Supplementary Material:
Model-based assessment of COVID-19 epidemic dynamics by wastewater analysis

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Country	City/area	Population served	Time range yy/mm/dd	Units of measure	Source

Spain	Barcelona Prat de Llobregat	2,000,000	20/08/24–21/07/26 (11 months)	SARS-CoV-2 RNA copies/day	`doi:10.5281/zenodo.4147073`
					
					`https://sarsaigua.icra.cat/`

Canada	Kitchener	242,000	21/01/11–21/08/22 (7 months)	SARS-CoV-2 RNA copies /PMMoV copies	`https://www.regionofwaterloo.ca/en/health-and-wellness/covid-19-wastewater-surveillance.aspx`
Slovenia	Kranj	40,000	20/10/08–21/08/02 (10 months)	SARS-CoV-2 RNA copies/PMMoV copies	`https://github.com/sledilnik/data`
Switzerland	Lausanne	240,000	20/10/01–21/08/04 (10 months)	SARS-CoV-2 RNA copies/day/100,000 equivalent inhabitants	`https://sensors-eawag.ch/sars/lausanne.html`
Slovenia	Ljubljana	280,000	20/09/10–21/08/02 (11 months)	SARS-CoV-2 RNA copies/copies PMMoV	`https://github.com/sledilnik/data`
Luxembourg	Luxembourg	610,000	20/02/25–21/08/02 (17 months)	SARS-CoV-2 RNA copies/day/100,000 equivalent inhabitants	`https://www.list.lu/en/covid-19/coronastep/`
USA	Milwaukee	615,934	20/08/25–21/08/04 (11 months)	MGC/person/day (gene copies per person per day)	`https://www.dhs.wisconsin.gov/covid-19/wastewater.htm`
Netherlands	Netherlands	17,178,109	20/09/07–21/07/30 (11 months)	SARS-CoV-2 RNA copies/day/100,000 equivalent inhabitants	`https://data.rivm.nl/covid-19/COVID-19$_$rioolwaterdata.csv`
USA	Oshkosh	78,300	20/09/15–21/08/19 (11 months)	MGC/person/day (gene copies per person per day)	`https://www.dhs.wisconsin.gov/covid-19/wastewater.htm`
USA	Raleigh	460,000	21/01/03–21/08/08 (7 months)	SARS-CoV-2 RNA copies/day/100,000 equivalent inhabitants	`https://covid19.ncdhhs.gov/dashboard/wastewater-monitoring`

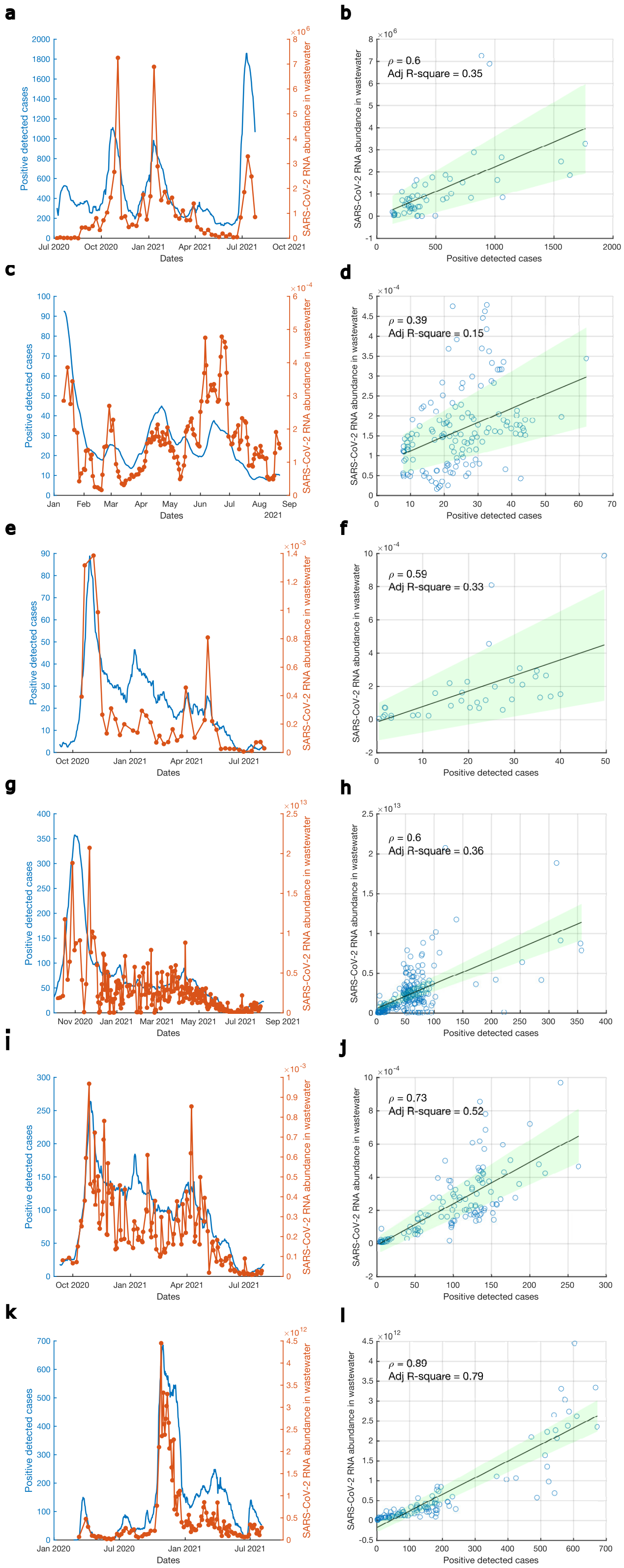
Spain	Riera de la Bisbal	100,000	20/07/06–21/07/26 (13 months)	SARS-CoV-2 RNA copies/day	`doi:10.5281/zenodo.4147073`
					
					`https://sarsaigua.icra.cat/`

Switzerland	Zürich	450,000	20/10/01–21/08/04 (10 months)	SARS-CoV-2 RNA copies/day/100,000 equivalent inhabitants	`https://sensors-eawag.ch/sars/zurich.html`

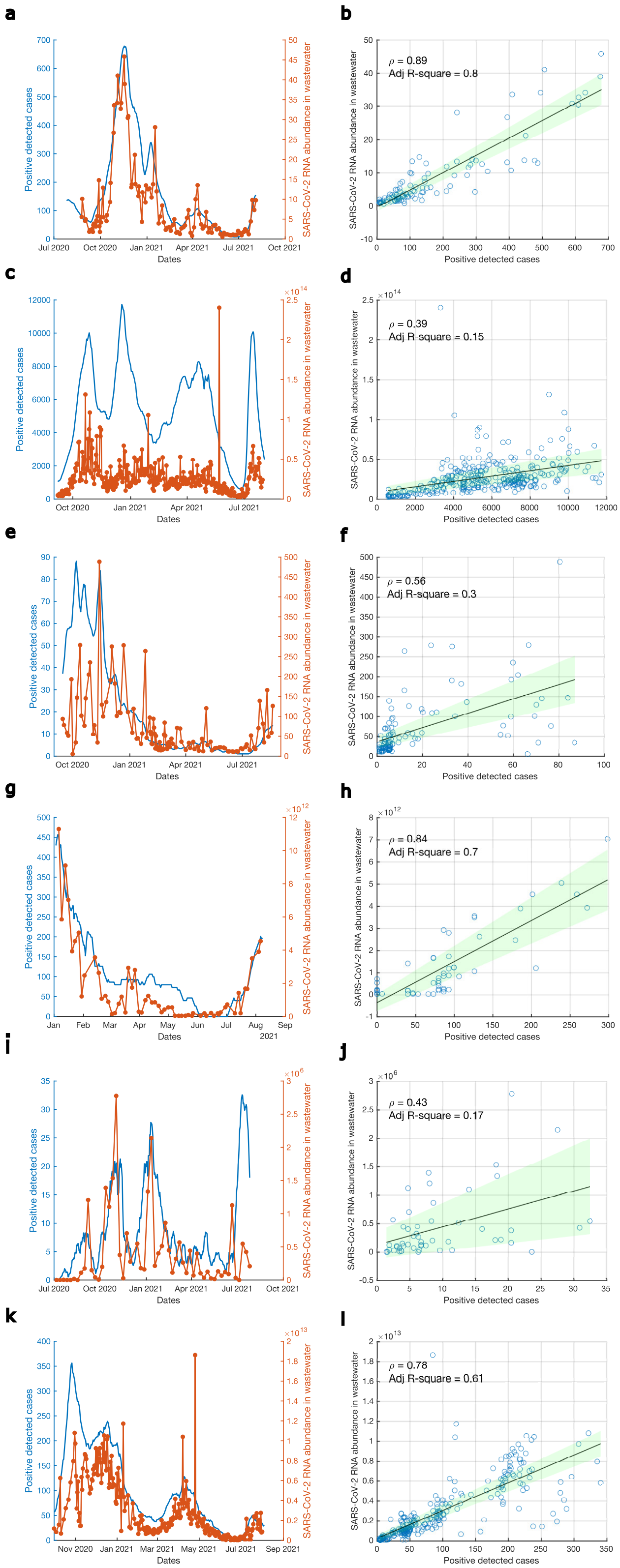
Supplementary table 1: **Considered regions, associated equivalent population served by sewage facilities (according to official sources), time ranges of data, units of measure of wastewater data, and their sources.** The equivalent populations is the ratio between the sum of the pollution load collected during 24 hours by sewage facilities and services and the individual pollution load in household sewage produced by one person in the same time; it is a proxy of the number of people who contributed to the wastewater load. The sources listed here also include the case numbers, detected in the same area covered by the sewage system of interest.

