

1 Household and climate factors influence *Aedes aegypti* presence in the arid city of Huaquillas,
2 Ecuador

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26 **Abstract**

27 Arboviruses transmitted by *Aedes aegypti* (e.g., dengue, chikungunya, Zika) are of major public
28 health concern on the arid coastal border of Ecuador and Peru. This high transit border is a critical
29 disease surveillance site due to human movement-associated risk of transmission. Local level
30 studies are thus integral to capturing the dynamics and distribution of vector populations and
31 social-ecological drivers of risk, to inform targeted public health interventions. Our study
32 examines factors associated with household-level *Ae. aegypti* presence in Huaquillas, Ecuador,
33 while accounting for spatial and temporal effects. From January to May of 2017, adult mosquitoes
34 were collected from a cohort of households (n = 63) in clusters (n = 10), across the city of
35 Huaquillas, using aspirator backpacks. Household surveys describing housing conditions,
36 demographics, economics, travel, disease prevention, and city services were conducted by local
37 enumerators. This study was conducted during the normal arbovirus transmission season (January
38 - May), but during an exceptionally dry year. Household level *Ae. aegypti* presence peaked in
39 February, and counts were highest in weeks with high temperatures and a week after increased
40 rainfall. Univariate analyses with proportional odds logistic regression were used to explore
41 household social-ecological variables and female *Ae. aegypti* presence. We found that homes were
42 more likely to have *Ae. aegypti* when households had interruptions in piped water service. *Ae.*
43 *aegypti* presence was less likely in households with septic systems. Based on our findings,
44 infrastructure access and seasonal climate are important considerations for vector control in this
45 city, and even in dry years, the arid environment of Huaquillas supports *Ae. aegypti* breeding
46 habitat.

47

48 **Author summary**

49 Mosquito transmitted infectious diseases are a growing concern around the world. The yellow
50 fever mosquito (*Aedes aegypti*) has been responsible for recent major outbreaks of disease,
51 including dengue fever and Zika. This mosquito prefers to bite humans and lay its eggs in artificial
52 containers such as water tanks and planters. This makes *Ae. aegypti* well suited to become
53 established in growing urban areas. Controlling these mosquitoes has been an important way to
54 reduce the risk of disease transmission. Studies that are undertaken to understand local factors that
55 contribute to the continued survival of the mosquito can be used to inform control practices. We
56 conducted a study in the largest Ecuadorian city on the border of Peru where we collected adult
57 mosquitoes from houses and surveyed household members about their behaviors, perceptions, and
58 housing infrastructure associated with the mosquito vector. Mosquitoes were most numerous in
59 weeks with high temperatures and a week after increased rainfall. We found that houses that had
60 unreliable water service were more likely have mosquitoes present, while houses that used septic
61 systems were less likely to have mosquitoes present.

62 **Introduction**

63 Arboviral diseases are an increasing global concern [1], exemplified by the large health
64 burden of dengue fever, where 58.4 million cases are reported annually worldwide [2]. The yellow
65 fever mosquito (*Aedes aegypti*) is the primary vector of dengue virus (DENV) and other medically
66 important arboviruses such as chikungunya, yellow fever, and Zika [1,3]. This mosquito species
67 is well-adapted to urban environments, as it is an anthropophilic container breeder that readily
68 exploits the built environment for ovipositional sites [4]. Globally, increasing trends in
69 urbanization, international trade, and travel have further facilitated the spread and establishment
70 of *Ae. aegypti* over the years, and consequently, the diseases it transmits [5].

71 Vector control remains a primary strategy in controlling arboviral diseases [6], largely due
72 to limited options for clinical treatment, and with the exception of yellow fever, lack of widely
73 marketable vaccines [7,8]. Although an integral tool in mosquito-borne disease management, there
74 is often a need to target mosquito control efforts, both to improve their effectiveness and to
75 conserve limited public health agency resources. *Aedes aegypti* mosquitoes are sensitive to abiotic
76 environmental factors such as climate, including temperature, rainfall and relative humidity, all of
77 which can be highly variable at fine spatial scales and influenced by features of the built
78 environment [9]. Further, the anthropophilic nature of *Ae. aegypti* mosquitoes makes them
79 sensitive to certain human behaviors and activities, [10] such as household water storage practices
80 or use of insecticides. Social-ecological factors that modulate vector populations represent
81 potential targets for mosquito control interventions. However, it has become increasingly apparent
82 that local drivers of vector populations can vary greatly in space and time [11,12], which has
83 significant implications for the planning of successful public health vector control programs. It is
84 therefore important to examine both the social and ecological components of a local environment

85 to understand sub-city risks of vector presence, and potential leverage points for intervention.
86 Thus, local studies conducted at appropriate spatiotemporal scales are necessary to assess place-
87 specific drivers and inform interventions [13].

