Characterization of Uncertainty in Estimation of Methane Collection from Select U.S. Landfills

Supporting Information (SI)

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32 Pages; 12 Tables, 20 Figures

Figures S1 to S11 present the location and schedule of waste disposal, the schedule of final cover and GCCS installation at case-study landfills; while Tables S1 to S10 include associated estimates of monthly collection efficiency (α_{ji}), based on information contained in Figures S1 to S11.

The estimates of MSW fractions and parameters for the dual phase model are given in Tables S11 and S12, respectively.

Figures S12 to S20 illustrate predicted methane collection, generation, and observed methane collection over the observation period for all landfills, except those presented in the manuscript.

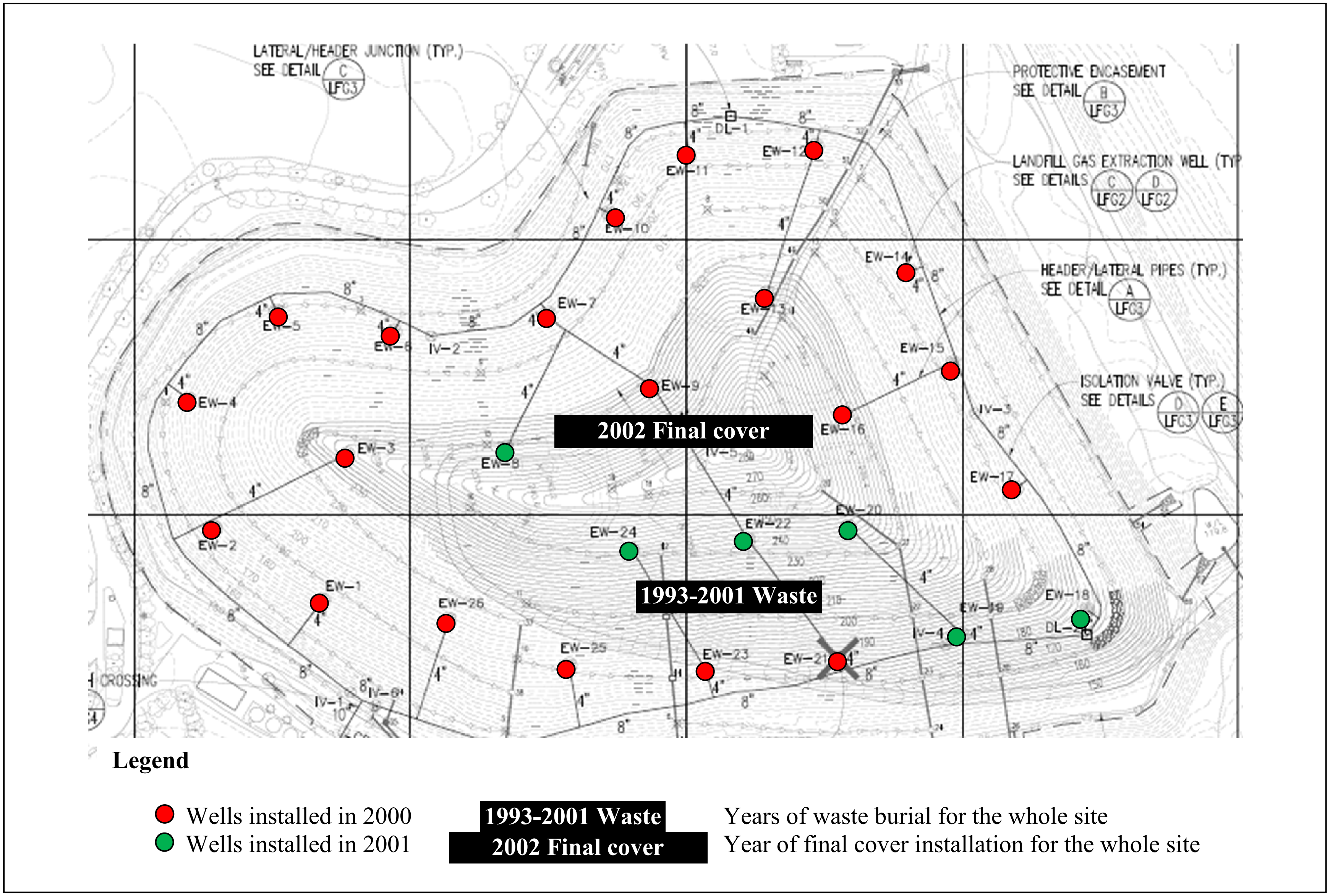


Figure S1. Location of waste disposal and schedule of final cover and GCCS installation at Landfill S.

Table S1. Estimates of Monthly Collection Efficiency (α_{ji}) from 2003 through 2007 for Gas Generated at Landfill S (%)[a]

Gas recovery period	Years of waste burial 1993-2001
01/03 – 12/03	85-95[b]
01/04 – 12/04	85-95[b]
01/05 – 12/05	85-95[b]
01/06 – 12/06	85-95[b]
01/07 – 12/07	85-95[b]

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation.
b. The gas collection wells and geomembrane final cover had been constructed by the end of 2002, so 85 to 95% collection efficiency was assumed for the gas generated from 2003 through 2007.

