Preliminary water budgets for the Arboleda and Taconazo watersheds, July 1998–June 1999. Water inputs to and outputs from the Arboleda are designated ‘Arbo in’ and ‘Arbo out’, respectively; ‘Taco in’ and ‘Taco out’ are the analogous totals for the Taconazo. There are large inputs of both high-solute bedrock groundwater and low-solute local water to the Arboleda by interbasin transfer (see ‘Arbo in’ bar). The Taconazo budget does not reveal any significant interbasin transfer.

model; based on the model, we would expect discharge from the low-solute water source would be lower during drier periods at La Selva, but discharge from the high-solute source would not be affected as much, and the net effect would be an increase in f_{water} during drier times, as shown.

The shorter period of record for the groundwater wells (15 months, as opposed to 53 months for the stream and seep samples) does not contain clear evidence of a difference in f_{water} between wet and dry months. These wells sample subsurface water that may be generally less sensitive to surface moisture conditions than some of the stream and seep sites (22 of the 25 wells are screened about 3 m below ground surface, the others are 0.95 m deep). The shorter record may also play a role; there were only four dry months in the 15 month groundwater sampling period, and 2–12 dry period groundwater samples per well cluster. It is possible that a longer record with greater numbers of samples might show evidence of a significant difference between wet and dry seasons.

5.3. Bedrock groundwater represents interbasin transfer

Two-solute mixing plots indicate the large chemical variation in natural waters at La Selva (Table 1) can be explained mainly by mixing of two distinct waters. Additional evidence and lines of reasoning point strongly to the conclusion that one of these waters (bedrock groundwater) represents interbasin transfer into La Selva.

(1) Tóth’s (1962, 1963) results show the likelihood of interbasin groundwater transfer into watersheds at the downgradient ends of regional topographic gradients. La Selva sits in such a position, where the foothills of the Cordillera Central meet the coastal plain. Watersheds in such positions may experience discharge of both local water (locally recharged) and deeper groundwater that has followed a long pathway through a regional groundwater system. Noting the large difference in subsurface residence time for these two waters, Tóth predicted large differences in the chemistry of water discharged from the local and regional systems. These differences have been confirmed and utilized to quantify interbasin transfer at La Selva, as in several previous studies in North America (Thyne et al., 1999; Johannesson et al., 1997, 1995; Naff et al., 1974; Maxey, 1968).

(2) Chemical data (e.g. Figs. 4–6) strongly suggest that water from Guacimo Spring is indicative of higher solute water discharging at La Selva. The spring does not lie within the topographic boundaries of any of the La Selva watersheds, and is surely fed by a deep groundwater source; the hillslope above the spring cannot supply water at a rate or chemistry sufficient to explain the spring outflow (the spring is the principal water supply for Puerto Viejo de Sarapiqui, a town of about 46,000 inhabitants). This points to a deep, regional source for the high-solute water that discharges at both Guacimo Spring and La Selva.

(3) Results presented here are consistent with a general conceptual model for subsurface interbasin transfer in this region of Costa Rica (Pringle et al., 1993). The model is based on water quality on and near the Barva, Poas, and Arenal volcanoes, and involves formation of acidic, relatively high-solute groundwaters at high elevation on these volcanic edifices. This groundwater moves downslope in the subsurface, evolving in composition through chemical weathering of rock (which increases pH, bicarbonate, and base cation concentrations), and eventually discharging in streams in the foothills and lowlands. While Barva is quiescent, the acidic sulfur-rich spring found on Barva upslope of La Selva suggests

continued hydrothermal processes at depth. Long-distance lateral flow and chemical evolution of groundwater as represented in this model are not uncommon in high-relief volcanic areas (e.g. Henley and Ellis, 1983). Thus, while our focus here is on interbasin transfer into La Selva and the Salto and Sura watersheds in particular, Pringle et al. (1993) draw the connection between this transfer and regional geothermal and weathering processes.

(4) High-solute water discharges only at lower elevation at La Selva, below about 45 m for the sampling reported here. If high-solute water were generated by internal hydrobiogeochemical processes at La Selva it would likely not be restricted to lower elevations (there are no major changes in soils, temperature, or vegetation over the elevation range of 35–130 m in the study area, at least none that would lead to the wide range of major ion concentrations shown in Table 1). The restriction of high-solute water to lower elevation is consistent with discharge of a deep groundwater source from below.

(5) The fraction of bedrock groundwater calculated from the mixing model is generally higher during drier periods at La Selva, and lower during wetter periods. This is consistent with the higher solute water being derived from a deeper source not sensitive to moisture conditions at La Selva, as expected for interbasin transfer.

(6) Preliminary water budgets demonstrate interbasin transfer into the Arboleda watershed. Stream discharge from both the Arboleda and Taconazo watersheds (46 and 26 ha, respectively) is measured at V-notch weirs. Detailed analysis of streamflow and ET measurements is underway for separate publication, but even a simple analysis is sufficient to unambiguously demonstrate interbasin transfer. Preliminary water budgets for the two watersheds were computed for a 12-month period (July 1998–June 1999; Fig. 9) using streamflow and rainfall data and two assumptions: (1) no change in water storage on the watersheds, and (2) ET was equal to 2228 mm, half of rainfall (Luvall, 1984). On this basis, rainfall on the Taconazo (4456 mm) is almost exactly accounted for by the sum of streamflow and ET (2213 and 2228 mm, respectively). This is consistent with chemical data that show the fraction of bedrock groundwater in the low-solute streamwater of the Taconazo is consistently indistinguishable from zero. Streamflow from the high-solute Arboleda averaged 42% bedrock groundwater and was much greater (12,371 mm, based on weir measurements) than the 4456 mm rainfall onto the watershed. The chemical and streamflow data suggest an interbasin transfer of 5196 mm of bedrock groundwater. This large transfer, more than the total rainfall, is roughly ten times larger than the uncertainty in its calculation.