88 The South American country of Ecuador has a history of high arboviral disease burden
89 [14,15]. Yellow fever dominated during early 20th century, and at the beginning of the 21st century
90 dengue fever emerged as the principal mosquito-borne disease, coinciding with a decline in
91 malaria cases [16,17]. More recently, the introduction of new viruses, such as chikungunya and
92 Zika, has resulted in major epidemics throughout the region [18]. There have been multiple studies
93 in recent years that have examined the influence of climate and social-ecological factors on *Ae.*
94 *aegypti* in coastal Ecuador [10,14,19–24]. These studies typically feature analyses conducted with
95 data aggregated to neighborhoods or census blocks, and much of the literature is primarily focused
96 on the city of Machala, Ecuador, located in El Oro province on the country’s southern coast.
97 Machala is an urban center with a steppe climate (BSh) per the Köppen climate classification
98 system, indicating conditions intermediate between desert and humid climates. Studies conducted
99 in Machala have repeatedly found that both climate and social-ecological factors influence the
100 presence of both immature and adult *Ae. aegypti* in neighborhoods, providing local health
101 authorities with valuable information for guiding local mosquito control campaigns [10,19–24].

102 To date, there have been no studies examining the impacts of climate and social-ecological
103 system (SES) on *Ae. aegypti* in the desert climates of Ecuador. Huaquillas is located in El Oro
104 province, on Ecuador’s southern border with Peru. Huaquillas has a distinct arid climate compared
105 to other coastal locations in Ecuador where previous vector-borne disease studies have typically
106 been conducted. Further, the position of Huaquillas near an international border presents an
107 additional opportunity for studying disease vectors in a novel SES within Ecuador. Differences in

108 environment, socio-economic status, access to healthcare, healthcare practices, and vector control
109 practices between countries can impact the burden of disease, abundance of vectors, and infection
110 levels of vectors, potentially leading to drastic differences in the SES of Huaquillas, relative to
111 other communities in Ecuador [25,26]. Cities along borders, such as Huaquillas, may also have
112 larger migrant populations than other cities, or may be a through-way for migrating populations,
113 who can serve as reservoirs of vector-borne disease [27,28]. Thus, describing the characteristics
114 that influence vector presence within Huaquillas may help in developing intervention strategies
115 that are tailored to meet the challenges of delivering effective mosquito control in a unique SES.

116 This study aims to describe the climatic and social-ecological aspects of household-level
117 *Ae. aegypti* presence in the arid border city of Huaquillas. These insights can lead to a better
118 understanding of how this vector-borne disease system functions and where potential levers of
119 control might be found. The knowledge gained can help inform intervention decisions in
120 Huaquillas and other similar settings. Additionally, this study, in combination with similar local-
121 scale studies in the region, can help answer questions relating to scale and heterogeneity in
122 arboviral disease systems.

123

124 **Methods**

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126 **Ethical review**

127 This study protocol was reviewed and approved by Institutional Review Boards (IRBs) at SUNY
128 Upstate University, the Luis Vernaza hospital in Guayaquil, Ecuador, and the Ministry of Health
129 of Ecuador. Prior to the start of the study, adult participants (≥ 18 years of age) engaged in a written

130 informed consent (conducted in Spanish). To protect the privacy of participants, data were de-
131 identified prior to use in any of the analyses conducted in this study.

132

133 **Study site**

134 Huaquillas is a coastal city located in southern Ecuador's El Oro province, with a population of
135 48,285 (Fig 1) [29]. Situated in a low-lying coastal region (3°28'33"S, 80°13'33"W; 15m
136 elevation), the city is highly suitable for *Ae. aegypti*, as underscored by endemic transmission of
137 DENV, which has led to major outbreaks of dengue fever in recent years [22]. Regionally, dengue
138 outbreaks in coastal Ecuador tend to peak during the hot and rainy season, which typically begins
139 in January [30]. Huaquillas is the primary crossing at Ecuador's southern border with Peru, and
140 became a major hub of transit and economic exchange between the two countries, following an
141 agreement to open the border in the 1990's [31,32]. In terms of total migration, Huaquillas is the
142 third most active city in Ecuador, with 622,405 arrivals and departures annually [31]. Increased
143 binational cooperation with Peru and the relaxation of trade and travel barriers in recent decades
144 has contributed to increased urban development at the border [33].