Region	Method	7-day window Error	SD	Difference	14-day window Error	SD	Difference
Barcelona	Case data	0.75	0.74		1.62	2.05	
	WW data	1.17	0.99	+55.7%	1.97	1.90	+21.9%
	WWip data	1.10	0.84	+46.6%	1.71	1.67	+5.4%
	All data	0.69	0.64	-7.6%	1.52	1.77	-6.2%
Kitchener	Case data	1.12	0.98		2.30	2.27	
	WW data	2.42	1.83	+115.7%	3.65	2.91	+58.4%
	All data	1.12	0.76	+0.2%	2.18	1.50	-5.2%
(modified)	WW data	1.51	0.96	+34.2%	2.68	1.61	+16.3%
	All data	1.04	0.81	-7.2%	2.12	1.66	-7.8%
Kranj	Case data	6.68	7.53		13.2	24.0	
	WW data	11.8	7.02	+76.0%	17.0	10.6	+28.6%
	WWip data	11.2	7.58	+67.6%	16.3	11.2	+23.2%
	All data	6.43	6.09	-3.8%	12.2	18.6	-7.3%
Lausanne	Case data	1.59	1.57		3.02	3.69	
	WW data	2.34	2.17	+47.4%	3.88	4.51	+28.4%
	All data	1.48	1.27	-6.5%	2.70	2.75	-10.5%
Ljubljana	Case data	1.66	1.99		3.34	5.6	
	WW data	2.37	1.81	+42.5%	4.05	2.73	+21.2%
	All data	1.51	1.70	-9.4%	3.07	4.81	-8.2%
Luxembourg	Case data	1.26	1.38		2.48	2.96	
	WW data	1.88	1.36	+49.3%	3.20	2.92	+29.0%
	All data	1.13	1.17	-10.7%	2.18	2.57	-12.0%
Milwaukee	Case data	0.84	0.74		1.71	1.45	
	WW data	1.66	1.23	+97.4%	2.90	2.20	+70.1%
	All data	0.83	0.75	-0.8%	1.67	1.52	-2.2%
Netherlands	Case data	0.30	0.75		0.92	3.40	
	WW data	0.44	0.29	+46.3%	0.74	0.60	-19.3%
	All data	0.29	0.73	-4.1%	0.87	3.21	-5.0%
Oshkosh	Case data	3.05	4.21		5.19	7.57	
	WW data	10.4	7.01	+241.5%	14.2	10.1	+174.2%
	All data	3.06	3.54	+0.6%	4.63	5.75	-10.8%
Raleigh	Case data	1.66	1.77		2.99	3.75	
	WW data	1.16	0.75	-30.4%	1.80	1.33	-39.9%
	All data	1.19	0.93	-28.5%	2.08	2.02	-30.4%
Riera de la Bisbal	Case data	3.11	2.60		5.22	4.23	
	WW data	4.20	3.44	+35.2%	5.86	5.85	+12.3%
	WWip data	4.13	3.45	+32.9%	5.81	6.23	+11.5%
	All data	2.73	2.42	-12.2%	4.61	3.75	-11.7%
Zurich	Case data	1.02	0.86		2.00	1.94	
	WW data	1.77	1.41	+73.6%	2.98	2.83	+49.0%
	All data	1.26	1.01	+23.3%	2.19	1.86	+9.3%

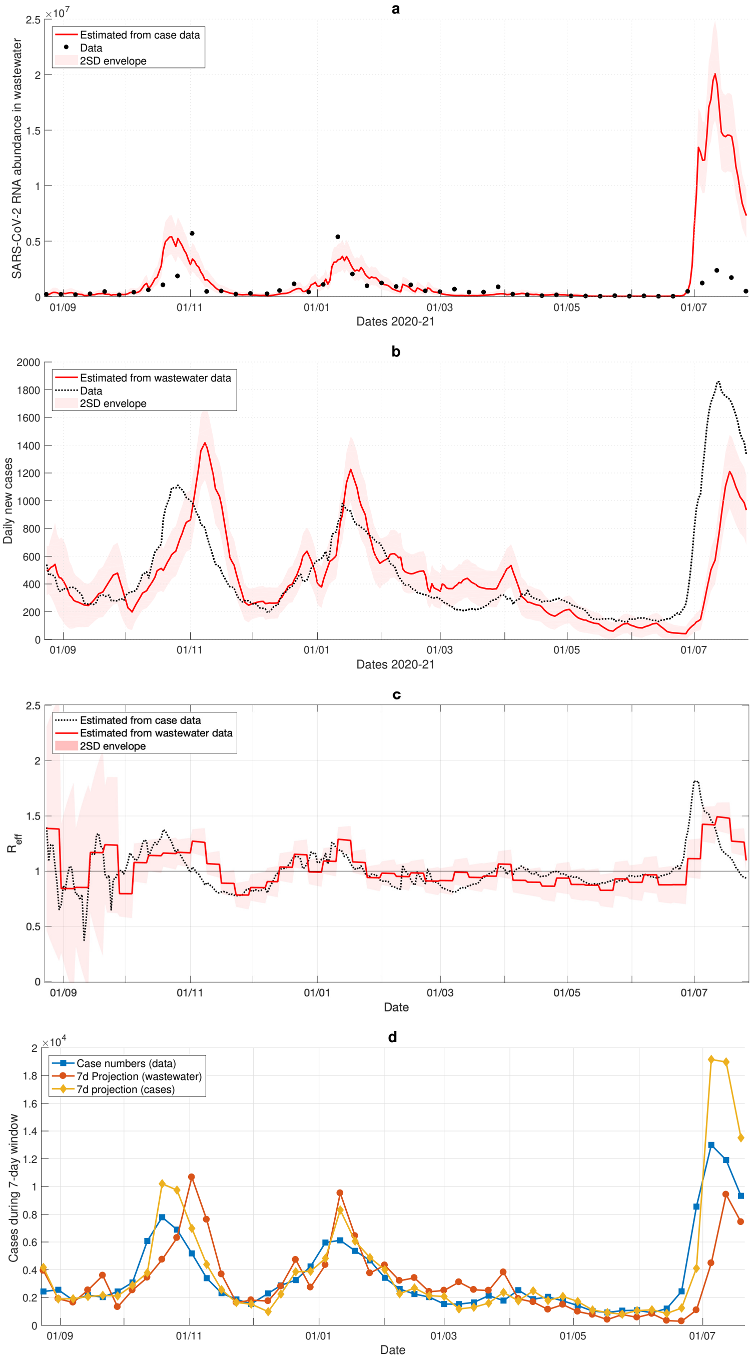
Supplementary table 2: **Summary results about short-term prediction performance, for different regions.** The table reports standardised and averaged prediction errors obtained from wastewater data alone or combined with case numbers, their standard deviations, and difference to benchmark (*i.e.* predictions based on case data). We consider either 7-day prediction window (left) or 14-day prediction window (right).
For Kitchener, the "modified" results are obtained by scaling the wastewater data after May 17, 2021 by a factor 0.4, as explained in Materials and Methods (Sec. 2.2). For three regions with low sampling frequency, results with interpolated wastewater data (WWip) are shown as well.
Projections made from wastewater data do not deviate much from those obtained from case numbers and are usually similar within error bounds. A notable exception is Oshkosh, for which the c_t parameter during the beginning of 2021 should be updated to reflect undertesting.
Wastewater-based projections yield relatively smaller errors on longer time horizons, potentially due to their lower sensitivity to daily fluctuations (compare 7-days and 14-days window projections).
Combining wastewater and case numbers usually improves the prediction performance, suggesting the possibility to complement the testing routines with wastewater data, in order to obtain more reliable projections about future epidemic trends. This can be particularly useful on targeted areas with higher infectivity risk, to assess the efficacy of interventions.



