Excess mortality during the COVID-19 pandemic: a geospatial and statistical analysis in Aden governorate, Yemen

SUPPLEMENTARY TABLES AND FIGURES

A. Population estimates

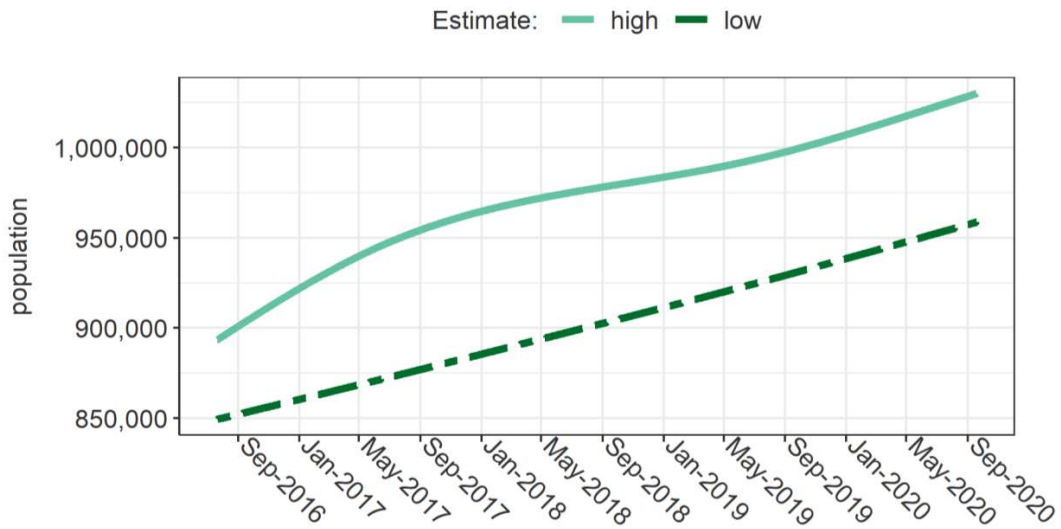

Figure S1. Estimated evolution of the population size of Aden governorate. The high-end estimate includes adjustment for displacement, and is adopted for the analysis. The low-end estimate is solely a weighted average of available base sources.

Table S1. Evaluation of the accuracy of existing population estimates. (note: *none of the estimates have a confidence interval)

Source	pop_worldpop_16-20		pop_cso_16-20	
	WorldPop		CSO Yemen	
Population ()	4.524.256		4.443.555	
criterion	sub-score	weight	sub-score	weight
Choice of method	0.60	0.25	0.80	0.25
Precision*	0.60	0.10	0.20	0.10
Bias	0.80	0.15	0.20	0.15
Expertise/credibility	1.00	0.10	1.00	0.10
Timing of data collection	1.00	0.15	0.00	0.15
Population included in estimation	1.00	0.15	1.00	0.15
Plausibility	0.60	0.10	0.60	0.10
Total Score	**0.79**		**0.56**	