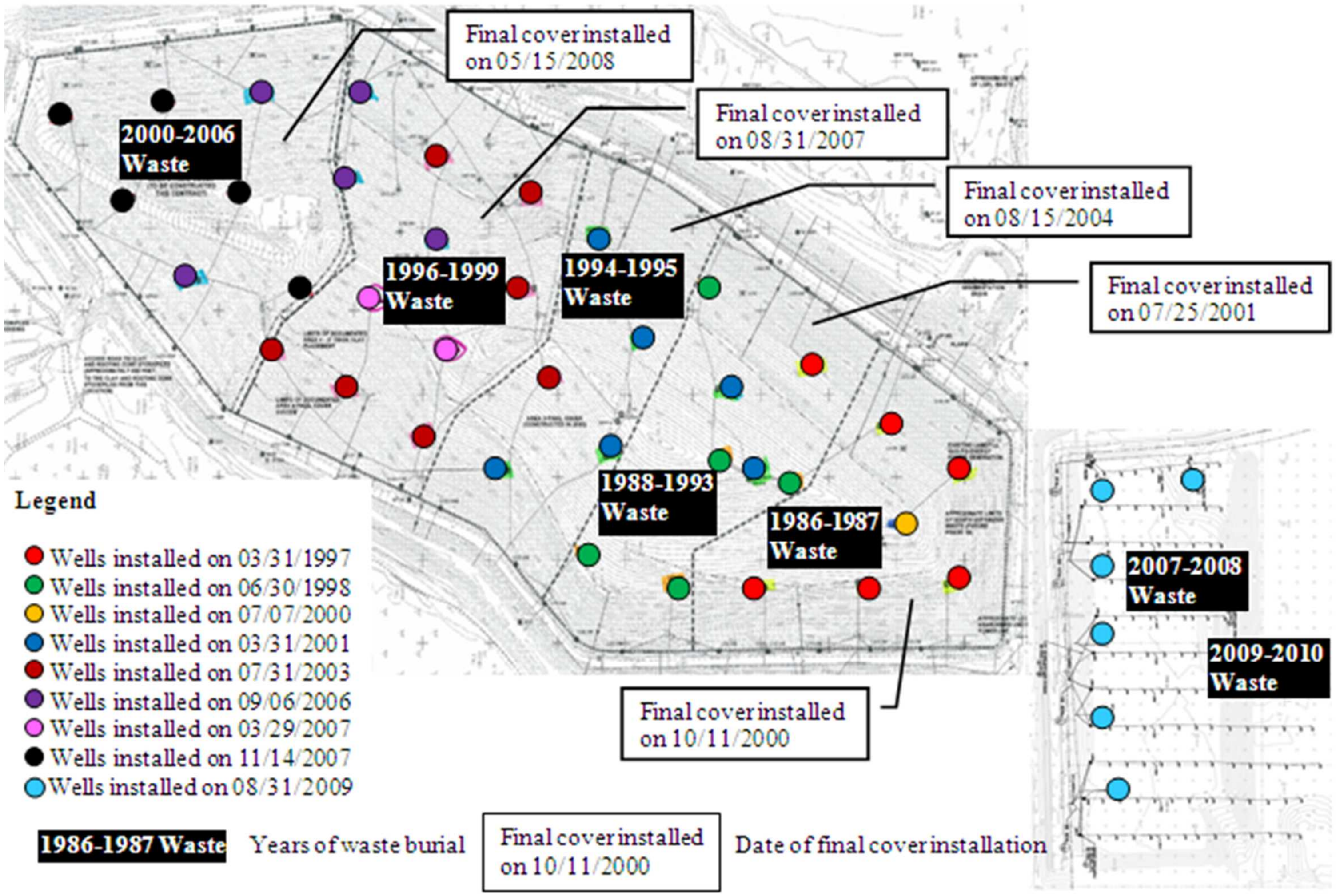


Figure S2. Location of waste disposal and schedule of final cover and GCCS installation at landfill G. The waste buried in 2007-2010 was in an expansion adjacent to the original landfill as shown.

Table S2. Estimates of Monthly Collection Efficiency (α_{ji}) from 2005 through 2010 for Gas Generated at Landfill G (%)[a]

Gas recovery period[b]	Years of waste burial						
	1986-1995	1996-1999	2000-2004	2005-2006	2007	2008	2009-2010
01/05 - 09/06	80-95	45-75	0-25	0	0	0	0
10/06 - 06/07	80-95	60-85	30-60	0	0	0	0
07/07 - 11/07	80-95	80-95	30-60	0	0	0	0
12/07 - 06/08	80-95	80-95	50-75	50-75	0	0	0
07/08 - 08/09	80-95	80-95	80-95	80-95	0	0	0
09/09 - 06/10	80-95	80-95	80-95	80-95	20-50	0	0
07/10 - 12/10	80-95	80-95	80-95	80-95	50-75	20-50	0

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation.
b. Observed methane collection data were available from Jan. 2005 through Dec. 2010, so the collection efficiencies required to calculate methane collected were only estimated for this period.

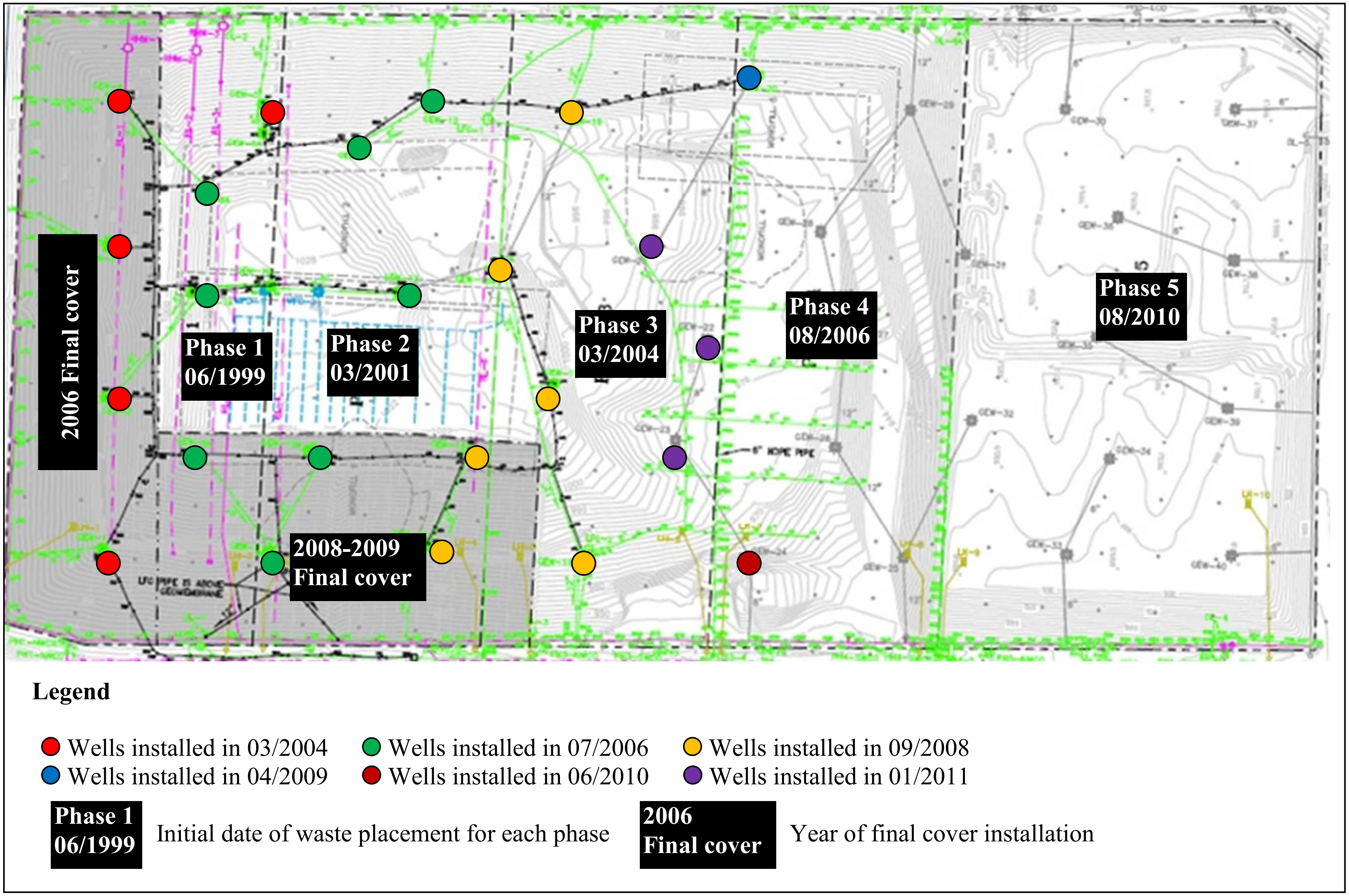


Figure S3. Location of waste disposal and schedule of final cover and GCCS installation at Landfill H.