145

146 **Fig 1. Map of the study area.** Huaquillas is located within South America, Ecuador, and El Oro
147 province. The map includes household cluster locations where sampling took place (white circles
148 denote areas where up to 5 houses were sampled, but precise household locations are not shown,
149 to protect identities) and the population density of Huaquillas at the census tract level. A)
150 location of Ecuador, B) location of El Oro province, C) location of Huaquillas (red), D)
151 Huaquillas population and sampling sites. This figure was produced in ArcMap 10.6.1 (ESRI,
152 Redlands, CA) using shapefiles freely available from the Natural Earth dataset ver. 4.1.0
153 (naturalearthdata.com) and georeferenced census data (2010) provided by the Ecuadorian
154 National Institute of Statistics and Census (INEC) and edited by JLM.

155

156 Huaquillas has a hot desert climate (BWh) per the the Köppen climate classification system [34].
157 While desert climates are often characterized by limited precipitation, intense sunlight, and little

158 vegetation, actual conditions can vary greatly by place. Huaquillas experiences a monsoon season
159 which occurs during the first half of the year, with monthly total rainfall peaking in February at
160 128 mm (Fig 2). Increased precipitation coincides with high temperatures. Annual mean
161 temperature ranges from 21.6-27.6°C. Minimum daily temperatures range from 18.8—22.3°C
162 annually and maximum daily temperatures range from 25.8—33.0°C annually. Fig 2 shows a
163 comparison of historic long-term average climate data (2000-2012) provided by the National
164 Institute of Meteorology and Hydrology (INAMHI), Ecuador, and the data provided by INAMHI
165 for the study period (2016-2017).

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176 **Fig 2. Climate in Huaquillas, Ecuador.** Monthly mean temperature in red and total monthly
177 precipitation as blue. Solid lines represent the climate during the study period (2016-2017) while
178 box plots represent the climatology from 2000-2012 (historical monthly averages and 95%
179 confidence intervals).

180

181 **Data sources**

182 All data cleaning and processing was conducted in R version 3.5.1 [35].

183 *Climate data* – The National Institute of Meteorology and Hydrology (INAMHI), Ecuador,
184 provided hourly climate data (March 2016—December 2017) from an automatic weather station
185 in Huaquillas. These data included minimum, maximum, and mean temperature, and total daily
186 precipitation. Hourly climate data were aggregated to weekly measures to match the resolution of
187 entomological sampling events for statistical analyses. Hourly precipitation readings during that
188 period were summed for weekly precipitation, and hourly temperature data were used to derive
189 daily mean, minimum, and maximum temperatures.

190

191 *Participating households* – Households were invited to participate in this study using a semi-
192 random selection process to capture clusters of households facing similar risk of exposure to *Ae.*
193 *aegypti* mosquitoes. Ten central households, representing the center of clusters, were chosen
194 throughout Huaquillas to maximize geographic coverage. Each cluster consisted of the central
195 household, and up to five additional households randomly enrolled into the study from within a
196 250m radius of the central household, a distance that approximates the flight range of *Ae. aegypti*
197 [36]. Enrolled houses were georeferenced onsite using handheld global positioning system (GPS)
198 units and given specific house and cluster codes. The resulting cohort of households was a
199 favorable balance between sufficiently accounting for the heterogeneity of the urban
200 environment in Huaquillas and the logistical feasibility of regularly visiting the households for
201 data collection.

