**Technical Appendix for: Modeling undetected live type 1 wild poliovirus circulation after apparent interruption of transmission: Pakistan and Afghanistan by Kalkowska et al.**

As mentioned in the main text, the DF for the ES describes the probability *s* of detecting the event of finding poliovirus in a sewage sample. For the SS approach we calculate *si* for the ith sampling site from the $DL\_{50}^{i}$ as:

$$s\_{i}=1-0.5^{\frac{EI\_{i}}{DL\_{50}^{i}×N\_{i}}}$$

where *Ni* is the catchment area population of the ith sampling site and EIi is the site-specific prevalence ([Kalkowska et al., 2019](#_ENREF_11)). For the SW approach we calculate *s* of detecting poliovirus in any sampling site given the total catchment area from all ES sites and the prevalence in the population as:

$$s (C)=\left({\sum\_{}^{}aN\_{i}}/{N}\right)^{-C×ln\left({EI}/{N}\right)}$$

where $\sum\_{}^{}aN\_{i} $equals the number of people covered by all active sampling sites, N equals the number of people in the population, EI is the general prevalence, and *C* represents a fitting coefficient ([Kalkowska et al., 2019](#_ENREF_11)).

We updated the list of ES sampling sites in Pakistan and Afghanistan used in ([Kalkowska et al., 2019](#_ENREF_11)) and the estimated populations in their catchment areas. Table A1 lists 119 historically and/or currently active sites (25 in Afghanistan and 94 in Pakistan) and their estimated catchment populations (top 25 rows correspond to sites in Afghanistan, bottom 94 rows correspond to sites in Pakistan). Figure A1 illustrates the updated absolute growth in surveillance activity by country for the full time period.

Similar to prior modeling ([Kalkowska et al., 2019](#_ENREF_11)), we first characterized monthly sampling activity and estimated isolation rates for each site for 2009-2021 by counting all samples positive for WPV1, VDPV2 and/or WPV3 for each site over time. We updated the estimates of the $DL\_{50}^{i}$ values for each site used in SS approach “by minimizing the difference between the observed isolation rates for each site and the modeled isolation rate (averaged over 1,000 stochastic iterations) as described in the main text and the prevalence (*EI/N*) from the deterministic differential-equation based model for each serotype” ([Kalkowska et al., 2019](#_ENREF_11)) between 2009-2021 (reciprocal presented in Table A1). We updated the estimates of the system-wide value of C used in the SW approach “by minimizing the difference between the estimated isolation rate and the modeled isolation rate using the same minimization method” ([Kalkowska et al., 2019](#_ENREF_11)) (see estimates in Table A2). For both ES approaches we considered the same three distributions of ES sampling sites over the modeled subpopulations as described previously in ([Kalkowska et al., 2019](#_ENREF_11)) and in the main text (see Figure A2 for CNC curves of Scenario 1 using ES alone).

Consistent with the laboratory approach of assessing ES site sensitivity including the detection of vaccine strains, we also updated our estimate of isolation rates for each site for 2009-2021 by counting all samples positive for any PV1, PV2 and/or PV3 (i.e., WPV, VDPV, or OPV-related virus) for each site over time. Using these rates, we updated the estimates of the $DL\_{50}^{i}$ values for each site used in the SS approach (see reciprocal $DL\_{50}^{i}$ estimates in Table A3) and the estimates of the system-wide value of C used in the SW approach (see estimates in Table A4), which we used for the results described in the main text.