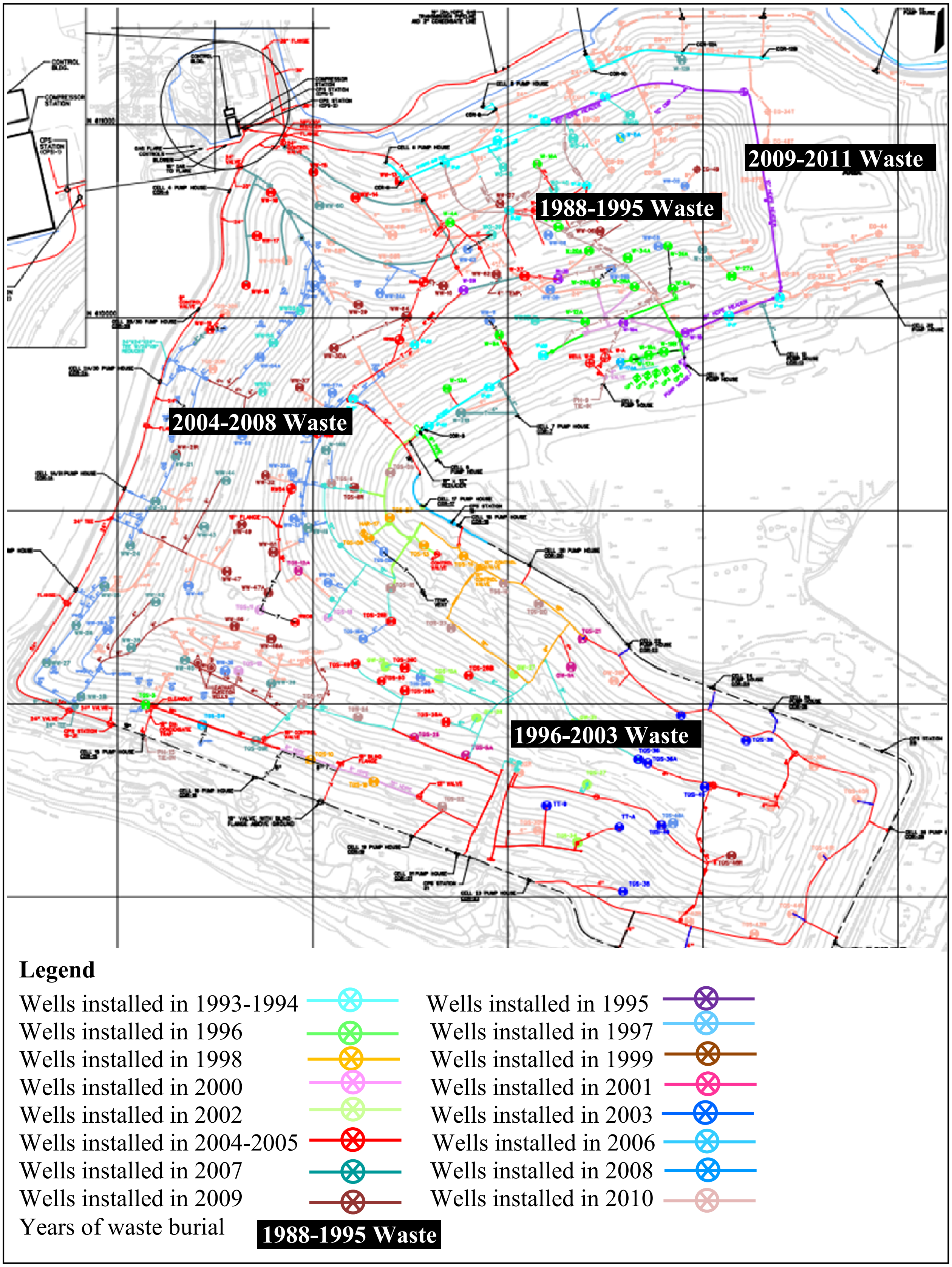
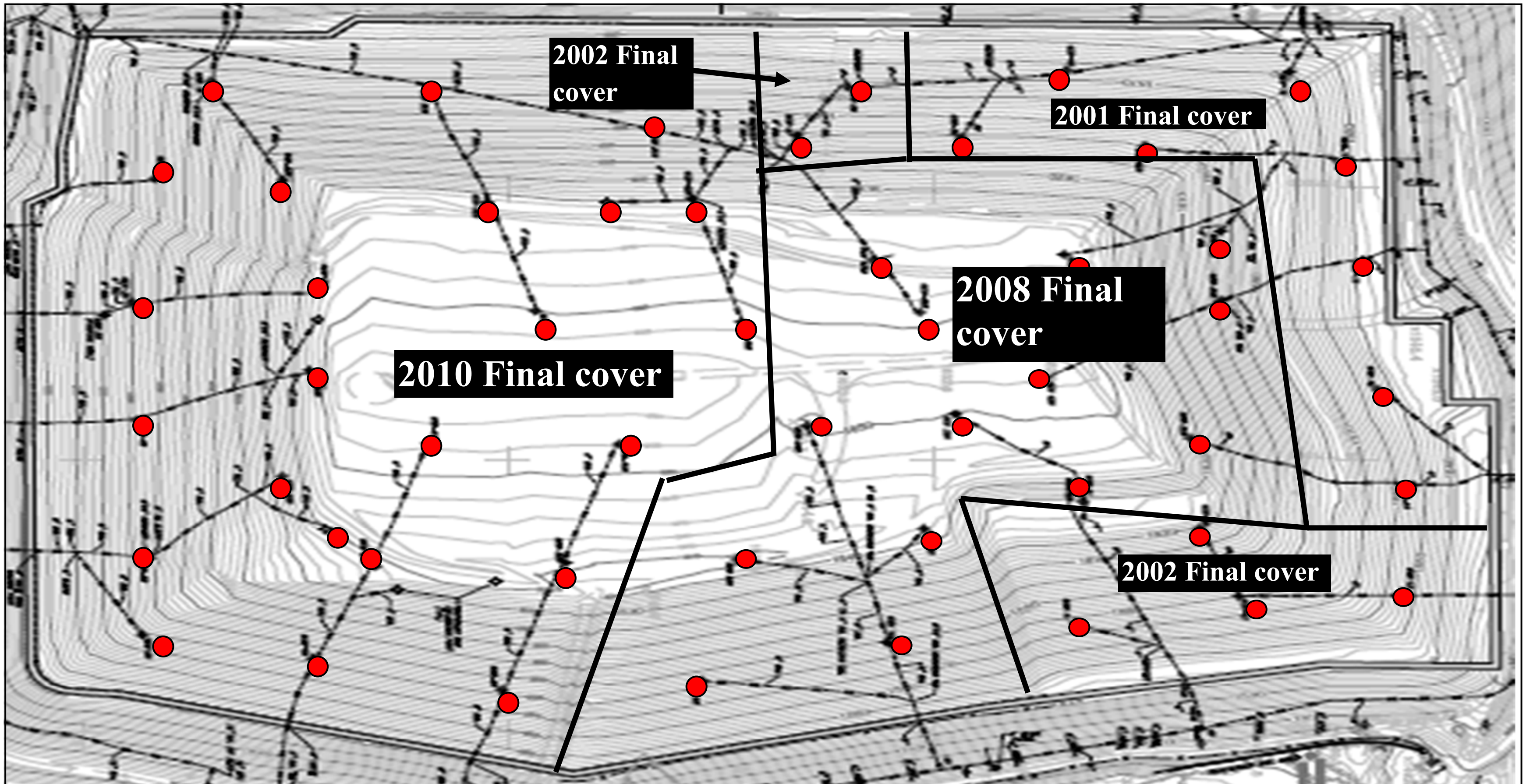


Figure S4. Location of waste disposal and schedule of final cover and GCCS installation at Landfill T.