202

203 *Household mosquito samples* – Teams of field technicians visited households biweekly during
204 January—May 2017 to collect adult mosquitoes from households using Prokopak backpack
205 aspirators. During a sampling event, all participating households in a cluster were surveyed for

206 adult mosquitoes. Not all clusters were sampled in a given sampling day for logistical reasons,
207 and consequently individual households were sampled for mosquitoes at 2-3 week intervals.
208 Mosquito collections were conducted during the daytime. The entomological sampling protocol
209 consisted of one technician operating the backpack aspirator and sampling the intradomicile (i.e.
210 within the home) for 20 minutes and the peridomicile (i.e. courtyard or patio associated with
211 home) for 10 minutes. Each room within a given household was sampled, starting at the floor,
212 sampling under furniture, and working up to the ceiling. Adult mosquitoes collected via
213 aspiration were stored on ice in a cooler and were transported to the entomology lab at the
214 Universidad Técnica de Machala, Ecuador, 74km by vehicle, where specimens were enumerated,
215 sorted by sex, and identified (i.e., *Ae. aegypti* and other). Due to low counts (e.g. <10),
216 household *Ae. aegypti* abundance was summarized as binary outcomes. Sampling events were
217 classified as “positive” if female *Ae. aegypti* mosquitoes were present in a given household, and
218 the proportion of positive households for each week was calculated for statistical analysis to
219 account for temporally discontinuous abundance sampling [37].

220

221 *Household surveys* – Upon study enrollment, field technicians administered a survey
222 questionnaire to the head of household (HOH); the complete survey tool is available in both
223 English and Spanish elsewhere [38]. Using the survey tool, technicians collected data on
224 household demographics, HOH occupation, household expenditures, access to public services,
225 knowledge and perceptions of mosquito-borne disease, and mosquito control and prevention
226 practices [38]. Field personnel concurrently performed an on-site visual assessment of housing
227 structures and conditions, following protocols used in previous studies conducted in the region

228 [10,38]. Collectively, data recorded during household surveys comprise the social-ecological
229 system (SES) variables used in statistical analyses.

230

231 **Statistical Analyses**

232 *Household mosquito samples* – To assess climate lags on household-level presence of female *Ae.*
233 *aegypti* in the study group, at a monthly scale, only households with sampling events in all
234 months were included. For each household, if multiple collections occurred in a month, one
235 collection record was randomly selected to represent *Ae. aegypti* presence in that month.

236 Cross correlation function (CCF) plots were visualized in R version 3.5.1 [35] for *Ae. aegypti*
237 presence and climate variables (precipitation, mean, maximum, and minimum temperature)
238 lagged from 0 to 6 weeks. Shapiro-Wilk normality tests indicated that the mosquito presence data
239 did not violate assumptions, while the temperature and precipitation variables did [39]. We therefore
240 ran Spearman's rank correlation tests on the lagged climate variables [40] (S1 Fig). Statistically
241 significant climate indicators were used to construct a beta regression model (link=logit,
242 link.phi=identity) in R with the package “betareg” [41,42] to capture the relationship between
243 climate and the proportion of positive households in sampling clusters [41,43]. Model residuals
244 were checked for normality with the Shapiro-Wilk test, and for autocorrelation with the
245 autocorrelation function in R.

246

247 *Social-ecological system (SES) models of household factors and Aedes aegypti presence* –
248 Associations between survey responses and household female *Ae. aegypti* presence during the
249 study period were measured using univariate statistical tests. Questions that addressed social-
250 ecological factors hypothesized to be important for vector population dynamics at this study site

251 (based on previous studies in this region) were selected from the full household survey for
252 analysis [10,20,38,44]. Hypothesized factors included water storage practices, building materials,
253 and economic status. Data inclusion criteria for SES models were stringent, and survey questions
254 that had a low rate of response were excluded to minimize observations discarded due to missing
255 data. Questions that had the same response for nearly every observation were also excluded
256 because they offer little ability to differentiate between houses with and without *Ae. aegypti*.
257 Households were required to have mosquito samples in all months of the study; those with more
258 than one sampling event per month had one event randomly selected for inclusion. Intraclass
259 correlation (ICC) values for household data were near zero (ICC=0.01), indicating that the
260 clustered study design did not greatly impact variance in the data, thus precluding the need for a
261 mixed-effects modeling structure [45,46]. Univariate proportional odds logistic regression was
262 used to assess differences in survey responses by monthly household *Ae. aegypti* presence [47–
263 49]. Models to assess the relationship between ordinal mosquito sampling (i.e. the number of
264 sampling events where *Ae. aegypti* were detected) and household variables were built in R with
265 the “MASS” package [50], using the default options of the ‘polr’ function to perform
266 proportional odds logistic regressions [49,51]. The Brant test [52] was used to confirm that
267 proportional odds models did not violate the parallel regression assumption [51], and was
268 implemented with the “brant” package in R [53].