B. Model to impute new graves based on new surface area

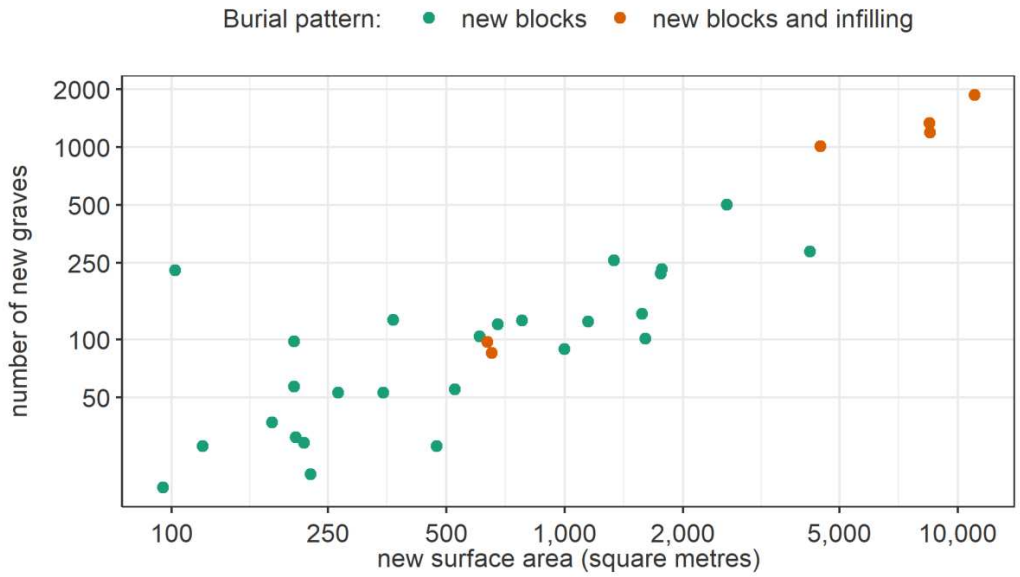

Figure S2. Correlation between the number of new graves and the new surface area expansion since the previous satellite image, by dominant burial pattern in the cemetery. Each plotted observation is an image (time point) within a given cemetery.

Model formula:

$$\log(b|u) = \beta_0 + \beta_a a + \log B_{\text{start}} + \mathbf{Z}u,$$

where the response variable $b = B_{t,u} - B_{t-1,u}$ i.e. the difference between burials B now and on the previous observation date in cemetery u, conditioned on u as the random effect; β_0 is the intercept; β_a is the fixed effect coefficient of $a = A_{t,u} - A_{t-1,u}$, namely the difference between cemetery area A now and on the previous observation date, $\log B_{\text{start}}$ is the offset and **Z** is the random effect design matrix; a quasi-Poisson model parameterises the variance of b as $\text{var}(b) = \theta\mu$, where μ is the expectation or mean of b and θ an overdispersion multiplier, reflecting the skewed distribution of observed burial counts.

Table S2. Predictive model to impute new graves based on new surface area and baseline grave count. Only fixed effects are shown.

Term	Coefficient	SE	p-value
intercept	-5.025	1.465	< 0.001
ln (new surface area in m^2)	0.821	0.079	< 0.001
AIC on training dataset:	396.5	Mean AIC across all LOOCV folds:	385.1

SE: Standard error. AIC: Akaike Information Criterion. LOOCV: leave-one-out cross-validation.