Table S3. Estimates of Monthly Collection Efficiency (α_{ji}) from 2006 through 2011 for Gas Generated at Landfill T (%)[a]

Gas recovery period	Years of waste burial								
	1988-2003	2004	2005	2006	2007	2008	2009	2010	2011
01/06 – 06/06	85-95	50-70	0-25	0	0	0	0	0	0
07/06 – 12/06	85-95	50-70	25-50	0	0	0	0	0	0
01/07 – 06/07	85-95	60-80	50-70	0-25	0	0	0	0	0
07/07 – 12/07	85-95	60-80	50-70	25-50	0	0	0	0	0
01/08 – 06/08	85-95	60-80	60-80	50-70	0-25	0	0	0	0
07/08 – 12/08	85-95	60-80	60-80	50-70	25-50	0	0	0	0
01/09 – 06/09	85-95	60-80	60-80	60-80	50-70	0-25	0	0	0
07/09 – 12/09	85-95	60-80	60-80	60-80	50-70	25-50	0	0	0
01/10 – 06/10	85-95	60-80	60-80	60-80	60-80	50-70	0-25	0	0
07/10 – 12/10	85-95	60-80	60-80	60-80	60-80	50-70	25-50	0	0
01/11 – 06/11	85-95	60-80	60-80	60-80	60-80	60-80	50-70	0-25	0
07/11 – 12/11	85-95	60-80	60-80	60-80	60-80	60-80	50-70	25-50	0

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. This facility was aggressive with GCCS installation, which is due to its proximity to populated areas and the importance of odor control. By Jan 2006, the wastes accepted from 1998 through 2003 had been capped under a geomembrane final cover. GCCS installation events occurred in multiple years as shown in Figure S4. The effective date for gas collection wells was assumed to be July of the well installation year, as the explicit dates of well installations were not available.



Legend

Wells installed in 2001 and 2002

2001 Final cover Year of final cover installation

Figure S5. Location of waste disposal and schedule of final cover and GCCS installation at Landfill C1.

Table S4. Estimates of Monthly Collection Efficiency (α_{ji}) from 2003 through 2008 for Gas Generated at Landfill C1 (%)[a]

Gas recovery period	Years of waste burial							
	1958-2000	2001	2002	2003	2004	2005	2006	2007
01/03 – 12/03	60-85	40-60	0	0	0	0	0	0
01/04 – 12/04	60-85	60-85	40-60	0	0	0	0	0
01/05 – 12/05	60-85	60-85	60-85	40-60	0	0	0	0
01/06 – 12/06	60-85	60-85	60-85	60-85	40-60	0	0	0
01/07 – 12/07	60-85	60-85	60-85	60-85	60-85	40-60	0	0
01/08 – 12/08	80-90	60-85	60-85	60-85	60-85	60-85	40-60	0

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. In 2003 through 2007, only a small fraction of the waste mass accepted between 1958 and 2000 was capped under the geomembrane final cover. In 2008, approximately half of the waste disposal area was capped under the final cover, so the collection efficiency for waste mass accepted from 1958 through 2000 was assumed to increase from 75 to 85%.

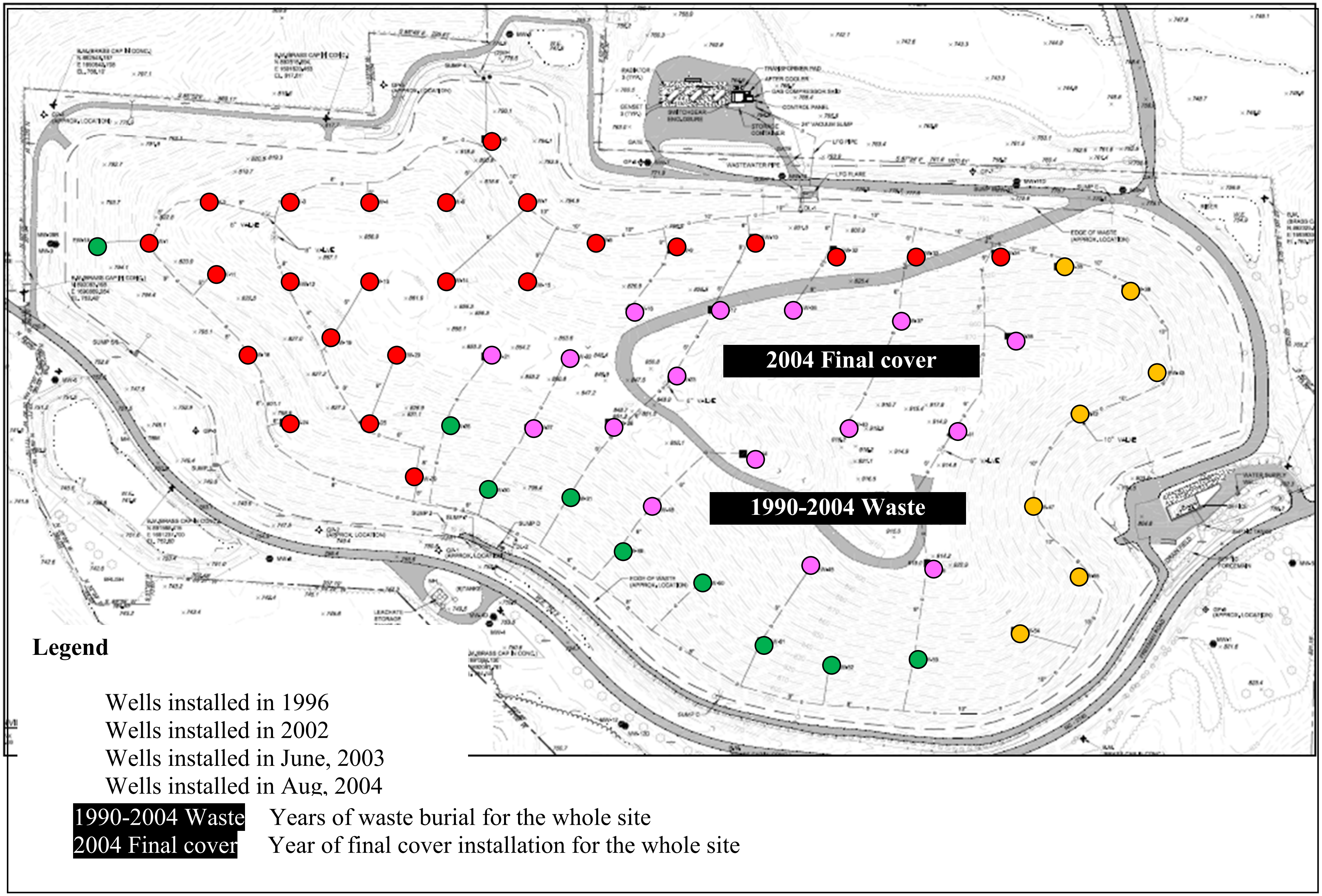


Figure S6. Location of waste disposal and schedule of final cover and GCCS installation at Landfill P1.

Table S5. Estimates of Monthly Collection Efficiency (α_{ji}) from 2005 through 2011 for Gas Generated at Landfill P1(%)[a]

Gas recovery period	Years of waste burial 1990-2004
01/05 – 12/05	85-95
01/06 – 12/06	85-95
01/07 – 12/07	85-95
01/08 – 12/08	85-95
01/09 – 12/09	85-95
01/10 – 12/10	85-95
01/11 – 12/11	85-95

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. The gas collection wells and geomembrane final cover had been constructed by the end of 2004, so 90% of collection efficiency was assumed for the gas generated from 2005 through 2011.