**Table A1:** ES sampling sites, estimated catchment populations, and DL50 estimates assuming three different allocation approaches, using isolation rates for each site based on samples positive for only WPV1, cVDPV2 and/or WPV3

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site No.  | Catchment population ([Novel-T Innovative Solutions](#_ENREF_15)) | 1/DL50 [people/infections] (ES sites distributed over the whole country) | 1/DL50 [people/infections] (ES sites distributed over the under- vaccinated subpopulation) | 1/DL50 [people/infections] (ES sites distributed over the general subpopulation) |
| 01  | 65,640\* |  600  |  200  |  28,000  |
| 02 | 65,640\* |  1,600  |  300  |  407,000  |
| 03 | 65,640\* |  300  |  100  |  2,000  |
| 04 | 65,640\* |  500  |  100  |  9,000  |
| 05 | 65,640\* |  100  |  100  | 0  |
| 06 | 65,640\* |  600  |  200  |  17,000  |
| 07 | 65,640\* |  4,100  |  700  |  8,133,000  |
| 08 |  97,760  |  6,500  |  800  |  3,841,000  |
| 09 |  127  |  8,300  |  1,000  |  5,723,000  |
| 10 | 33,469  |  4,800  |  700  |  9,992,000  |
| 11 | 65,640\* |  200  |  100  |  1,000  |
| 12 | 348,636  | 0  |  0  |  0  |
| 13 | 65,640\* |  0  |  0  |  0  |
| 14 | 65,640\* |  600  |  200  |  15,000  |
| 15 | 65,640\* | 0  | 0  | 0  |
| 16 | 8,427  |  6,900  |  800  |  3,954,000  |
| 17 | 65,640\* |  2,600  |  400  |  1,326,000  |
| 18 | 1  |  7,100  |  800  |  4,266,000  |
| 19 | 65,640\* |  3,000  |  400  |  1,446,000  |
| 20 | 65,640\* | 0  | 0  | 0  |
| 21 | 230  |  12,400  |  1,400  |  9,935,000  |
| 22 | 135,169  |  10,900  |  1,300  |  9,952,000  |
| 23 | 3,775  |  6,500  |  800  |  9,932,000  |
| 24 | 28,804  |  6,400  |  800  |  3,129,000  |
| 25 | 65,640\* |  900  |  200  |  48,000  |
| 26 |  96,642\*\*  |  400  |  100  |  1,000  |
| 27 |  96,642\*\*  | 0  | 0  | 0  |
| 28 |  96,642\*\*  |  3,800  |  400  |  158,000  |
| 29 | 1,703  |  31,400  |  1,800  |  9,999,000  |
| 30 |  96,642\*\*  |  24,000  |  1,400  |  9,936,000  |
| 31 | 19,595  |  5,600  |  600  |  687,000  |
| 32 | 2,282  |  8,500  |  700  |  2,074,000  |
| 33 |  96,642\*\*  |  2,600  |  300  |  17,000  |
| 34 | 33,067  |  34,500  |  2,100  |  9,933,000  |
| 35 | 42,262  |  13,100  |  800  |  7,416,000  |
| 36 | 8,106  |  32,600  |  2,000  |  9,920,000  |
| 37 | 527,879  |  14,800  |  900  |  9,431,000  |
| 38 |  96,642\*\*  |  9,800  |  600  |  4,892,000  |
| 39 | 16  |  5,000  |  500  |  512,000  |
| 40 |  96,642\*\*  |  800  |  100  |  1,000  |
| 41 |  96,642\*\*  |  700  |  100  |  1,000  |
| 42 |  96,642\*\*  |  9,000  |  800  |  1,937,000  |
| 43 |  96,642\*\*  |  1,200  |  200  |  2,000  |
| 44 |  96,642\*\*  |  600  |  100  |  1,000  |
| 45 |  96,642\*\*  | 0  | 0  | 0  |
| 46 |  96,642\*\*  |  400  |  100  |  1,000  |
| 47 | 39,784  |  10,700  |  900  |  3,197,000  |
| 48 | 4,798  |  200  | 0  | 0  |
| 49 | 384  |  1,700  |  200  |  4,000  |
| 50 | 155  | 0  | 0  | 0  |
| 51 | 593  |  4,600  |  200  |  1,197,000  |
| 52 | 483  |  800  |  100  |  3,000  |
| 53 |  96,642\*\*  |  700  |  100  |  1,000  |
| 54 | 60  |  1,500  |  100  |  397,000  |