269

270 **Results**

271 Sixty-three households participated in the study, and of these, fifty-eight heads of household
272 (HOHs) (92%) responded to the survey (Fig 3). The average distance between households within
273 clusters was 86 m. A total of 458 mosquito collections occurred over 10 individual weeks of

274 sampling. For assessments of climate impacts and temporal signals, 41 houses (65%) with 205
275 mosquito sampling events met the criteria for inclusion. For assessments of household
276 characteristics and SES models, 32 houses (51%) with 160 mosquito sampling events met the
277 criteria for inclusion (S1 Table).

278

279 **Fig 3. Diagram of household enrollment and data collection for the cluster study in**
280 **Huaquillas, Ecuador.** More restrictive criteria for data inclusion were used for statistical analysis
281 of SES factors.

282

283 *Climate*

284 Weekly *Ae. aegypti* female presence was significantly correlated with precipitation, at a 1-week
285 lag ($\rho=0.84$, $p=0.002$), 3 weeks ($\rho=0.73$, $p=0.018$), and 5 weeks ($\rho=0.69$, $p=0.026$). Weekly
286 *Ae. aegypti* female presence was also significantly correlated with current week mean temperature
287 ($\rho=0.624$, $p=0.012$), and negatively correlated with maximum temperature on a 5-week lag
288 ($\rho=0.70$, $p=0.03$). Minimum temperatures during this period were not significantly correlated
289 with *Ae. aegypti* presence at any lag.

290 A beta regression of the proportion of households with female *Ae. aegypti* presence as a
291 function of the significant climate lags had a pseudo R^2 of 0.77 ($p=0.023$), and precipitation at a
292 week lag ($\beta=1.91$, $p=0.03$) and mean temperature of the week ($\beta=0.69$, $p=0.008$) remained
293 individually significant and positive in the model.

294

295 *Temporal patterns of Ae. aegypti presence*

296 The proportion of positive households was highest in February and lowest in May (Fig 4). In
297 January, the proportion of positive households was 0.38; this increased to 0.59 in February before
298 steadily declining. The monthly differences were significant ($\chi^2=9.564$, $p=0.048$), but a post hoc
299 Fisher's exact test did not identify specific month-to-month differences (S2 Table).

300

301
302 **Fig 4. Female *Aedes aegypti* presence in households in Huaquillas, Ecuador, by month in**
303 **2017.** Month proportions and 95% confidence intervals for 41 households used in this dataset.
304 Chi-squared test for difference in proportions: 9.56, $p=0.0484$).

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309 **Univariate tests for SES factors**

310 All respondents considered dengue fever to be a severe disease and correctly answered
311 questions about the transmission cycle of the disease, so these variables were not included in this
312 analysis. Univariate model parameter estimates are given in Table 1, in which the odds ratio
313 (OR) denotes risk of exposure for $OR>1$, and $OR<1$ is protective against *Ae. aegypti* presence.
314 Demographic variables and factors describing the physical conditions of households were not
315 found to be significant predictors of female *Ae. aegypti* presence (Table 1). However, one of the
316 four variables describing infrastructure and public services was significant; interruptions in piped
317 water supply (OR=4.78) was positively associated with mosquito presence. An additional
318 infrastructure variable was on the threshold of statistical significance ($p=0.051$), use of a septic
319 tank (OR=0.13), which had a negative association. Mosquito prevention methods, employment,
320 and travel habits were not found to be significantly associated with household presence of *Ae.*
321 *aegypti*.

322 **Table 1. Household level social-ecological factors associated with female *Aedes aegypti***
 323 **presence (AA) in homes in Huaquillas, Ecuador.** Significant associations ($p < 0.05$) are in bold.