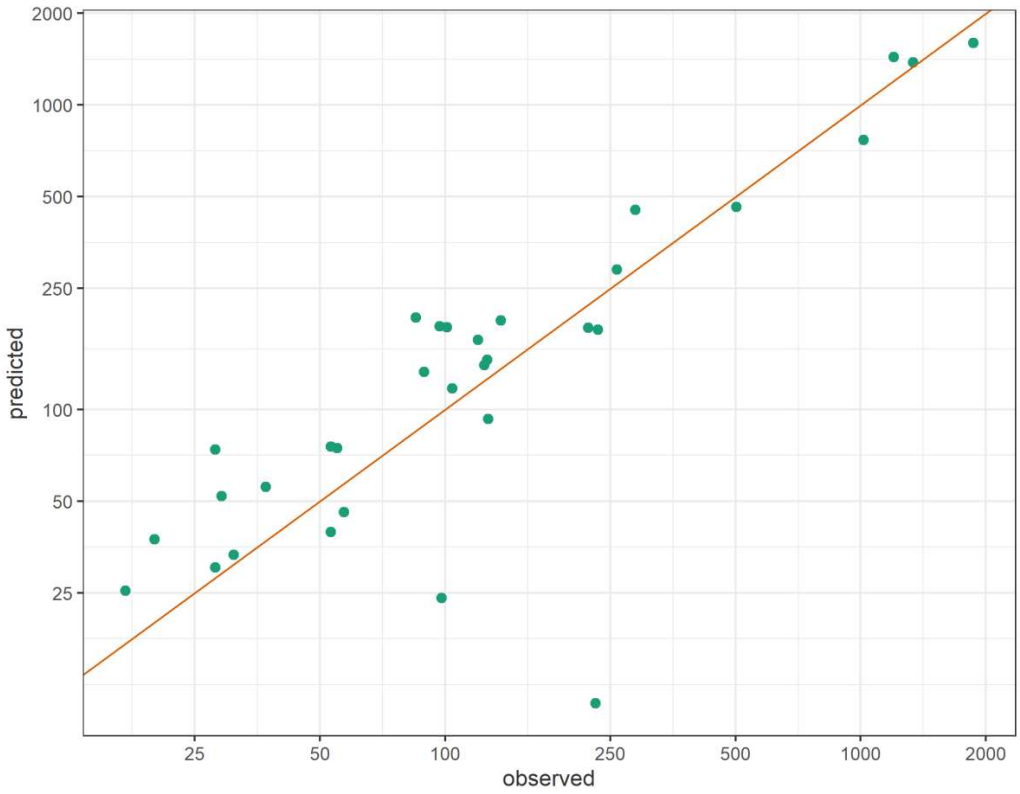

Figure S3. Predicted versus observed number of new graves after leave-one-out cross-validation. Each point indicates the observed and predicted values for the k^{th} fold (i.e. single observation) left out of the dataset, in turn. The red line indicates perfect agreement between observations and predictions.

C. Estimates based on case-based analysis

Table S3. Estimates of baseline, epidemic period and excess burials by cemetery, based on smooth spline interpolation. Estimates of excess burials cover the period 1 April 2020 to 6 July 2020.

Cemetery	Duration of periods (days)		Burial rate per day			Cumulative number of deaths		
	baseline	epidemic	baseline	epidemic	excess	counterfactual	actual	excess
Bir Ahmed	1350	96	0.46	1.76	1.27	47	169	122
Al-Qalua'a	1034	96	0.24	1.45	1.20	24	139	115
Aden Assougra	1350	96	0.59	1.98	1.36	60	190	130
Mansoura	1350	96	1.30	1.99	0.62	132	191	59
Abu Harbeh Aljadidah	1350	96	0.70	2.48	1.74	70	238	167
Kod Al-Othmani	483	96	0.07	0.11	0.04	7	10	4
Al-Othmani	1350	96	0.20	0.33	0.12	20	31	11
Radwan	1245	96	3.44	12.42	8.81	347	1192	846
Salah El-Din	1350	96	0.24	0.55	0.30	24	53	29
Faqam	1233	96	0.10	0.27	0.17	10	26	17
Al-Qateea	1350	96	1.18	0.73	-0.51	119	70	-49

Table S4. Estimates of baseline, epidemic period and excess burials by cemetery, based on linear interpolation. Estimates of excess burials cover the period 1 April 2020 to 6 July 2020.

Cemetery	Duration of periods (days)		Burial rate per day			Cumulative number of deaths		
	baseline	epidemic	baseline	epidemic	excess	counterfactual	actual	excess
Bir Ahmed	1350	96	0.46	1.78	1.29	47	171	124
Al-Qalua'a	1034	96	0.24	1.46	1.21	24	140	116
Aden Assougra	1350	96	0.58	2.05	1.44	59	197	138
Mansoura	1350	96	1.30	2.02	0.64	132	194	62
Abu Harbeh Aljadidah	1350	96	0.69	2.56	1.83	70	246	176
Kod Al-Othmani	483	96	0.07	0.11	0.04	7	10	4
Al-Othmani	1350	96	0.20	0.35	0.15	20	34	14
Radwan	1245	96	3.47	13.28	9.64	349	1275	926
Salah El-Din	1350	96	0.24	0.55	0.30	24	53	29
Faqam	1233	96	0.09	0.28	0.18	10	27	17
Al-Qateea	1350	96	1.17	0.76	-0.48	119	73	-46

D. Estimates based on GAMLSS model

Model formula:

$b \sim D(\mu, \sigma)$, where b, the response variable, is now $B_{t,u}$, i.e. total burials at a given time in a given cemetery, and is a function of D, a two-parameter distribution specified by

$$\log(\mu|u, t_{\text{base}}) = s_{\mu,u,t_{\text{base}}} t_{\text{base}} + s_{\mu,u,t_{\text{covid}}} t_{\text{covid}}$$

$$\log(\sigma|u, t_{\text{base}}) = s_{\sigma,u,t_{\text{base}}} t_{\text{base}} + s_{\sigma,u.t_{\text{covid}}} t_{\text{covid}}$$

Here, t_{base} is increasing time (days) from the start of the period, while t_{covid} is time since the assumed start of the pandemic in Aden; and s terms are polynomial smoothing functions that model the non-linear relationship between time and either the mean or the shape of the distribution of cumulative cemetery burials; these smoothing functions are themselves conditioned on the random effects of cemetery and time nested within cemetery.