| 55 | 51,547  |  3,200  |  400  |  94,000  |
| 56 |  96,642\*\*  |  1,800  |  200  |  5,000  |
| 57 | 13,534  |  500  |  100  |  1,000  |
| 58 | 48,335  |  9,300  |  600  |  4,678,000  |
| 59 |  96,642\*\*  | 0  | 0  | 0  |
| 60 |  96,642\*\*  |  1,800  |  200  |  5,000  |
| 61 | 39,421  |  29,900  |  1,600  |  9,997,000  |
| 62 | 3,106  |  2,000  |  300  |  6,000  |
| 63 | 131,360  |  7,400  |  600  |  1,398,000  |
| 64 | 286  |  4,700  |  400  |  985,000  |
| 65 | 9,308  | 0  | 0  | 0  |
| 66 | 6,713  |  1,200  |  200  |  2,000  |
| 67 | 4,583  |  400  | 0  |  228,000  |
| 68 |  96,642\*\*  |  5,400  |  500  |  692,000  |
| 69 | 20,914  | 0  | 0  | 0  |
| 70 | 21  | 0  | 0  | 0  |
| 71 |  96,642\*\*  | 0  | 0  | 0  |
| 72 |  96,642\*\*  |  3,300  |  500  |  15,000  |
| 73 |  96,642\*\*  |  11,000  |  600  |  346,000  |
| 74 |  96,642\*\*  |  19,700  |  1,000  |  591,000  |
| 75 | 205,847  |  7,300  |  400  |  3,484,000  |
| 76 | 1,223  |  7,800  |  500  |  3,547,000  |
| 77 | 1,215  |  12,700  |  900  |  3,456,000  |
| 78 | 988  |  14,500  |  1,000  |  4,440,000  |
| 79 | 16  |  4,000  |  300  |  1,292,000  |
| 80 | 3,753  |  1,700  |  100  |  216,000  |
| 81 | 2,409  |  2,500  |  200  |  578,000  |
| 82 |  96,642\*\*  |  1,000  |  100  |  2,000  |
| 83 |  96,642\*\*  |  2,900  |  100  |  1,414,000  |
| 84 |  96,642\*\*  |  800  | 0  |  403,000  |
| 85 | 111,375  |  9,700  |  700  |  3,798,000  |
| 86 | 93,226  |  15,100  |  800  |  9,619,000  |
| 87 |  96,642\*\*  | 0  | 0  | 0  |
| 88 |  96,642\*\*  |  4,300  |  300  |  21,000  |
| 89 | 3,562  |  800  |  100  |  1,000  |
| 90 |  96,642\*\*  |  3,000  |  500  |  10,000  |
| 91 |  96,642\*\*  |  1,600  |  300  |  3,000  |
| 92 | 768  |  3,200  |  400  |  57,000  |
| 93 |  96,642\*\*  | 0  | 0  | 0  |
| 94 | 7,336  |  11,700  |  700  |  6,126,000  |
| 95 |  96,642\*\*  | 0  | 0  | 0  |
| 96 | 5,624  |  18,900  |  1,200  |  9,980,000  |
| 97 |  96,642\*\*  |  14,500  |  1,100  |  9,811,000  |
| 98 | 17  | 0  | 0  | 0  |
| 99 | 171,871  |  3,700  |  200  |  1,773,000  |
| 100 |  96,642\*\*  |  9,700  |  500  |  6,722,000  |
| 101 |  96,642\*\*  |  3,900  |  200  |  1,812,000  |
| 102 |  96,642\*\*  |  4,400  |  1,900  |  17,000  |
| 103 |  96,642\*\*  |  59,500  |  5,200  |  16,000  |
| 104 | 270,512  |  6,500  |  400  |  2,952,000  |
| 105 | 1,127,740  |  8,900  |  500  |  4,517,000  |
| 106 | 141,682  |  20,000  |  1,300  |  8,890,000  |
| 107 | 167,546  |  20,700  |  1,100  |  9,965,000  |
| 108 | 356,007  |  59,800  |  3,300  |  9,954,000  |
| 109 | 19,583  |  6,500  |  400  |  2,926,000  |
| 110 | 828,700  |  20,400  |  1,400  |  9,971,000  |
| 111 |  96,642\*\*  |  37,500  |  2,200  |  9,888,000  |
| 112 |  96,642\*\*  |  28,500  |  1,900  |  9,885,000  |
| 113 | 34,482  |  28,600  |  1,800  |  9,774,000  |
| 114 | 623,662  |  50,000  |  2,900  |  9,935,000  |
| 115 |  96,642\*\*  |  61,000  |  5,300  |  14,000  |
| 116 |  96,642\*\*  |  23,300  |  1,600  |  9,838,000  |
| 117 | 1,399  | 0  | 0  | 0  |
| 118 | 27,819  |  6,000  |  400  |  2,188,000  |
| 119 | 5  |  3,600  |  300  |  955,000  |

