Supplementary Material

The provenance and persistence of the perennial Río Loa in the Atacama Desert: Links between crustal processes and surface hydrology.

John Houston

Correspondence: houston.jft@gmail.com

S1. Minor Springs

Apart from the major springs that represent surface water sources, given in the main text (Table 4) and incorporated into the main text analysis, small springs occur at several locations in the Loa catchment (main text Fig 2b): (a) near Angostura in the centre of the Calama Basin, (b) Laguna Inca Coya a doline close to the confluence of the Ríos Loa and Salado in the centre of the Calama Basin, (c) an unamed spring adjacent to the Río Salado between localities 17 and 18, (d) Aguada de la Teca in the south-east of the Calama Basin, and (e) Chitor in the central eastern part of the Calama Basin. The combined flow from these disparate springs was ≤ 0.02 m^3/s in March 2000, so that although their chemistry is interesting (see Table S4) they do not appear to be volumetrically important.

Table S1 Small spring chemistry compared with adjacent river or groundwater source.

Fig 2 ref #	Location	Date	Lat	Long	Elevation (m a.s.l.)	pH	TDS	Na	K	Ca	Mg	HCO3	SO4	Cl	mean ionic ratio	correlation coefficient	^{3}H (TU)
										mg/L							
a	Angostura spring	Mar-00	-22.46	-68.73	2475	6.62	3950	1054	59	156	91	470	198	2015	a/9 =	a:9 =	n/a
9	Rio Loa Angostura	Mar-00	-22.46	-68.73	2460	7.7	3431	920	55	180	83	233	161	1800	1.223	0.994	n/a
b	Chiu chiu doline	Mar-00	-22.33	-68.60	2545	8.1	4486	1290	103	149	85	93	166	2600	b/16 =	b:16 =	n/a
16	Rio Salado Chiu chiu rd	Mar-00	-22.33	-68.56	2555	7.21	3350	996	73.3	136	66	239	99	1740	1.234	0.993	n/a
c	Rio Salado spring	Mar-00	-22.28	-68.23	3090	7.4	5947	1660	117	356	106	811	127	2770	c/21 =	c:21 =	1.71±0.21
21	Rio Salado	Mar-00	-22.28	-68.23	3060	7.6	6839	2100	76	409	158	283	93	3720	1.264	0.979	n/a
d	Aguada la Teca	Mar-00	-22.60	-68.53	2950	7.8	798	70	2.4	147	18	158	331	71			1.98±0.22
22	El Tatio outflow	Mar-00	-22.33	-68.03	4228	7.9	4813	1630	123	87	10	77	75	2810	22/e =	22:e =	n/a
e	Chitor spring	Mar-00	-22.42	-68.17	3720	7.8	5385	1520	127	61	107	310	250	3010	0.720	0.993	n/a
PL	PL avg - Sn. Low. Aq.	Mar-00	-22.48	-68.55	2612	6.4	12028	3580	156	1023	142	633	490	6005	e/PL =	e:PL =	n/a
															0.510	0.985	

In Table S1 comparative samples for major ion analysis are given for March 2000. All spring samples were 22-26% more concentrated than the adjacent river sample, but otherwise indistinguishable (major ion correlation coefficients 0.979-0.993; $p<0.001$), suggesting that the springs incorporated small fluxes from adjacent bank or active storage during the waning stage of interflow. However, Chitor spring falls on an evolutionary path for Na:Cl and SO_4:Cl from El Tatio to the Southern Lower Aquifer (PL), a potential flow path distinct from others in the catchment. Aguada de la Teca stands alone with a low TDS, whilst having relatively high Ca and HCO_3 and a ^{3}H value of 1.98 TU, suggestive of modern water entering from the south-east.

The results for springs a-c therefore preclude the possibility of their origin being from the Lower Aquifers in the Calama Basin, although the sample from Chitor (e) does not.