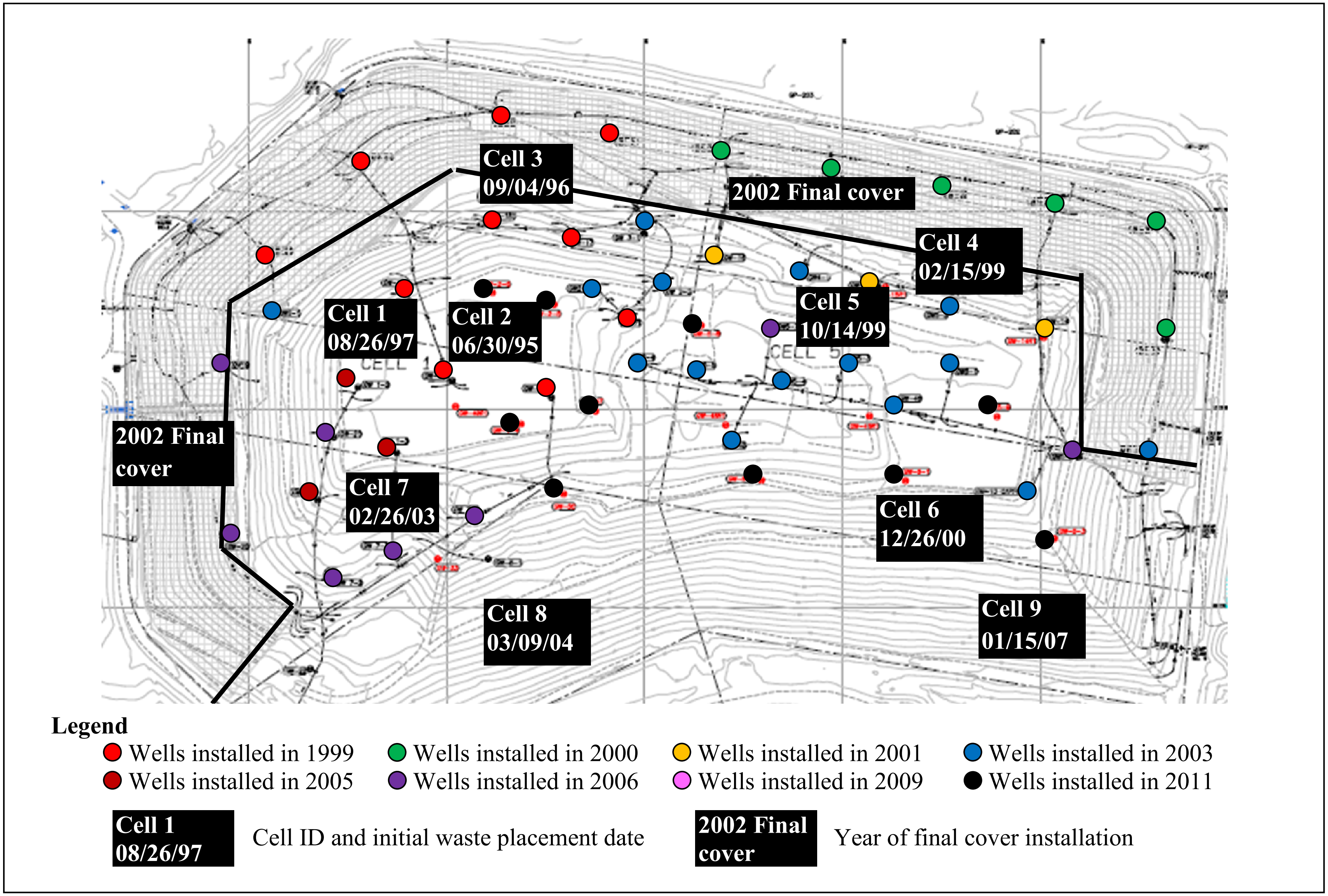


Figure S7. Location of waste disposal and schedule of final cover and GCCS installation at Landfill M.

Table S6. Estimates of Monthly Collection Efficiency (α_{ji}) from 2000 through 2010 for Gas Generated at Landfill M (%)[a]

Gas recovery period	Years of waste burial										
	1995-1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007-2009	2010
01/00 – 06/01	50-75	20-40	0	0	0	0	0	0	0	0	0	0
07/01 – 06/02	50-75	30-50	30-50	0	0	0	0	0	0	0	0	0
07/02 – 06/03	70-90	40-60	30-50	20-40	0	0	0	0	0	0	0	0
07/03 – 12/03	70-90	40-60	60-85	60-85	40-60	0-25	0	0	0	0	0	0
01/04 – 06/04	70-90	40-60	60-85	60-85	40-60	0-25	0-20	0	0	0	0	0
07/04 – 06/05	70-90	40-60	75-90	60-85	40-60	30-50	0-20	0	0	0	0	0
07/05 – 06/06	80-90	60-85	75-90	60-85	40-60	30-50	30-50	0	0	0	0	0
07/06 – 06/09	80-95	75-90	75-90	60-85	40-60	30-50	40-60	0-25	0	0	0	0
07/09 – 12/10	80-95	75-90	75-90	60-85	40-60	30-50	60-80	15-30	0-25	0-25	0-25	0

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. For gas generated from waste mass accepted after 1997, low collection efficiencies were assumed due to the low density of well coverage. Well installation events occurred in multiple years as shown in Figure S7. Gas collection wells were assumed to be effective in July of the well installation year, as the explicit dates of well installations were not available.