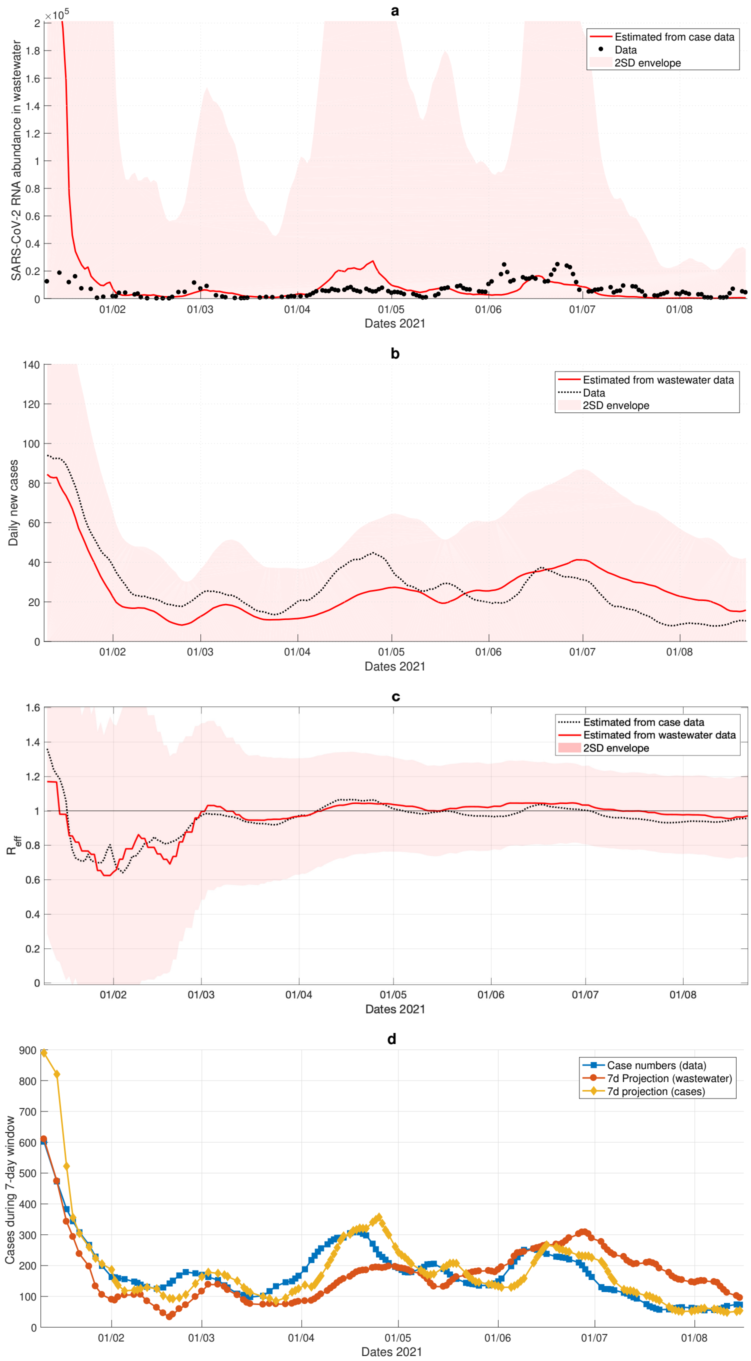
Supplementary figure 1. Measured wastewater data and daily positive cases. (a-b) Barcelona Prat de Llobregat, (c-d) Kitchener, (e-f) Kranj, (g-h) Lausanne, (i-j) Ljubljana, (k-l) Luxembourg. Left column: time series. Right column: wastewater data against daily positive cases: we observe a slight nonlinearity of cases vs wastewater samples, quantified by a Pearson's correlation $\rho < 1$ and by the adjusted R-square statistics for linear fit < 1 (both reported in the figure); the black line represents the linear fit, the green band is its $\pm 2\sigma$ error bound. Data sources and units of measures for wastewater data are reported in Supplementary Tab 1. Note that the reported correlation coefficients do not correspond to those reported in Fig. 2b of the main text: the latter represent the correlation of linear regression after data curation to reduce the noise, while the current ones are based on raw data.



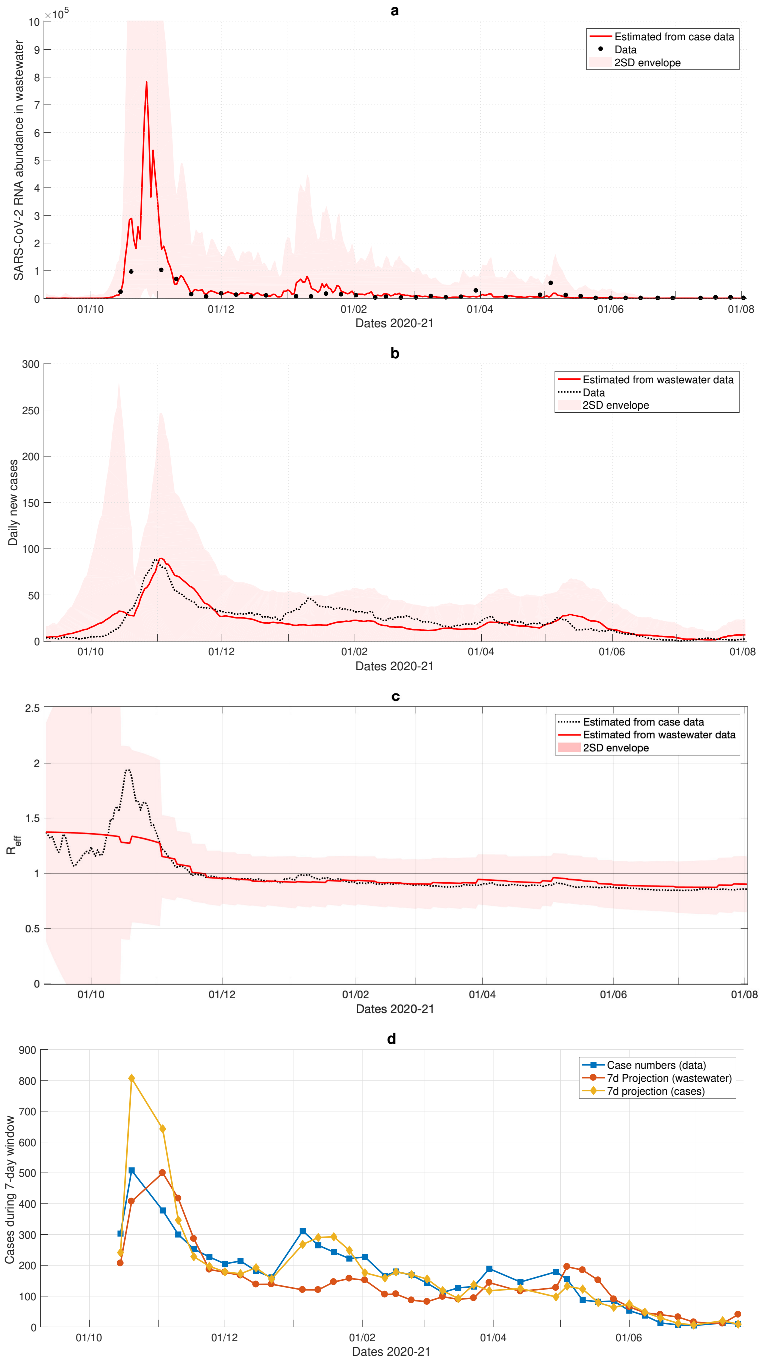
Supplementary figure 2. Measured wastewater data and daily positive cases. (a-b) Milwaukee, (c-d) the Netherlands, (e-f) Oshkosh, (g-h) Raleigh, (i-j) Riera de la Bisbal, (k-l) Zurich. Left column: time series. Right column: wastewater data against daily positive cases: we observe a slight nonlinearity of cases vs wastewater samples, quantified by a Pearson's correlation $\rho < 1$ and by the adjusted R-square statistics for linear fit < 1 (both reported in the figure); the black line represents the linear fit, the green band is its $\pm 2\sigma$ error bound. Data sources and units of measures for wastewater data are reported in Supplementary Table 1. Note that the reported correlation coefficients do not correspond to those reported in Fig. 2b of main text: the latter represent the correlation of linear regression after data curation to reduce the noise, while the current ones are based on raw data.