Table S5. Fit statistics for an alternative GAMLSS model featuring the rate of insecurity events as an additional predictor. Coefficients are exponentiated to provide linear scale rate ratios.

Term	Rate ratio	p-value
Penalised B-spline smoothing terms for the mean (expectation) parameter):		
Baseline growth (day)	1.004	< 0.001
Added epidemic growth (day)	0.996	< 0.001
Penalised B-spline smoothing terms for the shape (overdispersion) parameter):		
Baseline growth (day)	0.991	< 0.001
Added epidemic growth (day)	1.028	< 0.001
Daily number of conflict events within the sub-district where the cemetery is located:		
Each additional event	1.146	0.012
	Akaike Information Criterion = 746.9	Residual degrees of freedom = 47.0

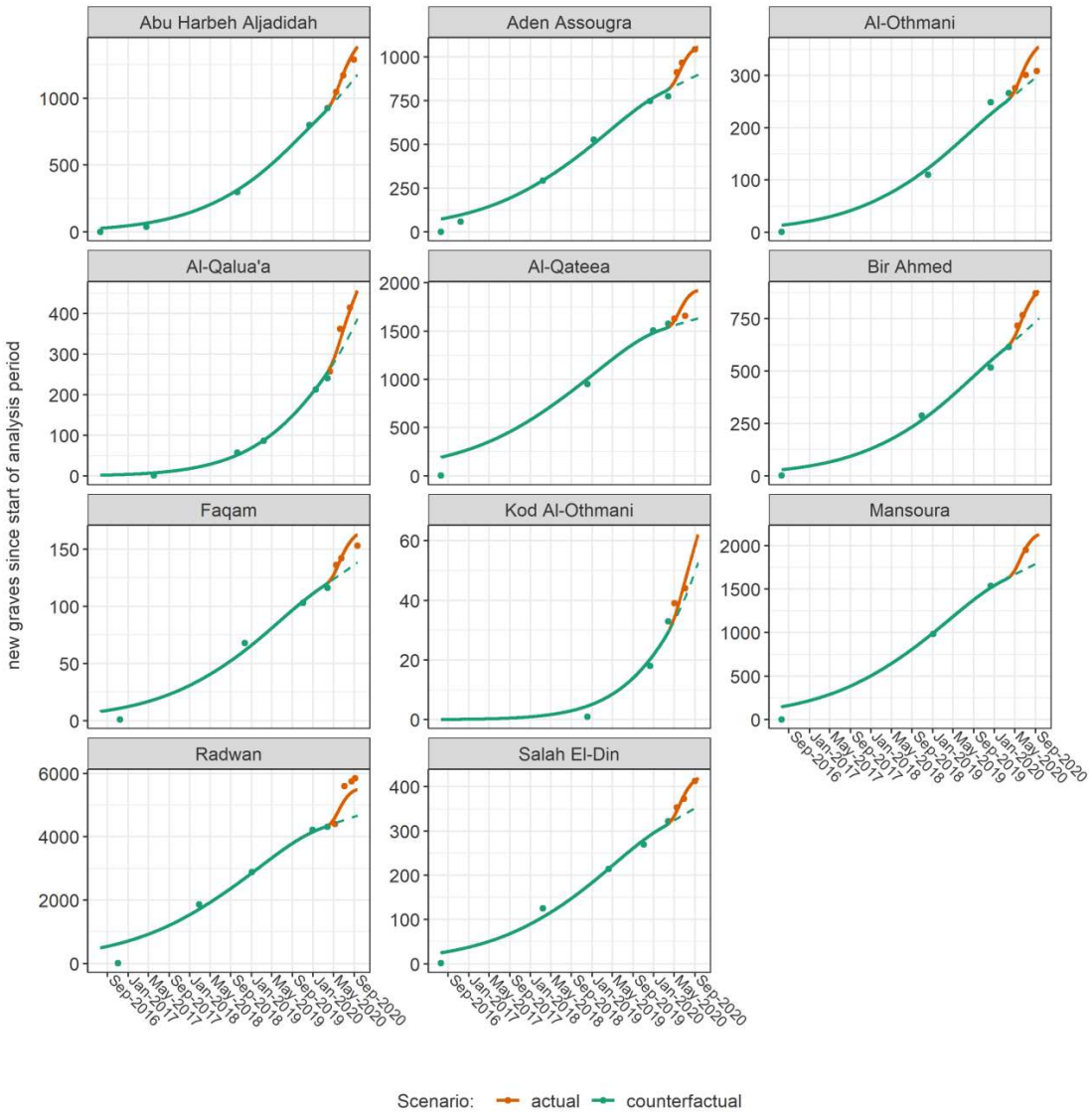

Figure S4. GAMLSS model predictions (lines) versus observations (dots), by cemetery. The dashed lines denote counterfactual predictions.