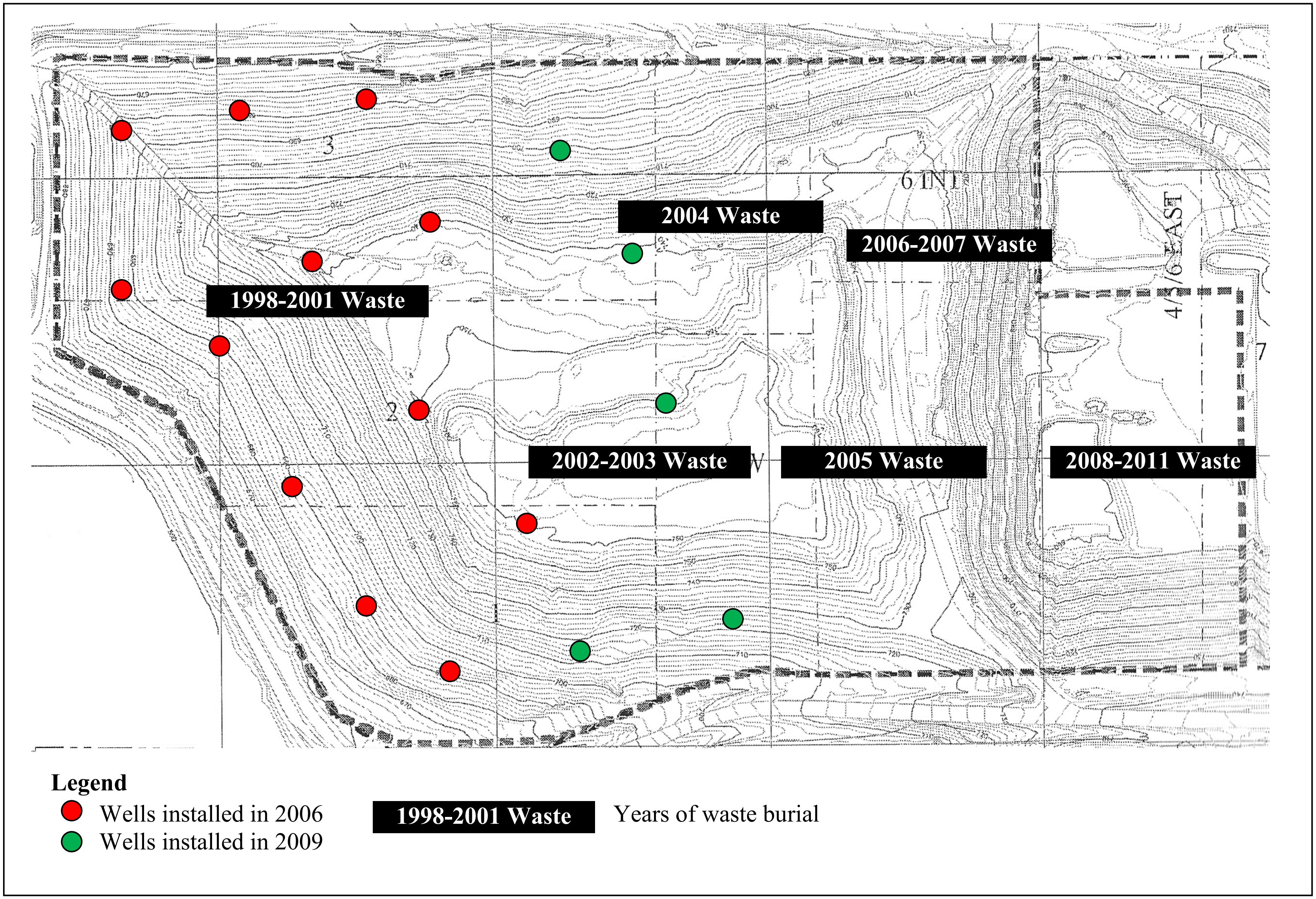


Figure S8. Location of waste disposal and schedule of final cover and GCCS installation at Landfill Q.

Table S7. Estimates of Monthly Collection Efficiency (α_{ji}) from 2006 through 2011 for Gas Generated at Landfill Q (%)[a]

Gas recovery period	Years of waste burial					
	1998-2001	2002	2003	2004	2005	2006-2011
01/06 – 06/06	0	0	0	0	0	0
07/06 – 06/09	60-85	10-25	10-25	10-25	10-25	0
07/09 – 12/11	60-85	50-80	50-70	50-70	50-70	0

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. For gas generated from the waste mass accepted in 2003 and 2004, low collection efficiencies were assumed due to a low density of well coverage. Well installation events occurred in 2006 and 2009, respectively, as shown in Figure S8. Gas collection wells were assumed to be effective in July of the well installation year, as the explicit dates of well installations were not available.

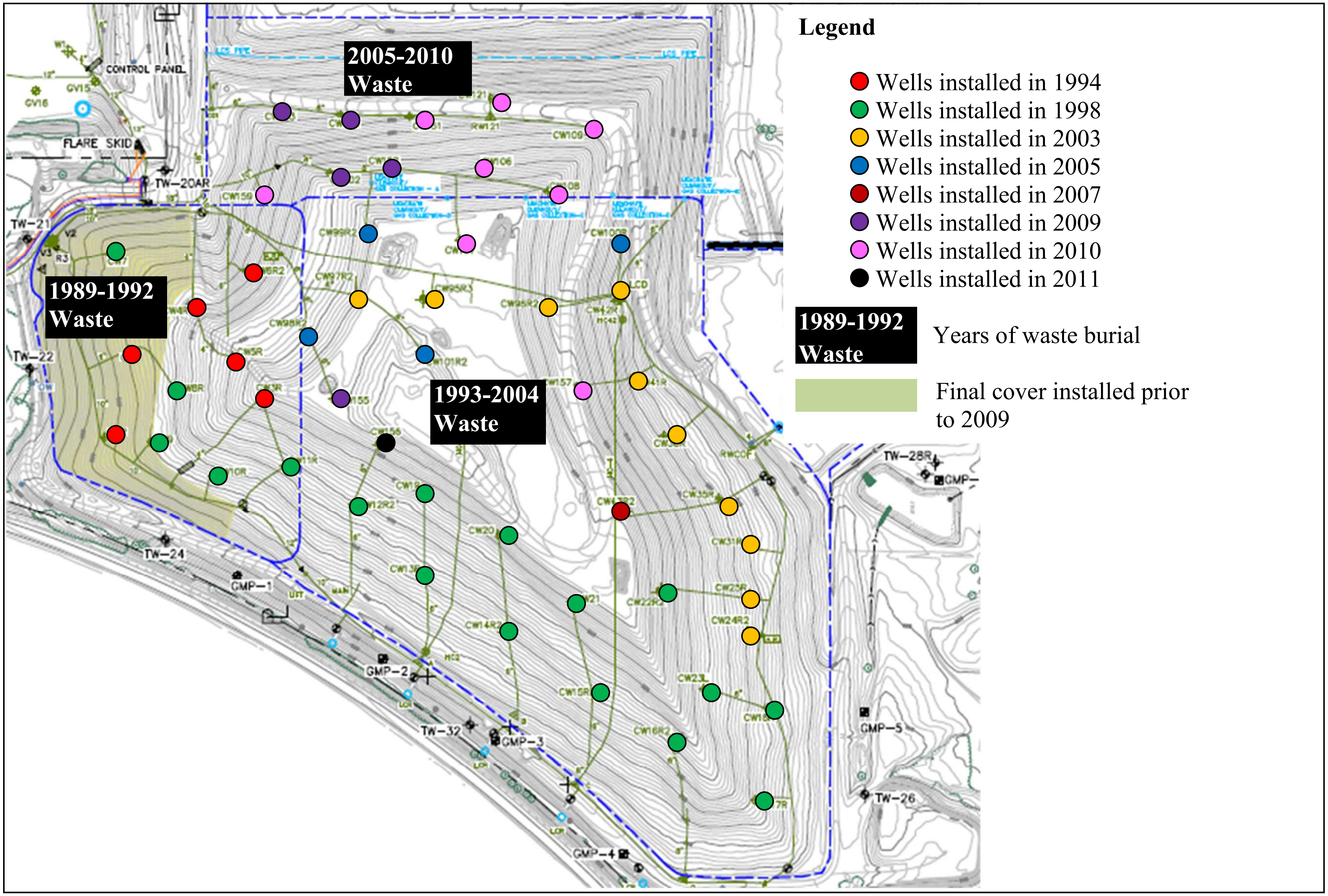


Figure S9. Location of waste disposal and schedule of final cover and GCCS installation at Landfill C2.