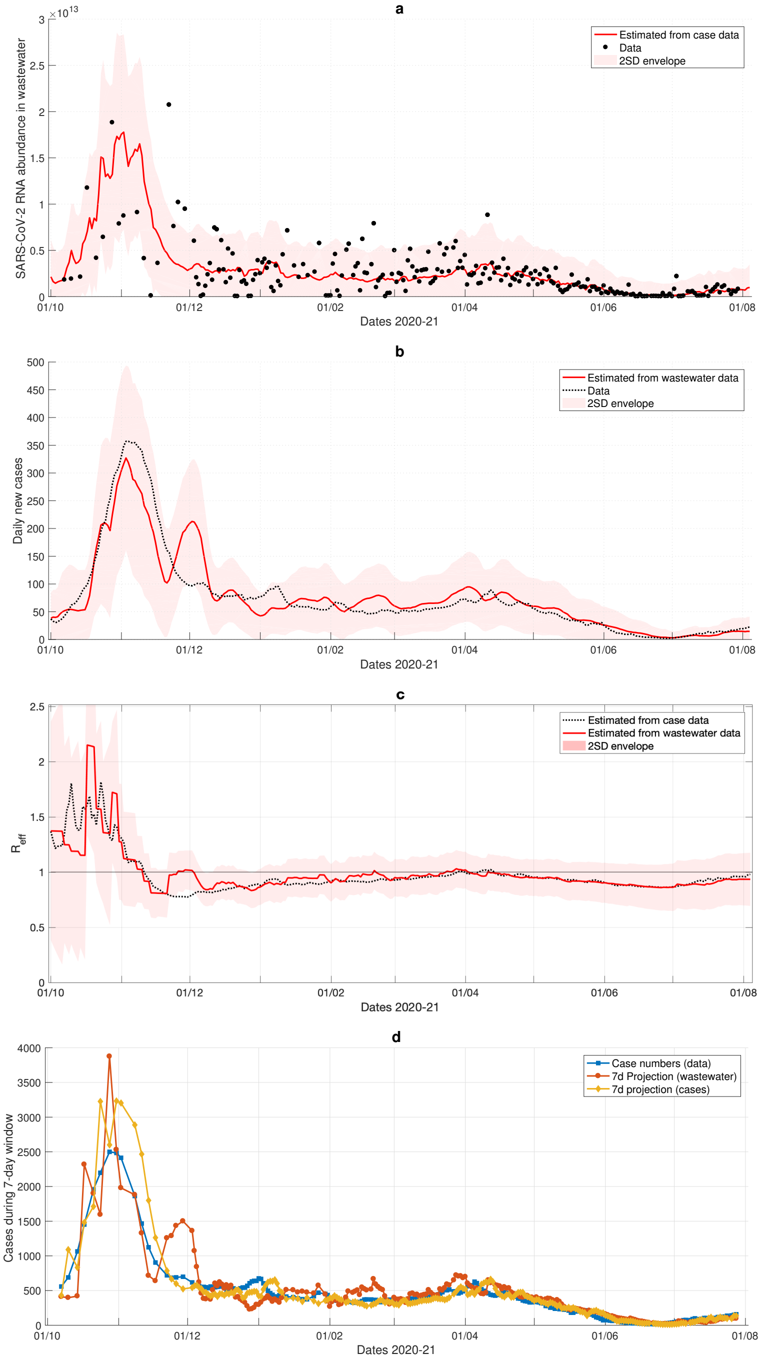
Supplementary figure 3. Results for Barcelona Prat de Llobregat. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



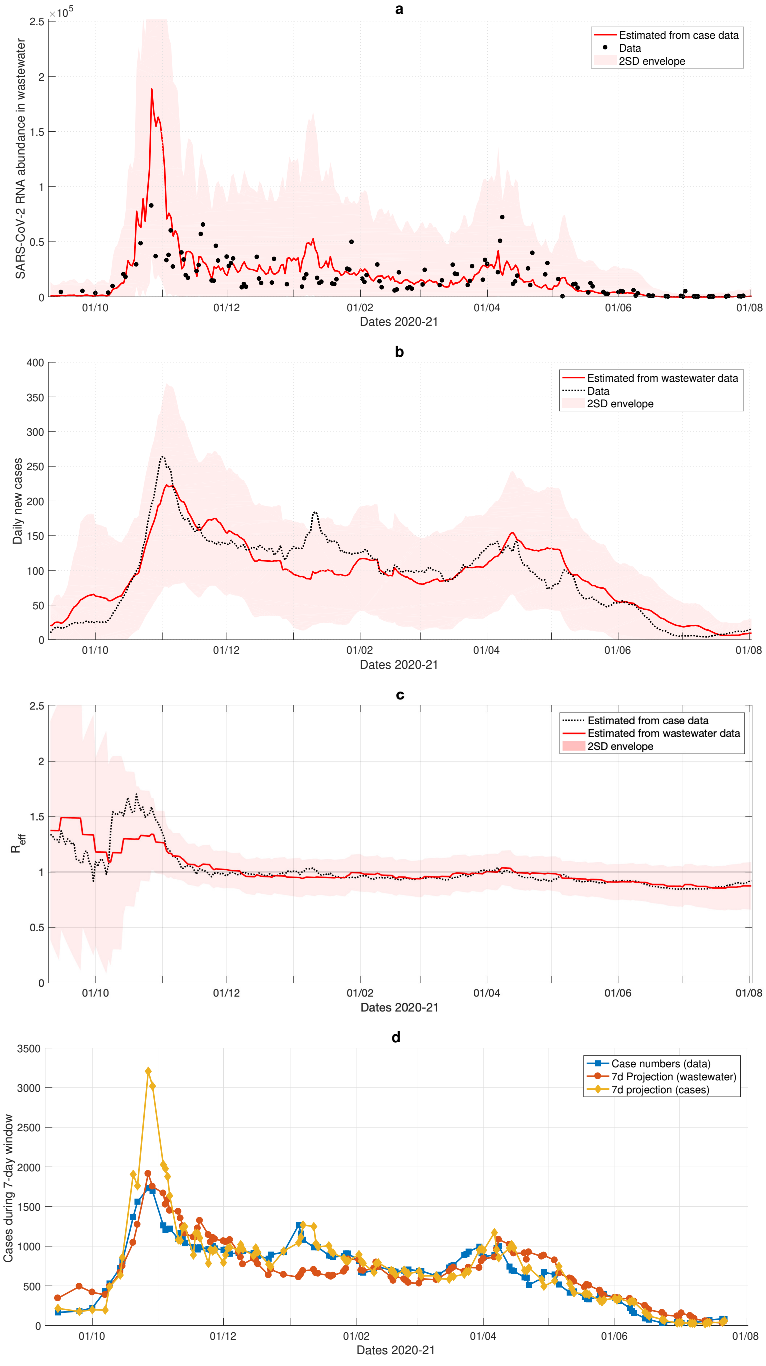
Supplementary figure 4. Results for Kitchener. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



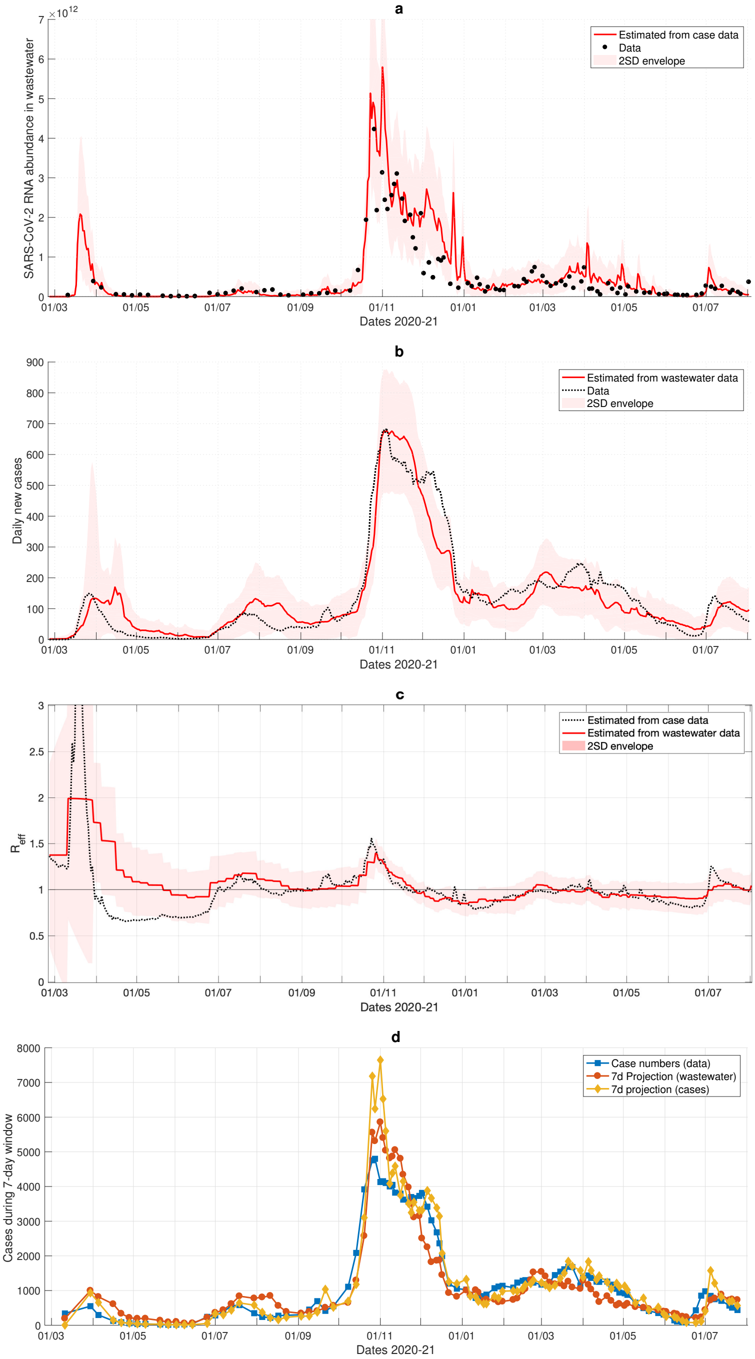
Supplementary figure 5. Results for Kranj. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