Abbreviations: DL50 , detection limit; ES, environmental surveillance;

+ assumed active post Dec-2021

\* Afghanistan’s average catchment population used in place of unknown

\*\* Pakistan’s average catchment population used in place of unknown

**Table A2:** Estimated wild poliovirus (WPV) and vaccine-derived poliovirus (VDPV) isolation rates, and estimated C coefficients for Pakistan and Afghanistan combined assuming three different allocation approaches, using isolation rates for each site based on samples positive for only WPV1, cVDPV2 and/or WPV3

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Country | EstimatedWPV and VDPV isolation rate during 2009-2017 | C  (ES sites distributed over the whole country) | C (ES sites distributed over the under- vaccinated subpopulation) | C (ES sites distributed over the general subpopulation) |
| Pakistan and Afghanistan | 0.10 | 0.046 | 0.247 | 0.017 |

Abbreviations: C, fitting coefficients; ES, environmental surveillance;

**Table A3:** ES sampling sites, estimated catchment populations, and DL50 estimates assuming three different allocation approaches, using isolation rates for each site based on samples positive for any PV1, PV2 and/or PV3

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site No.  | Catchment population ([Novel-T Innovative Solutions](#_ENREF_15)) | 1/DL50 [people/infections] (ES sites distributed over the whole country) | 1/DL50 [people/infections] (ES sites distributed over the under- vaccinated subpopulation) | 1/DL50 [people/infections] (ES sites distributed over the general subpopulation) |
| 01  | 65,640\* | 100 | 100 | 100 |
| 02 | 65,640\* | 300 | 300 | 300 |
| 03 | 65,640\* | 200 | 200 | 200 |
| 04 | 65,640\* | 0 | 0 | 0 |
| 05 | 65,640\* | 100 | 100 | 100 |
| 06 | 65,640\* | 200 | 200 | 200 |
| 07 | 65,640\* | 400 | 400 | 400 |
| 08 |  97,760  | 200 | 200 | 200 |
| 09 |  127  | 200 | 200 | 200 |
| 10 | 33,469  | 200 | 300 | 300 |
| 11 | 65,640\* | 100 | 100 | 100 |
| 12 | 348,636  | 0 | 0 | 0 |
| 13 | 65,640\* | 100 | 100 | 100 |
| 14 | 65,640\* | 100 | 100 | 100 |
| 15 | 65,640\* | 0 | 0 | 100 |
| 16 | 8,427  | 200 | 200 | 200 |
| 17 | 65,640\* | 500 | 600 | 500 |
| 18 | 1  | 300 | 300 | 300 |
| 19 | 65,640\* | 400 | 500 | 400 |
| 20 | 65,640\* | 200 | 300 | 200 |
| 21 | 230  | 400 | 500 | 400 |
| 22 | 135,169  | 500 | 600 | 600 |
| 23 | 3,775  | 400 | 400 | 400 |
| 24 | 28,804  | 300 | 300 | 300 |
| 25 | 65,640\* | 200 | 200 | 200 |
| 26 |  96,642\*\*  | 0 | 0 | 0 |
| 27 |  96,642\*\*  | 100 | 100 | 100 |
| 28 |  96,642\*\*  | 200 | 200 | 200 |
| 29 | 1,703  | 600 | 600 | 700 |
| 30 |  96,642\*\*  | 600 | 600 | 600 |
| 31 | 19,595  | 300 | 300 | 300 |
| 32 | 2,282  | 400 | 400 | 400 |
| 33 |  96,642\*\*  | 200 | 200 | 200 |
| 34 | 33,067  | 600 | 600 | 700 |
| 35 | 42,262  | 500 | 600 | 600 |
| 36 | 8,106  | 600 | 600 | 700 |
| 37 | 527,879  | 800 | 800 | 800 |
| 38 |  96,642\*\*  | 500 | 500 | 500 |