S2. Precipitation-runoff

Detailed analysis of the upper station hydrographs indicates a variable component to flow in some years. The variable component is taken to be flow rates above the given time-invariant component. By correlating daily rainfall with daily time-variant flow above a threshold (equal to time-invariant flow) and lagged by 1-5 days gives an indication of its significance. For the Río Salado at El Sifon (locality 17) the maximum correlation coefficient (r) with rainfall is 0.159 at a lag of 3 days ($N=9484$, $p<0.0001$), and for the Río Loa antes Lequena (locality 12) the maximum r is 0.233 at a lag of 1 day ($N=8707$, $p<0.0001$). Furthermore the significant correlation between rainfall and runoff greater than time-invariant flow occurs on average 18 days/year in the Río Salado and 28 days/year in the Río Loa. This illuminates the role of precipitation in generating time-variant flow, either by direct runoff or via interflow, whilst the shorter lag time for the Río Loa compared with the Río Salado suggests higher runoff - lower infiltration rates in the former catchment.

S3. Calculation of evaporation

Pan evaporation was corrected for actual evaporation at several sites within the Río Loa catchment (Houston, 2006) using a pan factor and multiplied by the evaporating area, which has been estimated as the product of riparian width and channel length to provide an estimate for catchment evapotranspiration (Table S2). Whilst channel length is known, the width contributing to evaporation is not. The width in Table S2 was iteratively changed until bulk evaporation losses were close to those estimated from the kinetic fractionation of ^{18}O (see main body text, section 4.4) equal to 34% of low flow for the Río Loa and 21% for the Río Salado. On this basis contributing widths orthogonal to the rivers are 20 m and 43 m for the Ríos Salado and Loa respectively. Such widths can be justified on the basis that they fall within measured riparian widths, coupled with the observation that the Río Salado is constrained by a narrow canyon throughout much of its length from its source to El Sifon, whilst the Loa flood plain is considerably wider, especially in the Calama Basin.

Table S2 Estimated catchment evaporation rates

	Salado El Sifon	Loa antes Lequena	Calama Yalquinche
Aerially weighted catchment elevation (m a.s.l.)	4216	4157	3650
Pan evaporation rate (mm/d)*	4.7	5.2	6.1
Pan factor pan>actual	0.88	0.88	0.88
Actual evapotranspiration rate (mm/d)	4.2	4.6	5.3
Reach length (km)	61	69	104
Reach riparian width (m)**	15	33	33
Actual evapotranspiration rate (m^3/s)	0.044	0.121	0.212
Actual evapotranspiration as % of baseflow	12%	20%	19%

* Houston, 2006

**based on balancing actual evaporation with $\delta^{18}O$ kinetic evaporation - see text

S4. Diffusivity

Diffusivity is defined as $D = Kb / Sy$ (main text equation 4). It is possible to make an informed guess for the bulk physical properties of the storage reservoirs, although such combinations are not unique. With D between ~1500-1900 m^2/s (main text Table 1 and Supplementary Table S2) for the upper subcatchments and assuming $Sy = 0.01$, and $b = 200$ m, K would be between 7-9x10^{-2} m/s, indicative of unconsolidated coarse clastic or pyroclastic deposits. For the total catchment at Calama the extremely high diffusivity is probably due to deep circulation in the Calama Basin. Thus, increasing b to 1000 m, the hydraulic conductivity would be ca. 2x10^{-1} m/s. This storage coefficient is chosen to represent semi-confined conditions, to be expected in these heterogenous, layered aquifers, whilst the values of inferred hydraulic conductivity are appreciably greater than pumping test values in the Calama and Turi Basins (Houston, 2004), conceivably due to scaling differences.

Table S3 Aquifer physical properties based on subcatchment diffusivity

	Salado El Sifon	Loa antes Lequena	Calama Yalquinche
$D = 4L^2 / \pi^2 k$ (m^2/s)	1509	1930	17538
Sy	1.0E-03	1.0E-03	1.0E-03
b (m)	200	200	1000
K (m/s)	7.5E-03	9.7E-03	1.8E-02
Calama basin ppg test K			1.2E-03
Turi basin ppg test K	2.3E-04		

S5. Saturation Indices

Calculated using PHREEQC (Parkhurst and Appelo, 2013) with the <phreeqc.dat> thermodynamic database for DIC, P_{CO2}, and saturation indices (SI) for calcite, dolomite, gypsum and quartz (see main text section 4.1).