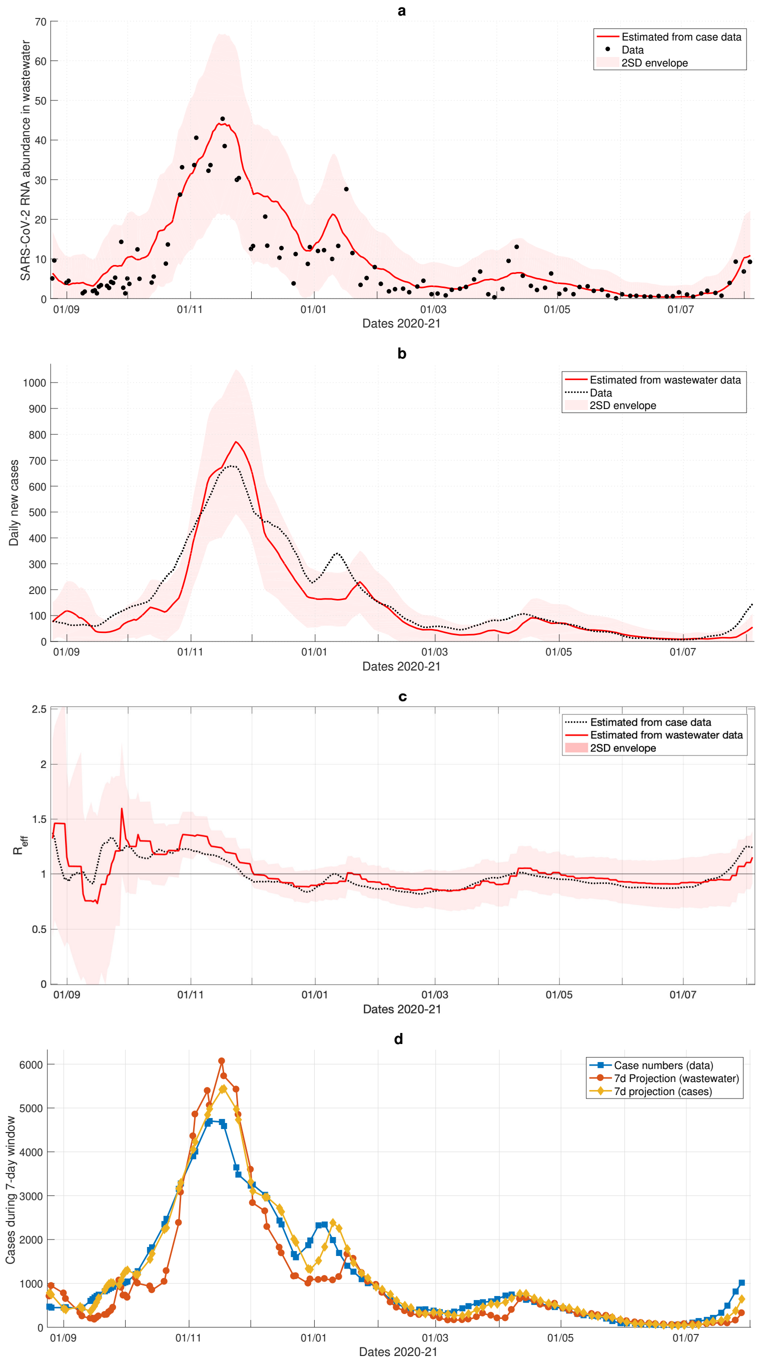
Supplementary figure 6. Results for Lausanne. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



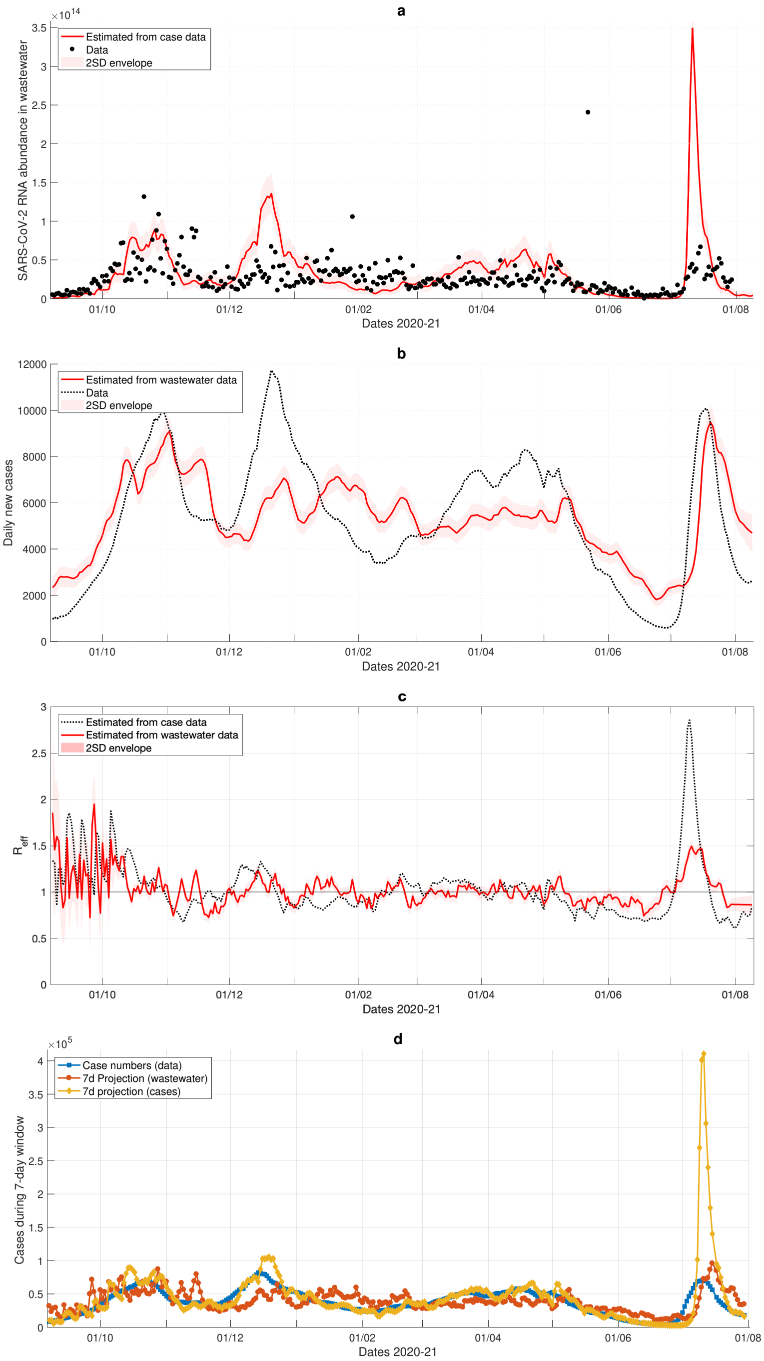
Supplementary figure 7. Results for Ljubljana. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