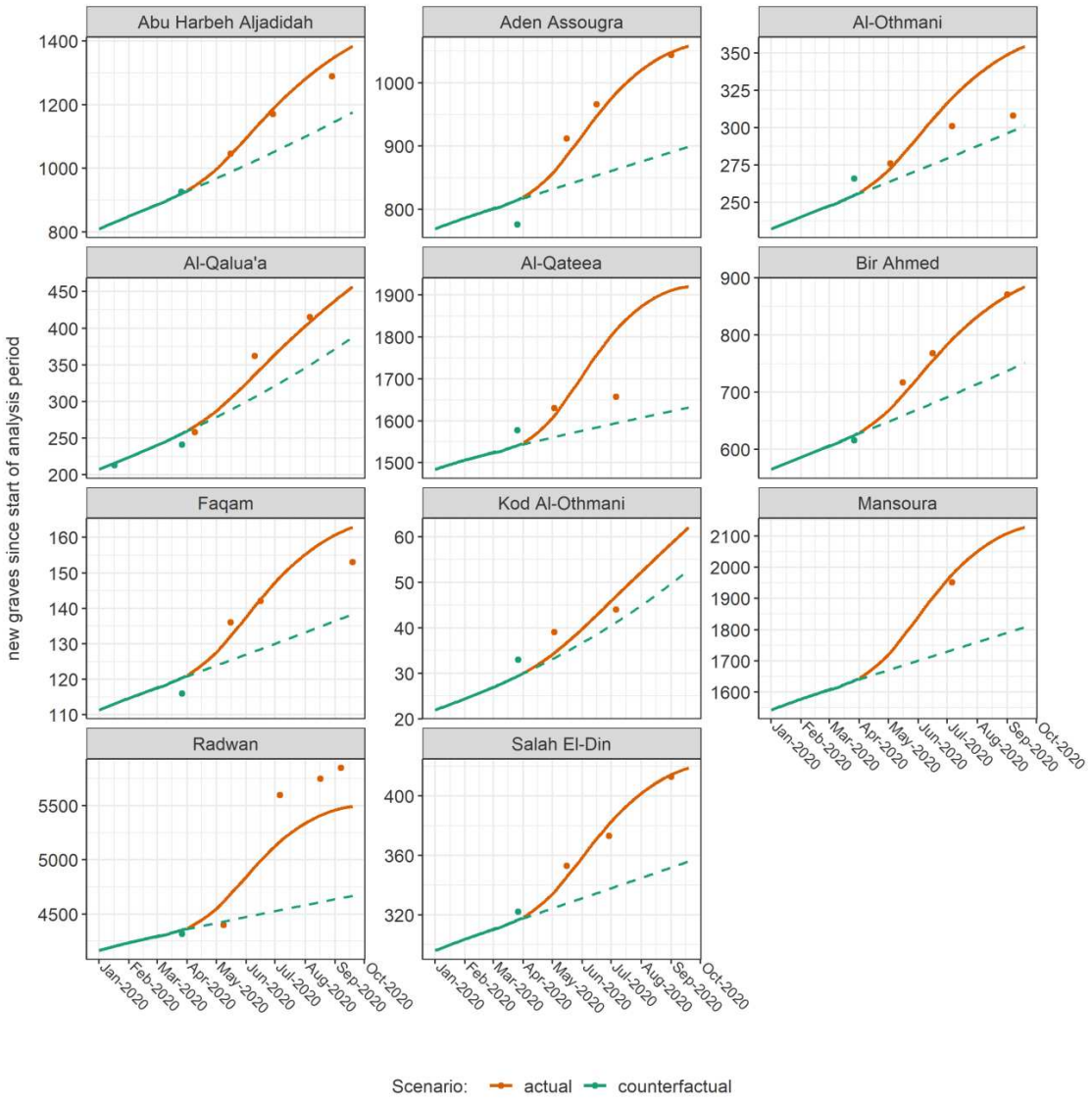

Figure S5. GAMLSS model predictions (lines) versus observations (dots), by cemetery, for the first 9 months of 2020. The dashed lines denote counterfactual predictions.