| 39 | 16  | 300 | 300 | 300 |
| 40 |  96,642\*\*  | 200 | 200 | 200 |
| 41 |  96,642\*\*  | 100 | 100 | 100 |
| 42 |  96,642\*\*  | 200 | 200 | 200 |
| 43 |  96,642\*\*  | 100 | 100 | 100 |
| 44 |  96,642\*\*  | 100 | 100 | 100 |
| 45 |  96,642\*\*  | 100 | 100 | 200 |
| 46 |  96,642\*\*  | 100 | 100 | 100 |
| 47 | 39,784  | 300 | 300 | 300 |
| 48 | 4,798  | 300 | 300 | 300 |
| 49 | 384  | 200 | 200 | 200 |
| 50 | 155  | 200 | 200 | 200 |
| 51 | 593  | 200 | 300 | 200 |
| 52 | 483  | 200 | 300 | 200 |
| 53 |  96,642\*\*  | 200 | 200 | 200 |
| 54 | 60  | 300 | 400 | 300 |
| 55 | 51,547  | 300 | 300 | 300 |
| 56 |  96,642\*\*  | 300 | 300 | 300 |
| 57 | 13,534  | 300 | 300 | 300 |
| 58 | 48,335  | 300 | 400 | 300 |
| 59 |  96,642\*\*  | 0 | 0 | 0 |
| 60 |  96,642\*\*  | 300 | 300 | 300 |
| 61 | 39,421  | 600 | 700 | 600 |
| 62 | 3,106  | 500 | 500 | 600 |
| 63 | 131,360  | 400 | 400 | 400 |
| 64 | 286  | 200 | 200 | 200 |
| 65 | 9,308  | 200 | 200 | 200 |
| 66 | 6,713  | 500 | 500 | 500 |
| 67 | 4,583  | 600 | 700 | 600 |
| 68 |  96,642\*\*  | 600 | 600 | 600 |
| 69 | 20,914  | 400 | 400 | 400 |
| 70 | 21  | 400 | 500 | 400 |
| 71 |  96,642\*\*  | 300 | 300 | 300 |
| 72 |  96,642\*\*  | 200 | 300 | 200 |
| 73 |  96,642\*\*  | 900 | 700 | 900 |
| 74 |  96,642\*\*  | 300 | 300 | 300 |
| 75 | 205,847  | 500 | 600 | 500 |
| 76 | 1,223  | 400 | 400 | 400 |
| 77 | 1,215  | 300 | 300 | 300 |
| 78 | 988  | 300 | 300 | 300 |
| 79 | 16  | 600 | 600 | 600 |
| 80 | 3,753  | 400 | 400 | 400 |
| 81 | 2,409  | 300 | 400 | 300 |
| 82 |  96,642\*\*  | 200 | 200 | 200 |
| 83 |  96,642\*\*  | 300 | 200 | 300 |
| 84 |  96,642\*\*  | 300 | 300 | 400 |
| 85 | 111,375  | 400 | 400 | 400 |
| 86 | 93,226  | 600 | 700 | 600 |
| 87 |  96,642\*\*  | 200 | 200 | 200 |
| 88 |  96,642\*\*  | 200 | 200 | 200 |
| 89 | 3,562  | 300 | 300 | 300 |
| 90 |  96,642\*\*  | 300 | 400 | 300 |
| 91 |  96,642\*\*  | 100 | 100 | 100 |
| 92 | 768  | 300 | 300 | 300 |
| 93 |  96,642\*\*  | 0 | 0 | 0 |
| 94 | 7,336  | 300 | 300 | 300 |
| 95 |  96,642\*\*  | 100 | 200 | 100 |
| 96 | 5,624  | 400 | 500 | 500 |
| 97 |  96,642\*\*  | 300 | 300 | 300 |
| 98 | 17  | 0 | 0 | 0 |
| 99 | 171,871  | 100 | 100 | 100 |
| 100 |  96,642\*\*  | 300 | 300 | 300 |
| 101 |  96,642\*\*  | 200 | 200 | 200 |
| 102 |  96,642\*\*  | 300 | 500 | 300 |
| 103 |  96,642\*\*  | 1,000 | 1,700 | 1000 |
| 104 | 270,512  | 300 | 300 | 300 |
| 105 | 1,127,740  | 300 | 300 | 300 |
| 106 | 141,682  | 200 | 200 | 200 |
| 107 | 167,546  | 400 | 400 | 400 |
| 108 | 356,007  | 600 | 600 | 600 |
| 109 | 19,583  | 400 | 500 | 400 |
| 110 | 828,700  | 300 | 300 | 300 |
| 111 |  96,642\*\*  | 700 | 700 | 800 |
| 112 |  96,642\*\*  | 300 | 300 | 300 |
| 113 | 34,482  | 400 | 400 | 400 |
| 114 | 623,662  | 400 | 400 | 400 |
| 115 |  96,642\*\*  | 700 | 1,200 | 700 |
| 116 |  96,642\*\*  | 300 | 300 | 300 |
| 117 | 1,399  | 100 | 100 | 100 |
| 118 | 27,819  | 200 | 200 | 200 |
| 119 | 5  | 300 | 300 | 300 |