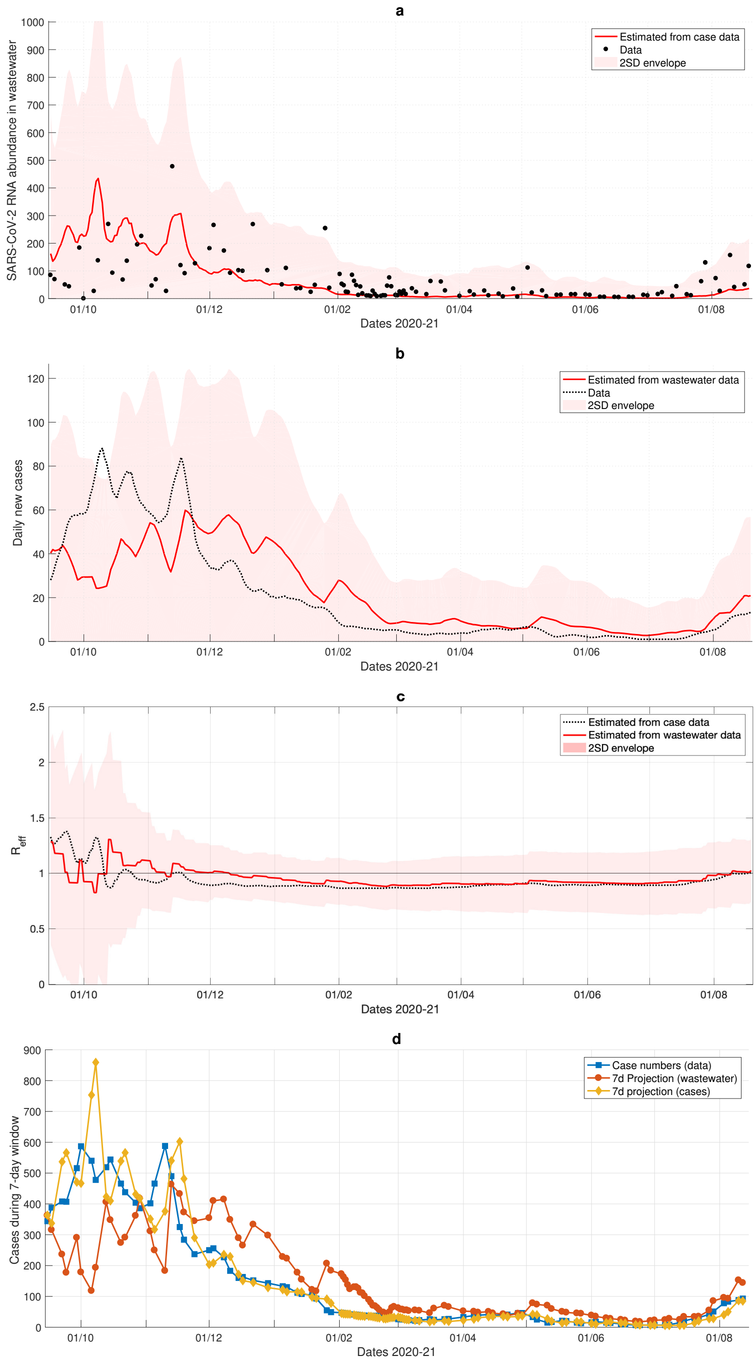
Supplementary figure 8. Results for Luxembourg. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: $R_{\rm eff}$ estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



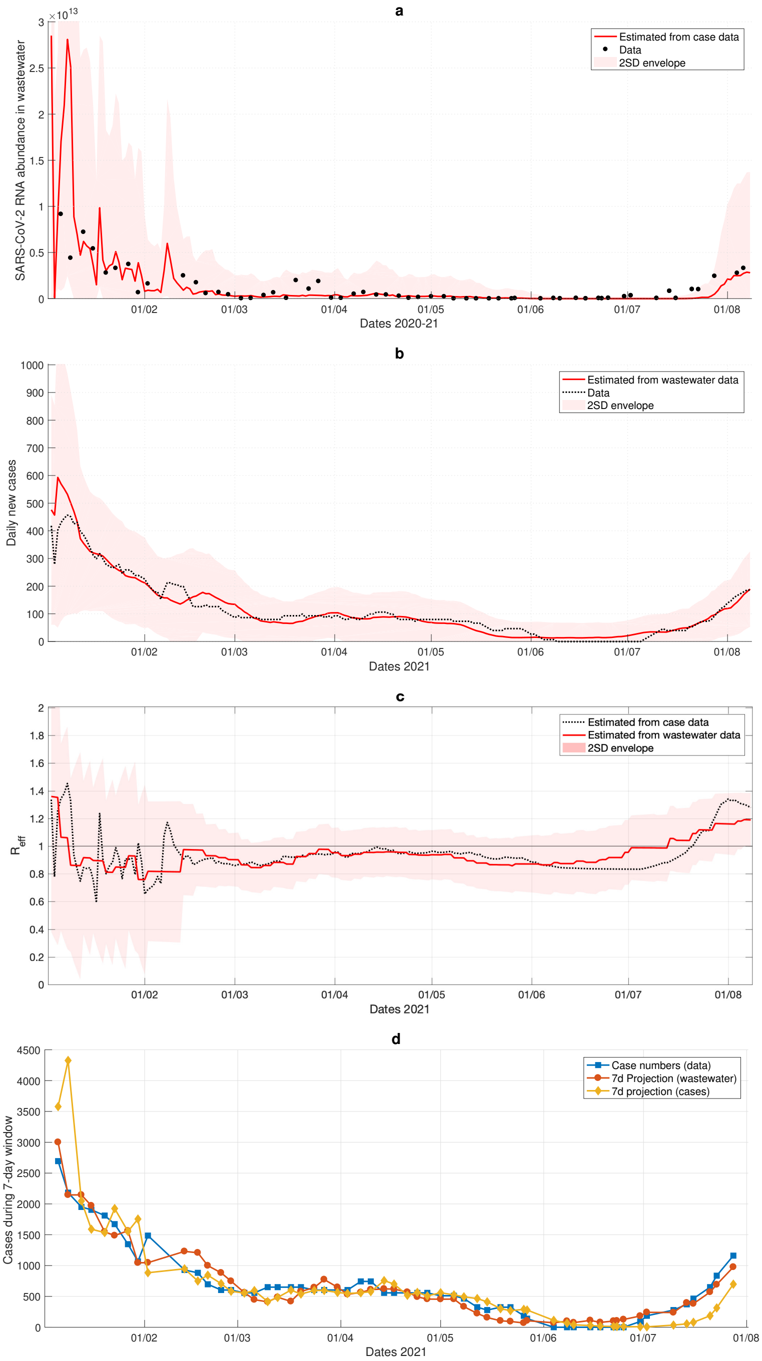
Supplementary figure 9. Results for Milwaukee. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



Supplementary figure 10. Results for Netherlands. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.