SES Factor	HH ^a (n=32)	Estimate	St. Error	OR	p-value	95% CI
People Living in the House (mean)	4.5	0.15	0.16	1.16	0.348	0.85 – 1.59
Years Living in Neighborhood (mean)	7.75	0.09	0.07	1.10	0.159	0.97 – 1.25
Age of HOH (mean)	47.13	0.01	0.02	1.01	0.715	0.97 – 1.05
Female HOH	6	0.49	0.78	1.64	0.529	0.35 – 7.92
HOH Beyond Primary Education	15	0.41	0.64	1.50	0.525	0.43 – 5.39
HOH Makes Basic Income	7	0.92	0.73	2.50	0.209	0.60 – 10.89
Number of Rooms (mean)	2.69	0.33	0.37	1.39	0.363	0.68 – 2.90
Good Overall Condition	16	0.15	0.63	1.16	0.814	0.34 – 4.00
Good Flooring	14	0.74	0.65	2.10	0.251	0.60 – 7.67
Screens on Windows	7	-0.24	0.77	0.79	0.755	0.167 – 3.60
Shaded Patio	27	0.21	0.78	1.23	0.789	0.26 – 5.85
Abandoned Houses Nearby	22	-0.59	0.67	0.56	0.383	0.14 – 2.06
Unpaved Road	20	-0.16	0.63	0.85	0.797	0.24-2.96
Stores Water	24	0.69	0.75	1.99	0.356	0.46 – 8.91
Water Interruptions	8	1.56	0.78	4.78	0.044	1.09 – 24.13
Uses Septic Tank	3	-2.07	1.06	0.13	0.051	0.01 – 0.98
Biweekly Trash Collection	20	1.27	0.68	3.57	0.061	0.97 – 14.13
Outdoor Labor	13	-0.32	0.65	0.73	0.625	0.20 – 2.62
Indoor Service	16	0.04	0.63	1.04	0.953	0.30 – 3.57
Treated Water in Past 30 days	11	0.94	0.68	2.55	0.171	0.68 – 10.14
Uses Abate Larvicide	29	-1.08	0.98	0.34	0.270	0.04 – 2.36
Drains Standing water	30	-0.07	1.09	0.93	0.946	0.10 – 8.95
Closes Windows and Doors	30	0.82	1.11	2.28	0.457	0.23 – 22.79
HOH Works Outside of the City	7	0.35	0.74	1.43	0.630	0.33 – 6.19
Does Not Leave Neighborhood for Work	30	0.37	1.15	1.45	0.745	0.14 – 15.73

324 ^a= Number of households with factor

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330 **Discussion**

331 In this study we investigated the drivers of household-level female *Ae. aegypti* presence in
332 Huaquillas, Ecuador, to identify social-ecological conditions that promote potential arboviral
333 disease risk to inform vector control and intervention strategies. Precipitation during the study
334 period was anomalously low compared to long-term averages (Fig 1). In several recent studies, the
335 role of drought in altering the way water storage occurs in urban landscapes has been highlighted
336 as a potential key factor in *Ae. aegypti* habitat in urban environments [54–60]. Given this was a
337 particularly dry year, in an already arid environment, the role of precipitation in the timing of *Ae.*
338 *aegypti* presence may be different than in an average year. We found that the prior week's
339 precipitation was an important predictor of *Ae. aegypti* presence, in combination with the current
340 week's temperature. Whether the role of precipitation is emphasized or diminished in a dry year is
341 likely mediated by human-driven water storage and use on the landscape. In outdoor, rain-filled
342 habitats, accumulated precipitation can generate oviposition sites for *Ae. aegypti*, but extreme
343 precipitation events can flush out those same larval habitats [61,62]. Thus, the relationship between
344 precipitation and vector population size is not linear, and may depend more on the intensity of
345 precipitation events [13,63]. In our study, *Ae. aegypti* presence was significantly correlated with
346 precipitation lagged by 1, 3, and 5 weeks, individually, but when included in a model with
347 temperature, the longer lags were no longer individually significant. In rain-filled habitats,
348 precipitation events increase the suitability of larval habitats, prompting eggs of *Ae. aegypti* to
349 hatch and begin development [64]. The 1-week lag in precipitation likely indicates sufficient
350 humidity and moisture for mosquito activity in the current week, and perhaps serves to trigger egg
351 hatching, but is likely too short a time-frame for development to flying adults. The 3-week and 5-
352 week lags identified in this study are longer than the typical development time for *Ae. aegypti* [65],

353 however in an arid environment such as this, larval habitat may dry after precipitation events,
354 increasing the time necessary to develop [66,67]. In the urban environment, the timing and degree
355 to which precipitation influences vectors is also highly modulated by the social-ecological
356 environment [10,68]. The role of precipitation may be more identifiable when containers and
357 buckets are visibly on household premises, but is diminished when alternative oviposition sites
358 such as water storage tanks, cisterns, and other water infrastructure sites are available [54,69].