Table S8. Estimates of Monthly Collection Efficiency (α_{ji}) from 2009 through 2011 for Gas Generated at Landfill C2 (%)[a]

Gas recovery period	Years of waste burial								
	1989-1992	1993-2004	2005	2006	2007	2008	2009	2010	2011
01/09 – 06/09	80-95	60-85	0	0	0	0	0	0	0
07/09 – 06/10	80-95	60-85	30-50	30-50	30-50	0	0	0	0
07/10 – 12/10	80-95	60-85	30-50	30-50	30-50	30-50	30-50	0	0
01/11 – 06/11	80-95	60-85	50-70	50-70	50-70	30-50	30-50	0	0
07/11 – 12/11	80-95	60-85	50-70	50-70	50-70	30-50	30-50	30-50	0

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. For gas generated from the waste mass accepted after 2004, low collection efficiencies were assumed due to the low density of well coverage. Well installation events occurred in 2009, 2010, and 2011, respectively. Gas collection wells were assumed to be effective since July of the well installation year, as the explicit dates of well installations were not available.

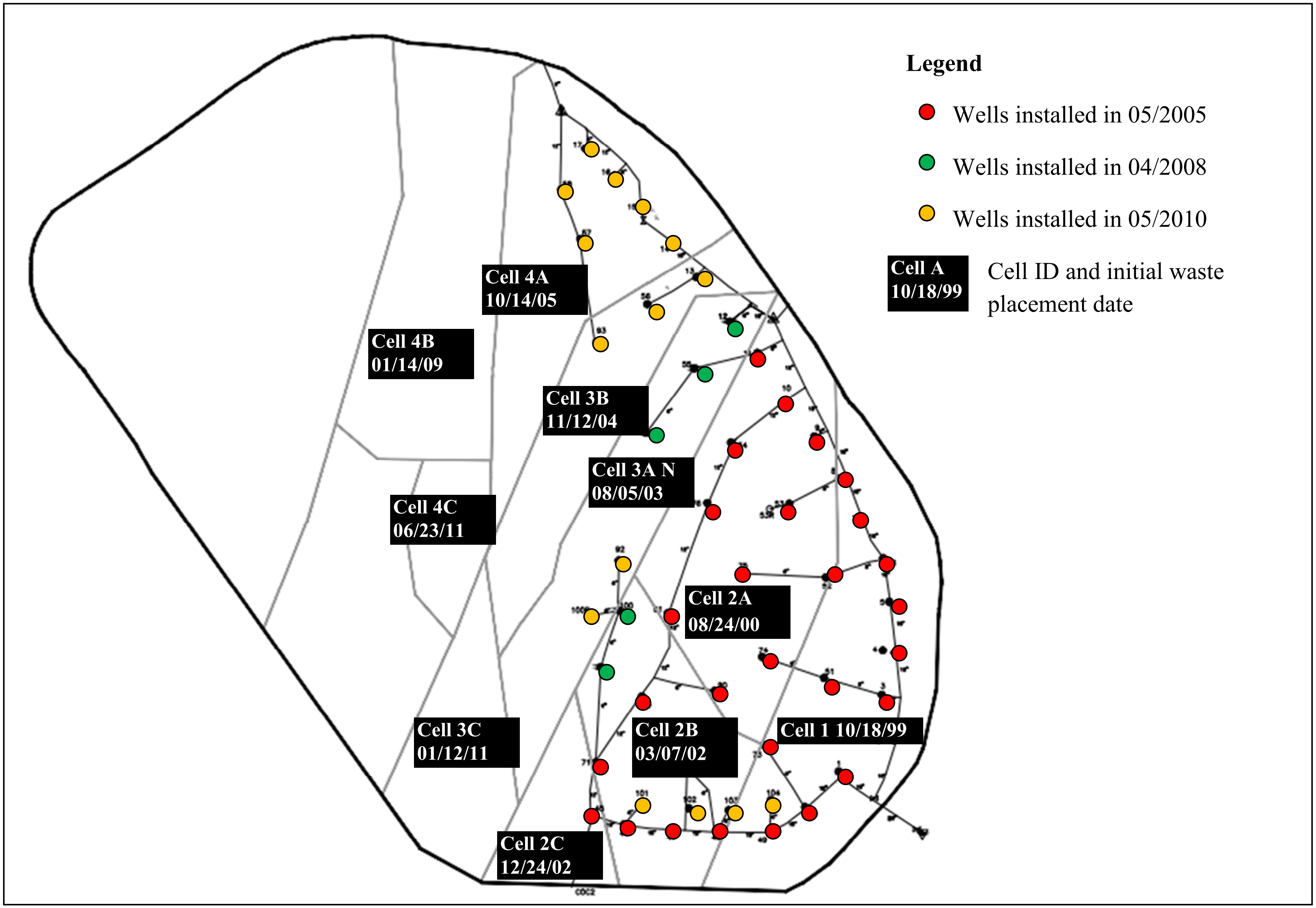


Figure S10. Location of waste disposal and schedule of final cover and GCCS installation at Landfill P2.

Table S9. Estimates of Monthly Collection Efficiency (α_{ji}) from 2006 through 2011 for Gas Generated at Landfill P2 (%)[a]

Gas recovery period	Years of waste burial											
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
01/06 – 04/08	60-85	60-85	60-85	0-30	0-10	0	0	0	0	0	0	0
05/08 – 05/10	60-85	60-85	60-85	50-70	50-70	0	0	0	0	0	0	0
06/10 – 12/11	60-85	60-85	60-85	60-85	60-85	40-60	40-60	40-60	40-60	0	0	0

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. For gas generated from the waste mass accepted after 2004, low collection efficiencies (40-60%) were assumed due to the low density of well coverage.