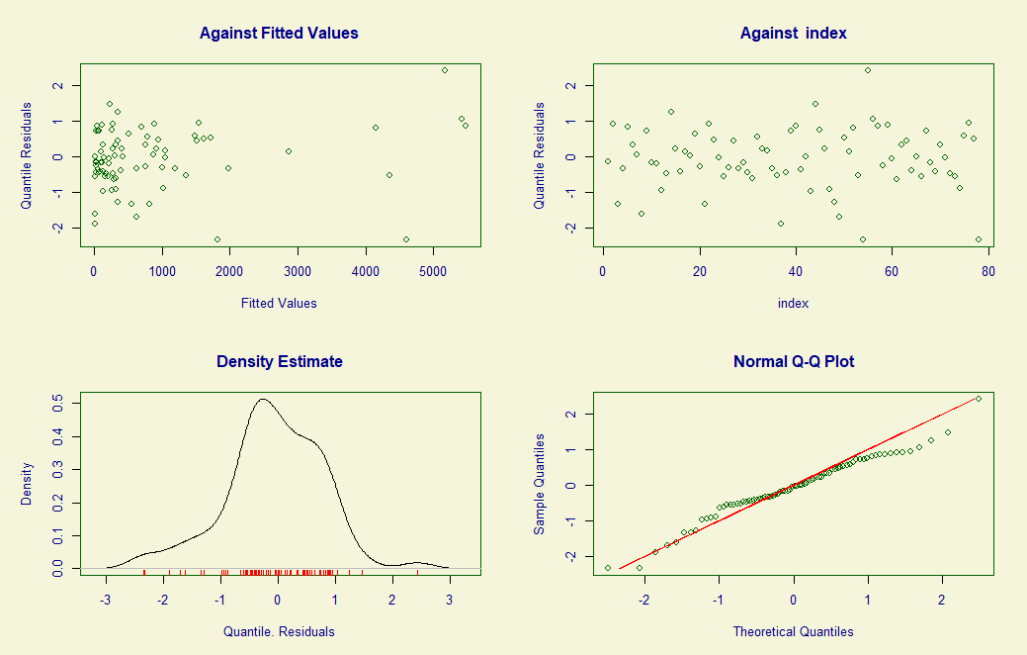

Figure S6. GAMLSS model diagnostic plots.

Table S6. Estimates of actual, counterfactual and excess burials by cemetery, based on the GAMLSS model. Estimates cover the period 1 April 2020 to 19 September 2020 (171 days).

Cemetery	Burial rate per day (95%CI)			Cumulative number of deaths (95%CI)		
	counterfactual	actual	excess	counterfactual	actual	excess
Bir Ahmed	4.39 (4.04 to 4.80)	5.17 (4.25 to 6.19)	0.76 (0.10 to 1.54)	751 (690 to 821)	884 (726 to 1059)	130 (17 to 263)
Al-Qalua'a	2.27 (2.04 to 2.51)	2.67 (2.12 to 3.23)	0.41 (0.07 to 0.74)	388 (349 to 429)	456 (362 to 552)	70 (12 to 127)
Aden Assougra	5.26 (4.88 to 5.67)	6.19 (4.99 to 7.49)	0.89 (0.12 to 1.83)	899 (835 to 969)	1058 (854 to 1280)	153 (21 to 313)
Mansoura	10.57 (9.87 to 11.23)	12.44 (10.04 to 15.04)	1.65 (0.29 to 3.58)	1807 (1688 to 1921)	2127 (1717 to 2571)	282 (49 to 613)
Abu Harbeh Aljadidah	6.87 (6.38 to 7.38)	8.09 (6.59 to 9.83)	1.19 (0.10 to 2.29)	1175 (1091 to 1262)	1383 (1127 to 1681)	204 (17 to 391)
Kod Al-Othmani	0.31 (0.23 to 0.40)	0.36 (0.26 to 0.49)	0.05 (0.03 to 0.09)	53 (39 to 69)	62 (44 to 83)	9 (5 to 15)
Al-Othmani	1.76 (1.55 to 1.98)	2.07 (1.63 to 2.53)	0.31 (0.09 to 0.54)	301 (265 to 339)	354 (279 to 433)	53 (16 to 93)
Radwan	27.31 (25.72 to 28.95)	32.15 (26.41 to 38.71)	4.98 (1.01 to 9.66)	4670 (4398 to 4951)	5498 (4516 to 6619)	852 (172 to 1652)
Salah El-Din	2.08 (1.86 to 2.30)	2.45 (1.98 to 3.02)	0.34 (0.06 to 0.68)	356 (318 to 393)	419 (338 to 517)	58 (10 to 116)
Faqam	0.81 (0.67 to 0.96)	0.95 (0.73 to 1.18)	0.14 (0.06 to 0.26)	138 (114 to 164)	163 (125 to 202)	24 (10 to 45)
Al-Qateea	9.53 (8.9 to 10.16)	11.22 (9.26 to 13.47)	1.73 (0.24 to 3.34)	1630 (1522 to 1738)	1919 (1583 to 2304)	295 (41 to 571)