Abbreviations: DL50 , detection limit; ES, environmental surveillance;

+ assumed active post Dec-2021

\* Afghanistan’s average catchment population used in place of unknown

\*\* Pakistan’s average catchment population used in place of unknown

**Table A4:** Estimated wild poliovirus (WPV) and vaccine-derived poliovirus (VDPV) isolation rates, and estimated C coefficients for Pakistan and Afghanistan combined assuming three different allocation approaches, using isolation rates for each site based on samples positive for any PV1, PV2 and/or PV3

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Country | EstimatedWPV and VDPV isolation rate during 2009-2017 | C  (ES sites distributed over the whole country) | C (ES sites distributed over the under- vaccinated subpopulation) | C (ES sites distributed over the general subpopulation) |
| Pakistan and Afghanistan | 0.43 | 0.035 | 0.132 | 0.034 |

Abbreviations: C, fitting coefficients; ES, environmental surveillance;

**Figure A1:** ES sampling site activity by month for 2009-2021 in Pakistan and Afghanistan for the: (a) number of active ES sampling sites, (b) total catchment population of active ES sampling sites, and (c) catchment population of active ES sampling sites

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**Figure A2:** Confidence about no circulation in Pakistan and Afghanistan as a function of the detected-event-free period (DEFP) assuming different ES approaches compared to perfect AFP surveillance without ES, and reference lines provided to indicate 95% and 99% confidence for WPV1 for Scenario 1, using isolation rates for each site based on samples positive for only WPV1, cVDPV2 and/or WPV3

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**Abbreviations:** AFP, acute flaccid paralysis; DEFP, detected-event-free period; ES, environmental surveillance; GS, general population sites distribution; IP, isolation-rate based prevalence; NS, national sites distribution; PP, proportional prevalence; SS, site-specific; SW, system-wide; US, under-vaccinated subpopulation sites distribution, WPV1, serotype 1 wild poliovirus