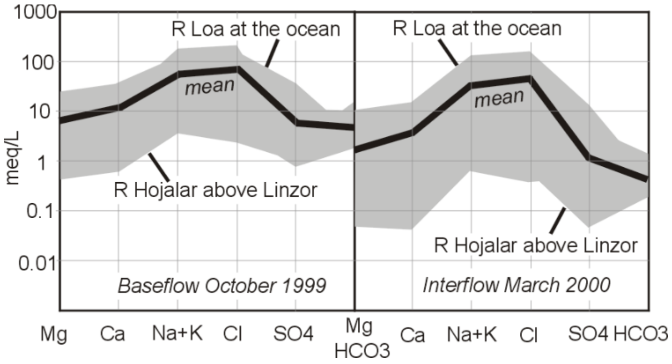
Table S3 Saturation indices for baseflow samples

Fig 1 ref #	Location	River system	Dist from ocean (km)	pH	DIC mmol/L	$SI_{calcite}$	$SI_{dolomite}$	SI_{gypsum}	SI_{quartz}
1	Rio Loa al mar	Loa	0	7.0	3.9	0.14	0.29	-0.31	0.89
2	Rio Loa Quillagua	Loa	60	7.8	6.2	0.99	2.15	-0.77	0.93
3	Cruce Las Torres	Loa	138	8.7	6.1	1.45	3.77	-0.91	0.96
4	Rio Loa Chacance	Loa	173	7.8	7.8	0.89	1.26	-0.87	0.98
5	Rio San Salvador Chacance	San Salvador	175	8.1	7.6	1.36	2.79	-0.84	1.12
6	Ojos de Opache	San Salvador	226	7.9	7.2	1.16	2.32	-1.02	1.15
7	Rio Loa Cascad	Loa	228	8.1	6.7	1.36	2.78	-1.29	1.11
8	Rio San Salvador above OdeO	San Salvador	231	8.2	7.8	1.43	2.79	-0.82	0.79
9	Rio Loa Angostura	Loa	258	8.0	7.8	1.22	2.41	-1.19	1.04
10	Rio Loa Lasana	Loa	281	8.4	6.7	1.32	2.92	-1.49	1.02
11	Rio Loa above Conchi	Loa	333	8.0	11.7	0.71	1.43	-1.36	1.16
12	Rio Loa above Bol rly	Loa	370	7.8	4.5	0.45	0.73	-1.43	1.17
13	Chela sp	Loa	411	8.3	3.2	0.93	1.24	-1.61	1.18
14	Ojos de San Pedro	San Pedro	351	8.3	5.8	0.18	0.49	-1.94	1.25
15	Incaliri	San Pedro	363	8.0	2.1	-0.32	-0.69	-2.43	0.99
16	Rio Salado Chiu Chiu rd	Salado	312	8.0	4.3	0.81	1.79	-1.69	1.00
17	Rio Salado Sifon	Salado	321	8.0	11.0	0.53	0.87	-1.60	1.18
18	Rio Toconce at Toconce repr	Toconce	341	8.1	1.6	-0.09	-0.29	-2.60	1.13
19	Rio Toconce at Linzor	Toconce/Hojalar	360	7.3	6.8	-1.50	-3.01	-2.43	1.15
20	Rio Hojalar above Linzor	Toconce/Hojalar	356	8.1	2.4	-0.79	-1.58	-2.83	1.11
21	Rio Salado	Salado	332	7.7	1.4	1.24	2.60	-1.58	0.79
22	El Tatio outflow	Salado	359	7.4	2.0	0.02	-0.98	-1.81	1.46

S6. Interflow vs baseflow chemistry

Interflow chemistry sampled in March 2000 shows dilution when compared with baseflow chemistry sampled in October 1999 (main text, Table 4). The Schoeller plot (Fig S1 below) shows concentrations of samples for the two conditions. Interflow demonstrates similar characteristics to the baseflow samples, the main difference being a concentration dilution across all ions of 16-24%.

Figure S1 Comparison of ionic strengths of interflow and baseflow for the Río Loa catchment using a schoeller plot of the data in Table 4, main text.



Supplementary References

Houston, J., 2004. High-resolution sequence stratigraphy as a tool in hydrogeological exploration in the Atacama Desert. *Quarterly Journal of Engineering Geology and Hydrogeology*, *37*(1), pp.7-17.

Houston, J., 2006. Evaporation in the Atacama Desert: An empirical study of spatio-temporal variations and their causes. *Journal of Hydrology*, *330*(3-4), pp.402-412.

Parkhurst, D.L. and Appelo, C.A.J., 2013. Description of input and examples for PHREEQC version 3—a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. *US geological survey techniques and methods, 6*(A43), p.497.