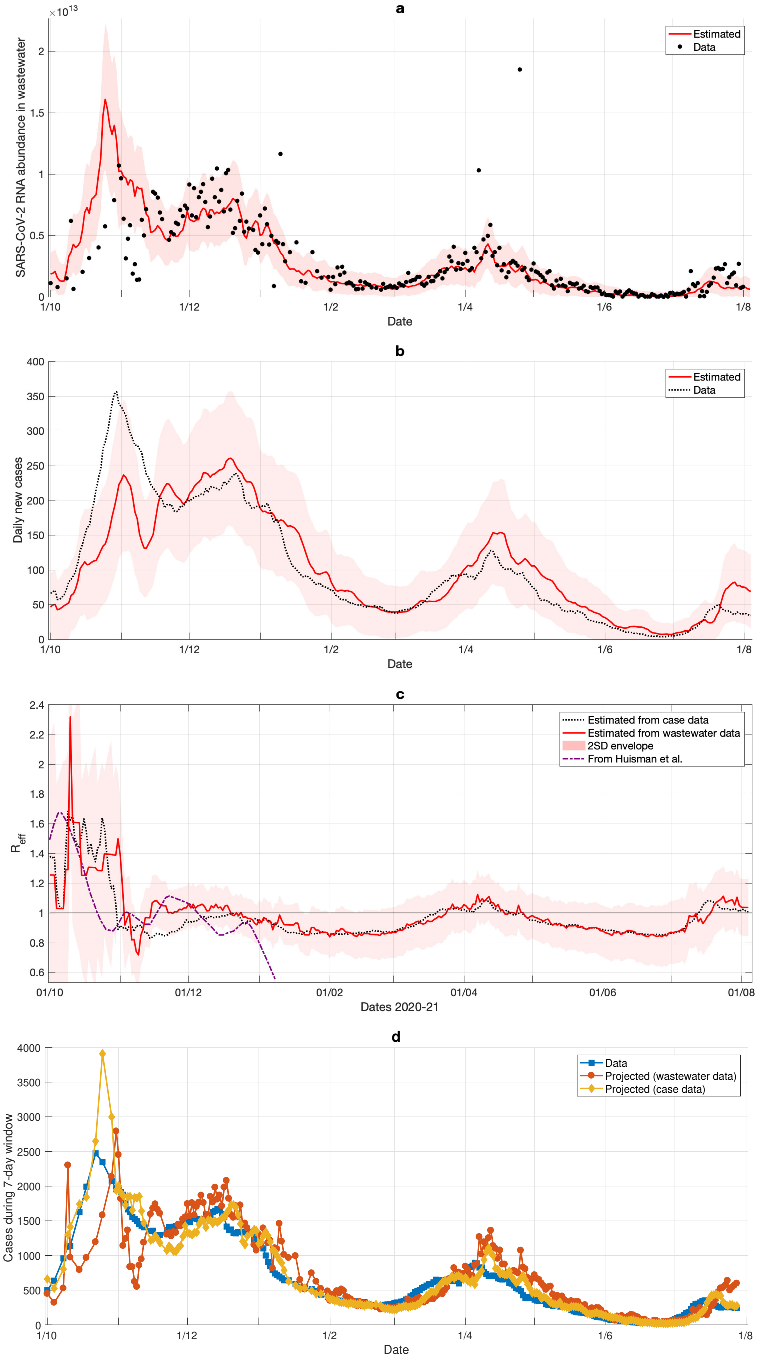


Supplementary figure 11. Results for Oshkosh. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.

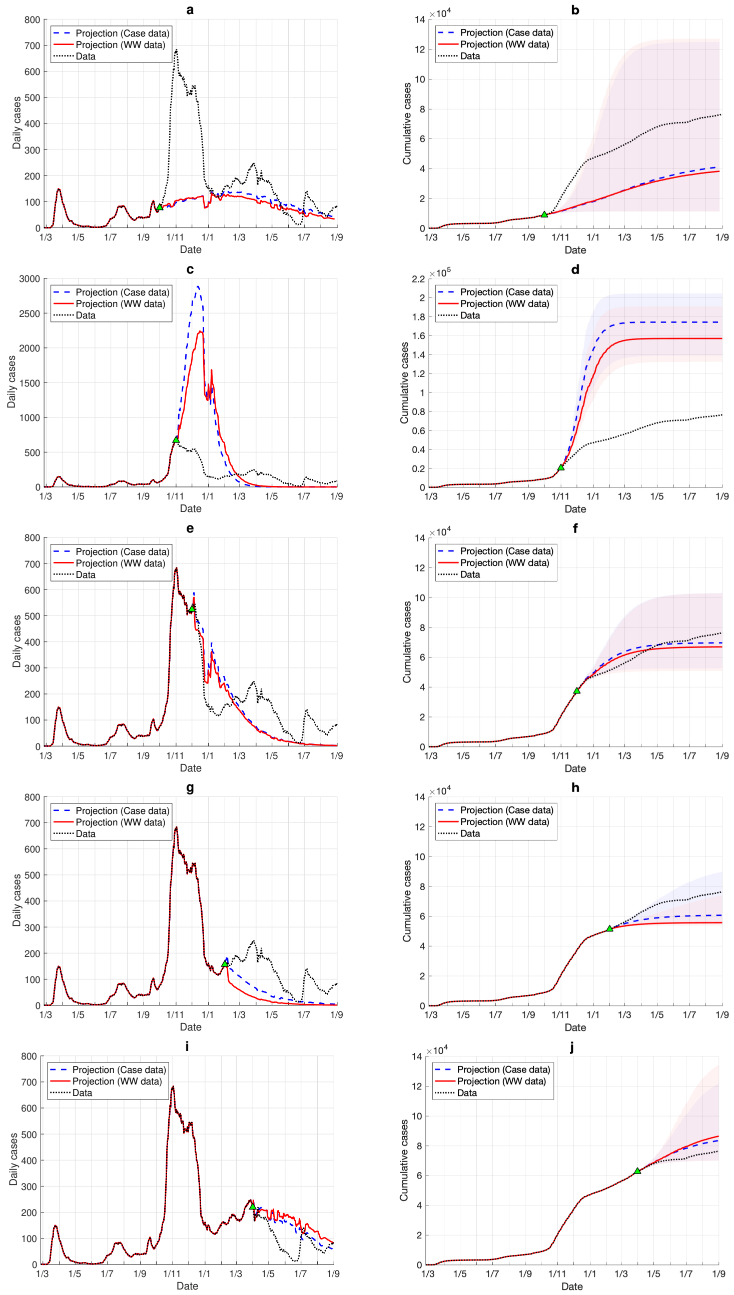


Supplementary figure 12. **Results for Raleigh**. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.

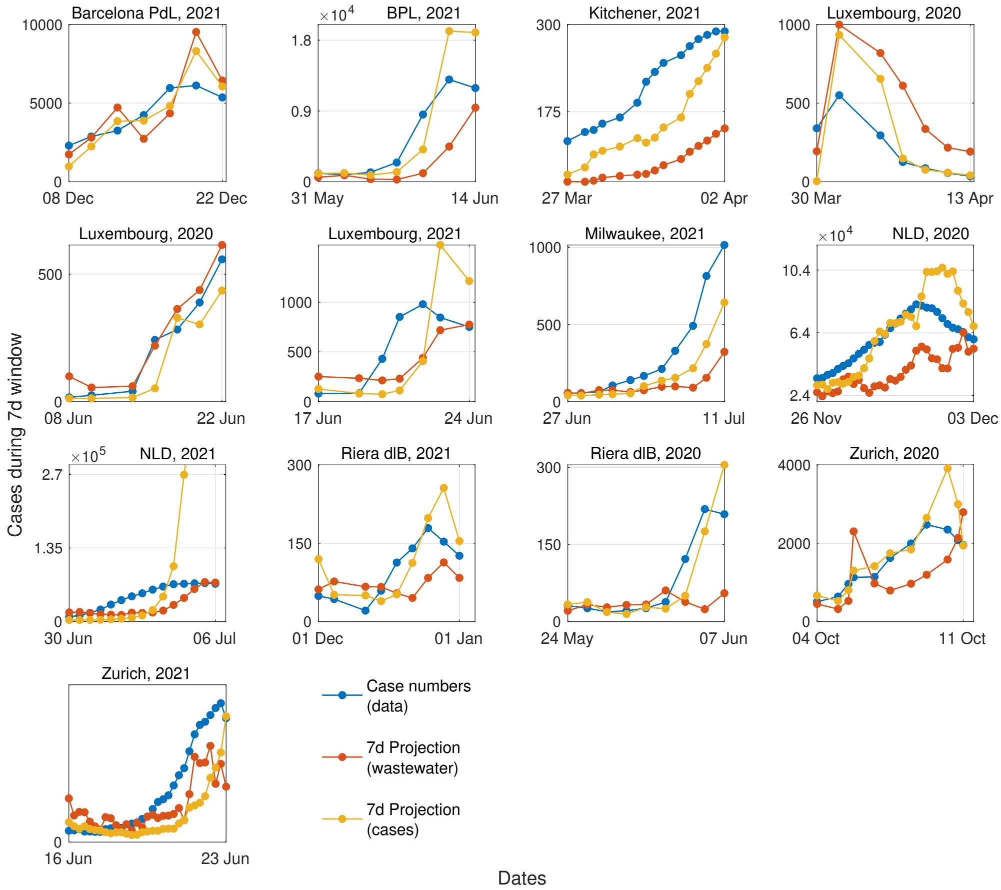
Supplementary figure 13. Results for Riera de la Bisbal. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