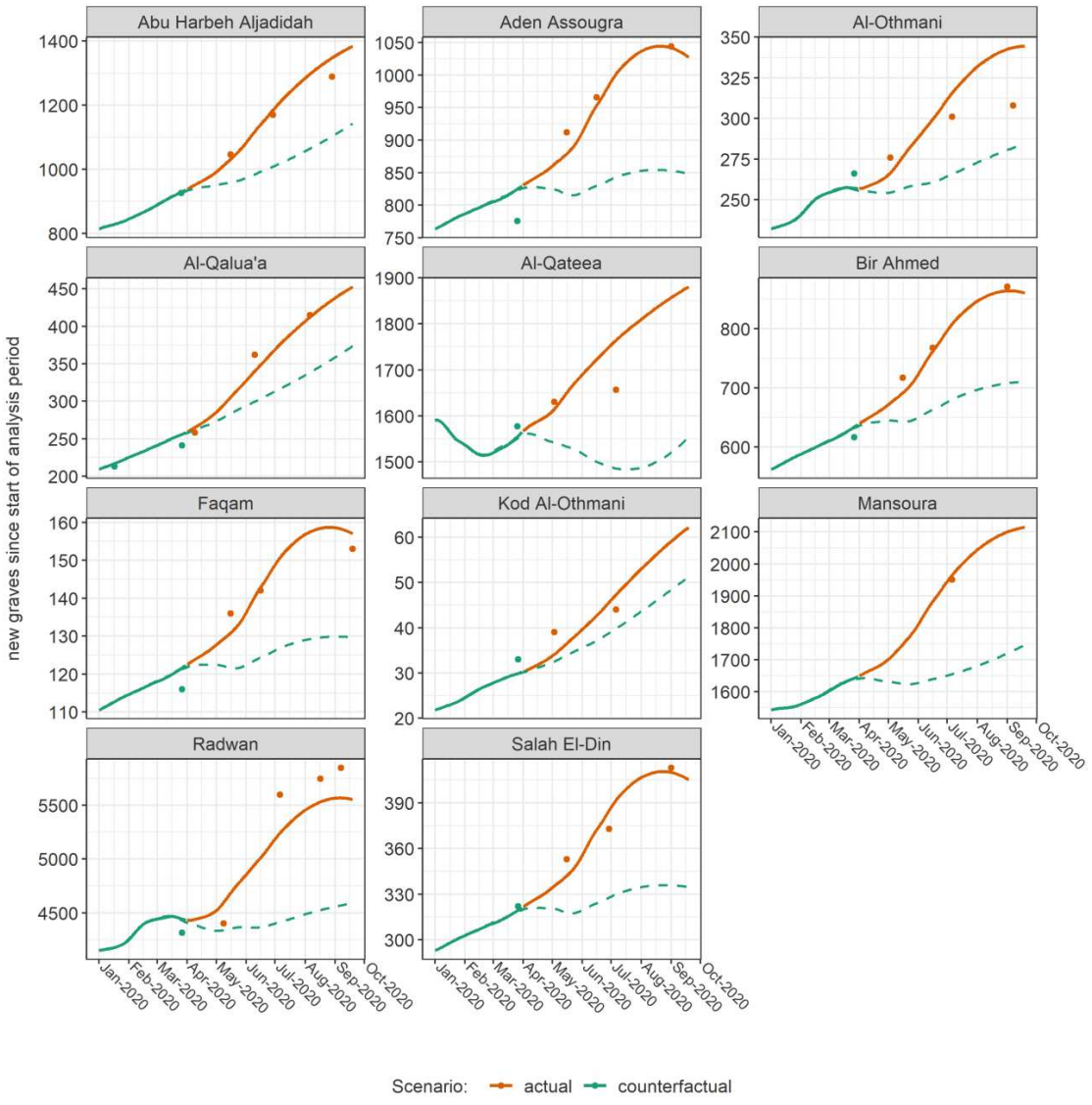

Figure S7. Predictions (lines) versus observations (dots), by cemetery, for the first 9 months of 2020, from an alternative GAMLSS model featuring the rate of insecurity events as an additional predictor. The dashed lines denote counterfactual predictions. Prediction lines have been moderately smoothed to avoid the jaggedness resulting from daily insecurity event fluctuations.