The remaining 7175 mm of streamflow from the Arboleda (12,371 − 5196) was due to low-solute local water, though rainfall only contributed about 2228 mm to this. Most of the local water exported by streamflow must have been due to an interbasin transfer of local water into the Arboleda (about 4947 mm), something that would have been impossible to detect with chemical data alone. It is reasonable to ask whether all the interbasin transfer into the Arboleda (local water and bedrock groundwater) should be considered as a single source rather than two sources, though we think distinguishing two sources is more sound and consistent with the local hydrogeology. The chemical mixing line on which water samples fall clearly indicates two distinct waters, including a high-solute source with concentrations at least as high as at Guacimo Spring. If a single source accounted for all the interbasin transfer to the Arboleda watershed, that source would necessarily have lower solute concentrations than those at Guacimo Spring (by almost half). There is no plausible mechanism by which bedrock groundwater (as sampled at Guacimo Spring) could lose half its solute load in the few km between the spring and the Arboleda watershed. Its concentration could be reduced by mixing with overlying local water, though that is equivalent to saying that interbasin transfer into the Arboleda consists of both bedrock groundwater and local water; we think this is a more correct way to view the overall water budget in the Arboleda.

6. Summary

Interbasin transfer of deep groundwater adds substantially to the water and chemical fluxes into and through lowland rainforest watersheds at La Selva Biological Station in Costa Rica. We expect this conclusion would apply to other locations in the foothills and transitional lowlands along Costa Rica's

Cordillera Central (Pringle et al., 1993; Pringle and Triska, 2000). The work of Tóth (1962, 1963) and others suggests this phenomenon may be widespread (though perhaps difficult to detect in the field). At La Selva we found two direct hydrogeological signals of interbasin transfer: a large chemical contrast between interbasin transfer and local water (the principal basis for the results presented here) and a discrepancy in watershed-scale water budgets (ongoing work for which preliminary results were discussed in Section 5.3).

Most of the variability in water chemistry at La Selva can be explained by mixing of two distinct water sources: high-solute bedrock groundwater and low-solute local water. In addition, evidence summarized in Section 5.3 indicates that bedrock groundwater represents subsurface interbasin transfer into watersheds at La Selva. The fraction of water due to interbasin transfer (f_{water}) ranged from zero to about 0.49 for major streams at La Selva; f_{water} values were even higher (up to 0.84) for small riparian seeps and shallow groundwater near the Salto stream. The relative contribution of chemicals (major ions) by interbasin transfer was even more significant than of water itself. f_{water} values of 0.49 and 0.84 correspond to f_{Cl} values of 0.92 and 0.99, respectively (f_{Cl}, the fraction of dissolved chloride in a La Selva water sample that is due to interbasin transfer, is approximately equal to the fraction of all major ions contributed to the sample by interbasin transfer, given the observed correlation between Cl and the other major ions). f_{water} and f_{Cl} of streams and riparian seeps varied on both long (monthly/seasonal) and short (storm event) time scales, in each case decreasing as conditions at La Selva became wetter (in accord with an increasing contribution from lower-solute local water).

The high f_{water} values found in riparian groundwater and seeps indicate that local water and high-solute bedrock groundwater derived from interbasin transfer mix in the shallow subsurface at La Selva, not just in stream channels. The proportion of local water in riparian groundwater samples increases closer to the foot of adjacent hillslopes (the sources of local water drainage to the riparian zones). With f_{water} values up to 0.84, it appears that some areas of riparian wetland (e.g. the swampy area between the Salto and Pantano streams) may be maintained largely by interbasin transfer.

Interbasin transfer accounts for almost half the discharge in some streams (the Arboleda and Salto), over 80% of some subsurface water samples, and well over 90% of the major ions in many stream and subsurface water samples. This suggests the potential ecological significance of deep groundwater discharge in the Costa Rican lowlands (e.g. Pringle et al., 1993). Water and solutes from interbasin transfer affect both terrestrial (e.g. wetland) and aquatic ecosystems. For example, waters affected by interbasin transfer at La Selva have elevated phosphorus concentrations, up to 300 ppb SRP in some riparian seeps (Pringle et al., 1990). These high SRP levels increase rates of algal growth (Pringle and Triska, 1991) and microbially mediated decomposition (Ramirez, 2000; Rosemond et al., 2001).

These results suggest the importance of a regional approach to land use planning in this and similar environments with long-range hydrogeochemical connections through groundwater systems. Costa Rica experienced rapid deforestation (about 40,000 ha/year) in the 1980s; more recently the rate has fallen to about 8000 ha/year (e.g. Pringle et al., 2000). Some forests remain at risk, at least from squatters if not large scale logging operations (Pringle and Scatena, 1999). Forests in the area around La Selva are being cleared as a result of population growth and associated urban and agricultural expansion, particularly linked to the increase in banana cultivation during the 1990s (Pringle and Scatena, 1999). Deforestation and other changes in land use could affect the quantity and quality of water at La Selva and other 'protected' areas, if these changes reduce, contaminate, or otherwise alter recharge to the deep groundwater systems that discharge in the lowlands. Complete protection of lowland streams, wetlands, and ecosystems at La Selva requires protection of a deep interbasin groundwater system whose precise volume, boundaries, and recharge areas are not presently known. Recharge likely occurs on Volcan Barva and/or adjacent uplands, but further study of subsurface geology and hydraulic head conditions are needed to define flowpaths and travel times. This would help quantify the susceptibility of specific lowland areas to alterations in land use and groundwater flow from adjacent uplands.

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