359 During the study period, mean temperatures in Huaquillas were within historical ranges
360 (Fig 1). Laboratory studies of *Ae. aegypti* have found nonlinear relationships between mean
361 temperature and physiological traits [70,71]. The weekly mean temperatures assessed in our climate
362 analysis ranged from approximately 26 and 28°C. Biting, development, fecundity, and mortality
363 have been shown to be positively correlated with mean temperatures within this range [72]. We
364 found that weekly *Ae. aegypti* presence was significantly associated with mean temperatures of
365 the same week. This captures the immediate effect of temperature on *Ae. aegypti* presence in
366 households where people reside [73]. Outdoor temperatures higher than 21°C may drive *Ae.*
367 *aegypti* indoors to reduce mortality [74]; indoor resting behavior is characteristic of *Ae. aegypti*,
368 especially while processing blood meals [75], so sheltering in shade indoors may be an adaptive
369 strategy for cooling, when outdoor temperatures exceed optimal temperatures. Prior studies of *Ae.*
370 *aegypti* in desert climates have occurred in Texas, Arizona, and parts of Mexico [76,77]. In Mexico,
371 a study found differences in the age structure of *Ae. aegypti* populations between two cities in
372 desert and steppe climates, with older *Ae. aegypti* populations in the desert [76]. While precipitation
373 did not differ much between the two sites, the cooler steppe population underwent a period of low
374 humidity, which may impact survival. This is important for disease transmission, as *Ae. aegypti*
375 must live long enough to feed and become infectious, and the authors suggested that the higher

376 population turnover in the steppe may contribute to the surprising lack of dengue establishment.
377 This points to the complexities of interactions between temperature (which can exceed optima for
378 survival), precipitation, and sufficient humidity in an arid environment. Here, we were limited by
379 a lack of available local humidity data;. given the arid conditions in Huaquillas, investigating the
380 role that humidity plays in modulating mosquito presence and survival is a potential target for
381 future studies.

382 In this study, the presence of *Ae. aegypti* at the household level differed across months.

383 Changes in *Ae. aegypti* presence at coarse temporal scales are driven by climatic factors [78,79],
384 and increased household *Ae. aegypti* presence in Huaquillas during the study period can be
385 attributed to differences in precipitation and temperature. The seasonal nature of Huaquillas'
386 climate may thus point to time periods when targeted vector control interventions would be
387 optimally effective.

388

389 **Social-ecological drivers of risk**

390 In univariate models, we found that only factors related to infrastructure were significant predictors
391 of *Ae. aegypti* presence. Interrupted water supply was the only statistically significant risk factor
392 identified in this study, where having an unreliable water supply in the household was associated
393 with increased risk of mosquito presence. The role of water infrastructure in exposure risk to *Ae.*
394 *aegypti* at the household level has been found in previous studies, and points to the fundamental
395 and vital role reliable water supply and urban infrastructure play in *Ae. aegypti* endemic
396 environments [80]. Notably, the link between interruptions in water service and either *Ae. aegypti*
397 presence or dengue fever risk has been documented previously in Ecuador, in the coastal city of
398 Machala [38,80]. Unreliable water sources underpin many of the water storage behaviors that create

399 suitable ovipositional sites for *Ae. aegypti*, such as when water for household activities (e.g.
400 bathing, washing clothes, etc) is stored in open containers, such as buckets, drums, or basins.
401 Further, the arid climate of Huaquillas may exacerbate water storing practices in absence of
402 reliable piped water. Other studies in Latin American and the Caribbean have demonstrated links
403 between drought conditions and increased mosquito abundance and dengue fever risk [22,81]. In
404 these instances, extreme climatic events like drought drive water scarcity, which in turn promotes
405 water storing practices, increasing the number of water containers in and around homes. While our
406 study was conducted in an exceptionally dry year, the long-term arid climate of Huaquillas may
407 promote greater water storage in absence of reliable water, compared to other locations in Ecuador.
408 Given the clear role of water availability, our findings suggest that urban infrastructure around
409 water supply and use is playing a large role in the risk of *Ae. aegypti* presence in the household in
410 Huaquillas. These findings have implications for Ministry of Health mosquito control efforts,
411 where emphasizing removal of standing water and features that collect water around homes may
412 supplement existing outreach messaging. More broadly, long-term interventions that target and
413 improve infrastructure, namely water reliability or water storage systems, may serve to mitigate
414 these risk factors in the future [18].