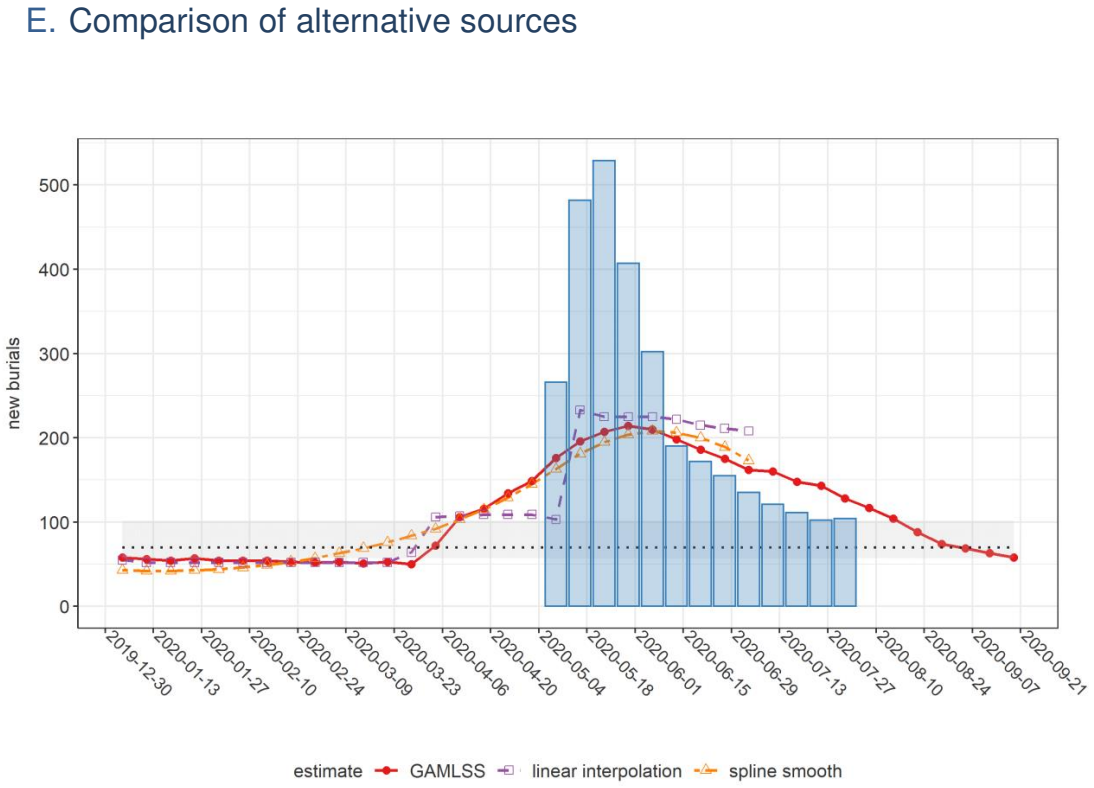

Figure S8. Comparison of weekly estimates of new burials across Aden governorate, by analysis method, and corresponding records from the Civil Registry office (blue columns), during 2020. The horizontal dotted line and shaded area indicate the median, minimum and maximum weekly burials based on the 2017-2019 Civil Registry time series.