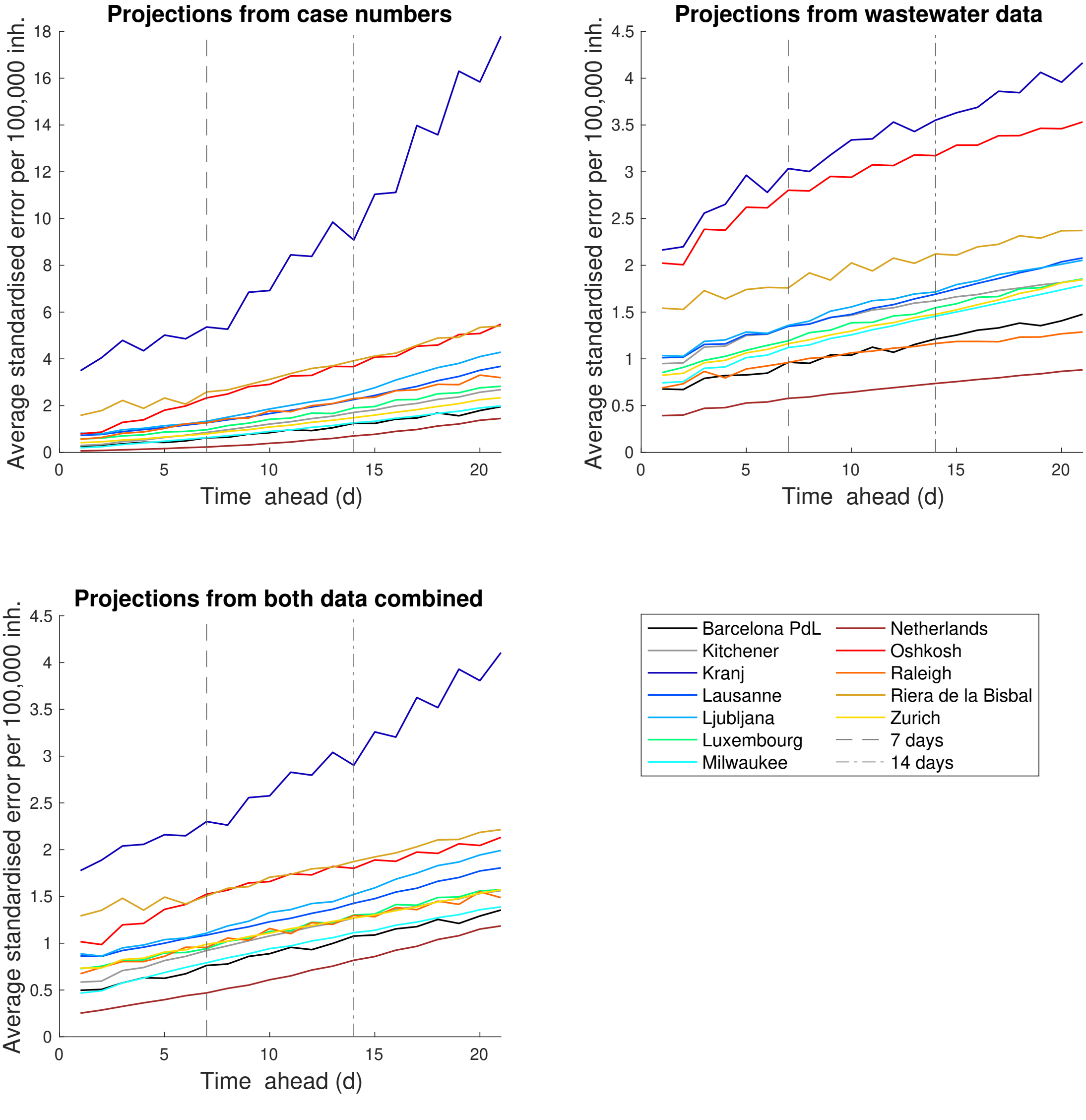
Supplementary figure 14. Results for Zurich. a: Reconstruction of wastewater data from case numbers. b: Reconstruction of case numbers from wastewater data. c: R_{eff} estimated from case data and wastewater data, as well as an estimate from (Fig. 1d, N1 marker, Huisman et al. (2021)) based on wastewater data. d: 7-day projections done at each day when wastewater sampling is done. The data shows number of cases in the 7-day time frame for which the projection is done.



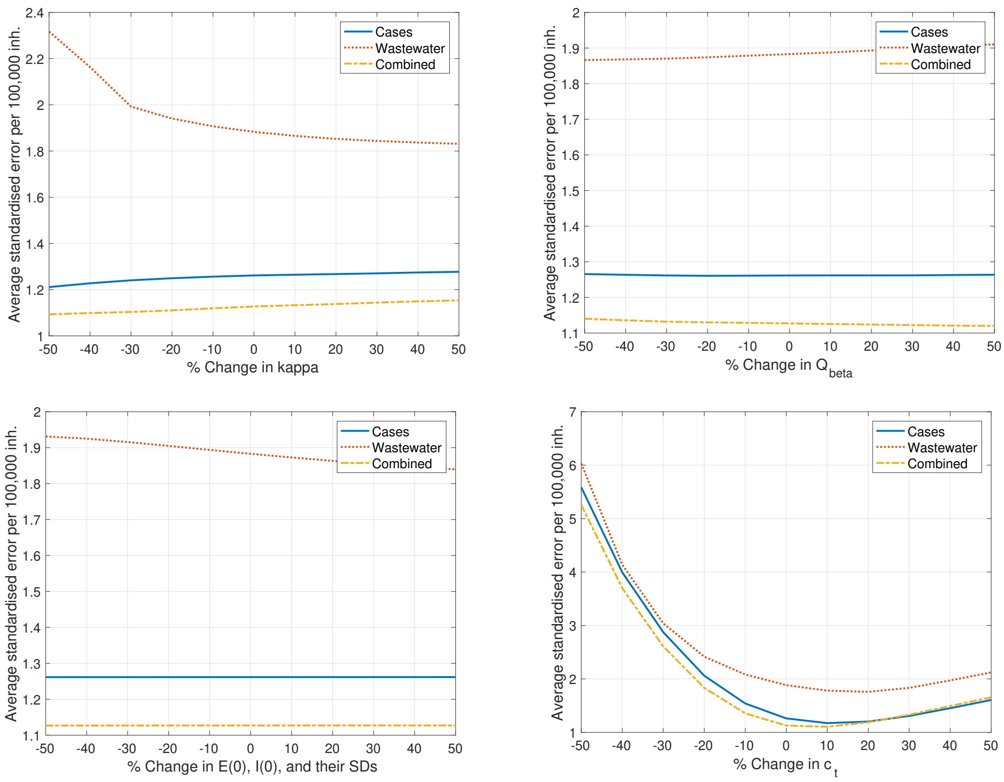
Supplementary figure 15. Mid and long-term projections. Start dates are: 01/10/2020 (a-b), 01/11/2020 (c-d), 01/12/2020 (e-f), 01/02/2021 (g-h), and 01/04/2021 (i-j). From these figures, we can draw other insights that remind to interpret mid-term estimates as plausible projections, rather than forecasts. Notably, making projections during stable or decreasing low-number periods might overlook unexpected outbreaks (panels 15a-b and g-h). Projections obtained when case numbers are high and increasing tend to overshoot on the long run (panels 15c-d) because of a constant β corresponding to $R > 1$ (a reproductive number greater than 1 corresponds to diffusing epidemics). During stable trends, particularly if the forecasting horizon is not extremely long, the precision improves (panels 15e-f and i-j). These observations hold for both projections made with wastewater or testing cases: they are consistent with each other within error bounds, therefore making wastewater data a valuable resource for this kind of analysis as well. The large uncertainties reflect the set of potential changes of conditions: assumptions on the underlying SEIR model, large variability of social activities, non-pharmaceutical interventions being imposed, and so on. The EKF learns about epidemic changes only when new data are available, reflecting the effect of the various interventions and allowing the comparison of different scenarios for epidemic management.



Supplementary figure 16. Zoom into the epidemic resurgences visually recognised in the considered regions. The figure displays short-term projections, made from wastewater data or case numbers, as well as true data for the 7-day time frame for which the projection is done. This figure completes Fig. 4 of main text with other epidemic resurgences observed in the considered regional areas. In general, consistent and noise-aware increasing trends need to be observed for some days before an online detection system can trigger a reliable alert. In addition, the wastewater sampling frequency plays a role in tuning the lead time of the warning. Hence, we do not often observe very advanced early warnings (as one might infer from retrospective observations like in Supplementary Fig. 1 and 2), but we quantitatively verify the need for cautious interpretation.



Supplementary figure 17. Average standardised error vs projection time frame, for all countries. The three panels refer to projections made from case numbers, from wastewater data, or from both data combined. Their mean values and 80% confidence intervals are reported in Fig. 3c of main text. Values at 7 and 14 days correspond to the ones reported in Supplementary Tab. 2.



Supplementary figure 18. Sensitivity analysis against changes in hand-picked parameters. The plots show the changes in 7-day window prediction performance for Luxembourg when a parameter is changed. The no-change numbers (0%) are those shown for Luxembourg in Supplementary Tab. 2. The "normalised error" corresponds to the measure employed throughout the main text and defined in Eq. 7 of the main text. Change in c_t (the share of detected cases) is compensated by a change in ν by the same amount. Note that other parameters are kept fixed. Some of the change could be compensated by re-running the parameter tuning pipeline. Note that +50% change in c_t corresponds to a situation where 83% of total cases are detected.