415 While our threshold for statistical significance was set at $\alpha=0.05$, it is worth noting that the
416 association between another infrastructural variable, biweekly trash collection (OR=3.57, CI: 0.97
417 – 14.13), and mosquito presence approached statistical significance ($p=0.061$). The association of
418 mosquito risk with regular trash collection seems counterintuitive, where potential ovipositional
419 sites for *Ae. aegypti* are reduced in the immediate environment. Yet, associations between garbage
420 collection and *Ae. aegypti* presence or dengue fever were also observed in Machala and Guayaquil,
421 two other coastal cities in Ecuador, possibly indicating that access to municipal services like trash

422 collection may be a proxy indicator of built environments in Ecuador that are easily exploited by
423 *Ae. aegypti* for reproduction [44,80].

424 In the single variable model, septic tanks were found to be protective against mosquito
425 presence though marginally significant (p-value=0.051, OR=0.13 CI: 0.01 – 0.98). This is perhaps
426 another counterintuitive finding, as septic tanks act as persistent oviposition sites in other locations
427 [82–84]. Yet, it must be noted that all three households with septic tanks in this study were located
428 in a single cluster. Additionally, septic tanks in Huaquillas are typically underground with no
429 suitable entrance for mosquitoes, and are used widely in the periphery of the city where sewer
430 infrastructure has only recently become available. Given that septic tanks occur in peripheral areas
431 where municipal water and sewer infrastructure is a recent addition, this relationship warrants
432 further examination.

433

434 **Conclusion**

435 In this study we explored climatic and social-ecological factors associated with household-level
436 female *Ae. aegypti* presence, and temporal and spatial trends across an arid border city in Ecuador.
437 The results of our analyses may inform potential control strategies (timing) and interventions
438 (improved water infrastructure) to reduce vector-borne disease risk in the city of Huaquillas in
439 southern coastal Ecuador. Given that this study was conducted in an exceptionally dry year and
440 the evidence for water supply and usage as major factors in household-level risk, water-related
441 interventions at multiple scales could be important.

442 The social-ecological environment that influences the urban *Ae. aegypti* mosquito varies
443 substantially from place to place. Local studies are especially needed to guide policy and inform
444 interventions. Integrated vector control requires information collection, assessment, and decision

445 making at local scales. While there is value in national to global studies of *Ae. aegypti* populations,
446 these studies produce information that is of most relevance for national or international decision-
447 makers. We acknowledge that there are logistical and resource related challenges inherent in
448 conducting investigations at smaller scales, and in this study, while leveraging an immensely rich
449 dataset over several months, we still ran into issues of small sample size. However, in order to
450 integrate social-ecological systems approaches into essential local-scale work, we suggest that the
451 design and methodological approach of this study is one example of how some of these challenges
452 can be met. Identifying local risk factors for vector presence is critical for the successful control
453 of mosquito-borne diseases, particularly in cities near international borders that serve as economic
454 and transportation hubs, like Huaquillas, which has been the focus of binational efforts with Peru
455 to control vector-borne diseases. As many parts of the world become increasingly urban and ever
456 more connected to global transportation networks, the number of places with endemic *Ae. aegypti*
457 populations will increase. Climate change throughout the 21st century is also set to increase the
458 area suitable for *Ae. aegypti* presence [85]. These developments will further increase the
459 importance of research at multiple scales to guide management and policy. Vector control will
460 continue to be a critical component of arboviral disease prevention, even as additional intervention
461 options become available. Understanding the systems which allow vectors to exist, persist, and
462 transmit disease will remain critical in promoting human health and wellbeing for the foreseeable
463 future.

464

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471

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720 **Supporting information**

721 **S1 Table.** The number of households with a given SES factor, shown by sampling clusters.
722 Factors in bold were statistically significant in univariate analyses.

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725 **S2 Table.** Matrix of *p* values from post hoc tests on pairs of months.

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727 **S1 Fig.** Spearman's rank correlation values (rho) for climate variables and household *Ae.*
728 *aegypti* presence, lagged up to five weeks. Asterisks denote significant lags.

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