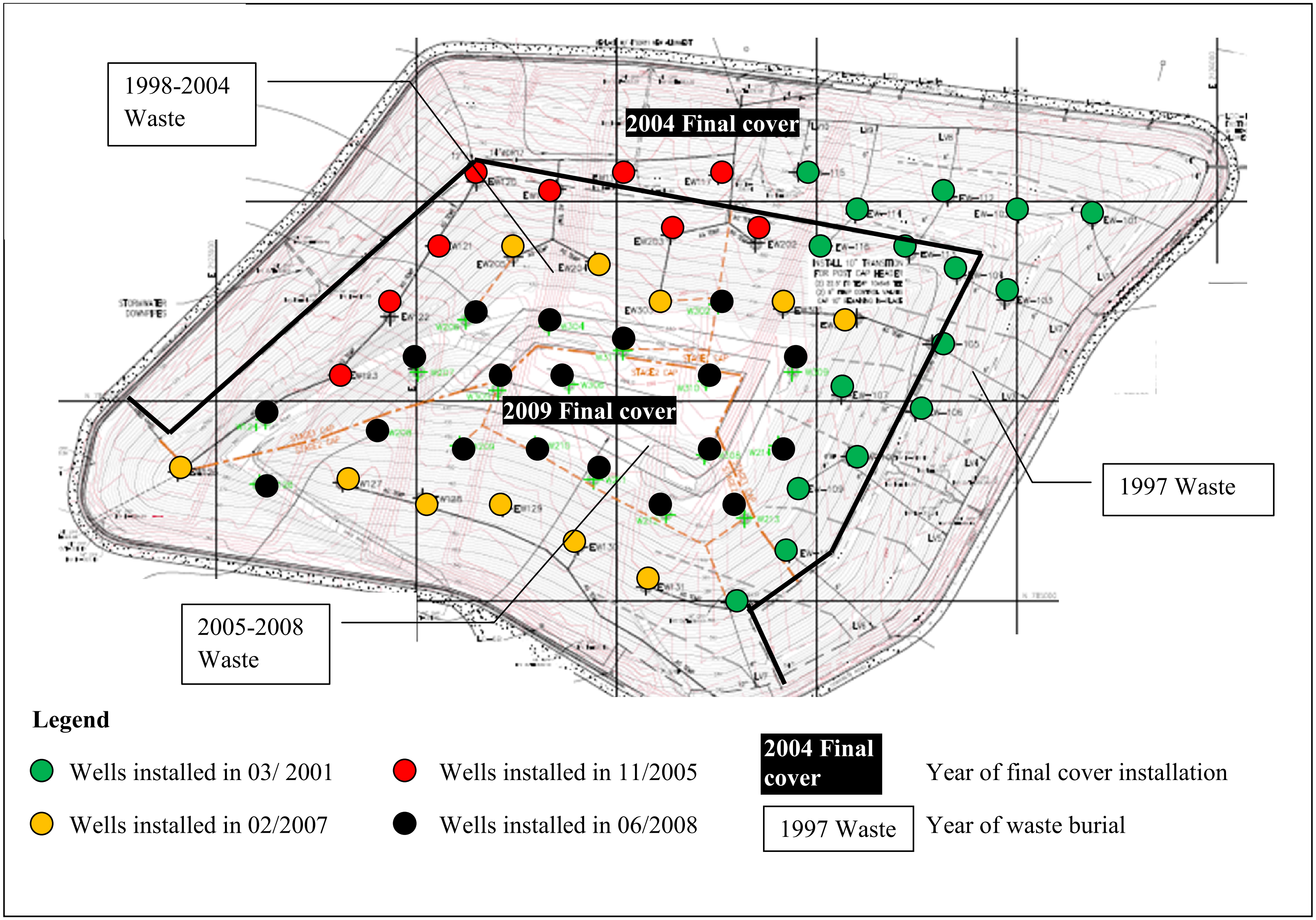


Figure S11. Location of waste disposal and schedule of final cover and GCCS installation at Landfill N.

Table S10. Estimates of Monthly Collection Efficiency (α_{ji}) from 2005 through 2011 for Gas Generated at Landfill N (%)[a]

Gas recovery period	Years of waste burial							
	1986-1996	1997	1998-2003	2004	2005	2006	2007	2008
01/05 – 12/05	70-90	80-95	0	0	0	0	0	0
01/06 – 02/07	70-90	80-95	50-70	10-30	0	0	0	0
03/07 – 06/08	70-90	80-95	60-85	50-70	50-70	50-70	0	0
07/08 – 06/09	70-90	80-95	70-90	60-85	60-85	60-85	60-85	50-70
07/09 – 12/11	70-90	80-95	80-95	80-95	80-95	80-95	80-95	80-95

a. Collection efficiency was estimated using expert judgment based on cover type, and the schedule of waste placement and GCCS installation. Wastes accepted between 1986 and 1996 were placed in an unlined area of this facility (not shown in Figure S11). A relatively low collection (70-90%) was assumed for the gas generated from this portion of the waste mass since 2006, although the waste mass is capped under the final cover.

Table S11. Estimates of MSW Fraction for Studied Landfills

Landfill ID	MSW fraction used in previous study[a] (%)	MSW fraction used in current study[b] (%)
S	65	55-75
G	69	59-79
H	33	23-43
T	85	75-95
C1	76	66-86
P1	85	75-95
M	89	79-99
Q	49	39-59
C2	49	39-59
P2	85	75-95
N	85	75-95

a. The fraction of total waste comprised of MSW used in previous study.[1] The value is the average of available annual data and was assumed as 85% for Landfills P1, P2 and N where waste composition data were not available.
b. The range of MSW fraction in total waste used in Monte Carlo simulations.

Table S12. Estimates of Methane Yields, Decay Rates, and Fractions of Rapidly and Slowly Degradable Waste for Dual-Phase Model

Waste Category[a]	Waste Component	L_0[f] m^3 CH_4 dry Mg^{-1}	k[g] yr^{-1}	Moisture Content[h] wet fraction	L_0 m^3 CH_4 wet Mg^{-1}	Discarded MSW Composition[i] %, wet	Weighted L_0[j] m^3 CH_4 wet Mg^{-1}	Weighted k[j] yr^{-1}	Weighted Average L_0[k] m^3 CH_4 wet Mg^{-1}	Weighted Average k[k] yr^{-1}	Adjusted L_0[l] m^3 CH_4 wet Mg^{-1}
Rapidly degradable									76.5	15.1	113.3
	Yard trimmings[b]	72.0	17.04	0.39	43.9	5.9	2.6	1.0			
	Food waste	300.7	15.02	0.70	90.2	13.6	12.3	2.0			
	Glossy paper (coated paper)	84.4	12.68	0.06	79.3	2.2	1.8	0.3			
	Miscellaneous organics[c]	128.1	12.86	0.40	77.3	2.7	2.1	0.3			
	Sub-total					24.5	18.7	3.7			
Slowly degradable									113.9	3.8	168.5
	Newspaper	74.3	3.45	0.06	69.8	4.2	2.9	0.1			
	Office paper	217.3	3.08	0.06	204.3	3.5	7.1	0.1			
	Mixed paper	145.8	3.27	0.06	137.1	6.6	9.1	0.2			
	OCC/Kraft bags	152.3	2.05	0.05	144.7	9.3	13.5	0.2			
	Composite/miscellaneous[d]	132.1	5.32	0.06	124.5	11.2	13.9	0.6			
	Textiles	46.4	3.08	0.10	41.7	4.7	1.9	0.1			
	Wood (non-C&D)[e]	11.7	6.52	0.10	10.5	3.4	0.4	0.2			
	Sub-total					42.9	48.8	1.6			
Non-degradable (inert)						32.6	0.0[m]		0.0[m]		0.0[m]
Total						100.0	67.6		67.6		100.0

a. Biodegradable waste components in MSW are grouped into rapidly and slowly degradable fractions, based on their laboratory-scale decay rates are greater or less than 10 yr^{-1}.
b. Weighted averages based on relative contribution of grass 30.3%, leaves 40.1%, and brush 29.6%.
c. Averages of wood (non-C&D), food waste and yard trimmings.
d. Average of newspaper, office paper, glossy paper, and OCC/Kraft bags.
e. Weighted average based on relative contribution of 58.3% lumber, 22.2% PW, 8.3% OSB and 11.1% PB and MDF.
f. Dry basis, adopted from Eleazer et al.[2] except wood (non-C&D) value from Wang et al.[3]
g. Adopted from De la Cruz and Barlaz[4] except wood (non-C&D) value from Wang et al.[3]

h. Adopted from Staley and Barlaz[5] except wood (non-C&D) value from Wang et al.[3]
i. Mean of a 11 state waste characterization studies adopted from Staley and Barlaz.[5]
j. Weighted L_0 and k for each waste component was calculated multiplying component specific L_0 and k by their corresponding fractions in discarded MSW stream.
k. Weighted average L_0 and k for rapidly and slowly degradable fractions are calculated dividing sub-total L_0 and k by sub-total of discarded waste composition of each fraction.
l. As described in the Methods section, the weighted average L_0 is adjusted to ensure the methane yield for bulk MSW (including non-degradable fraction) equals to EPA default value of 100 m^3 CH_4 wet Mg^{-1} which was used in the SPM.
m. Non-degradable fraction with a L_0 of zero.

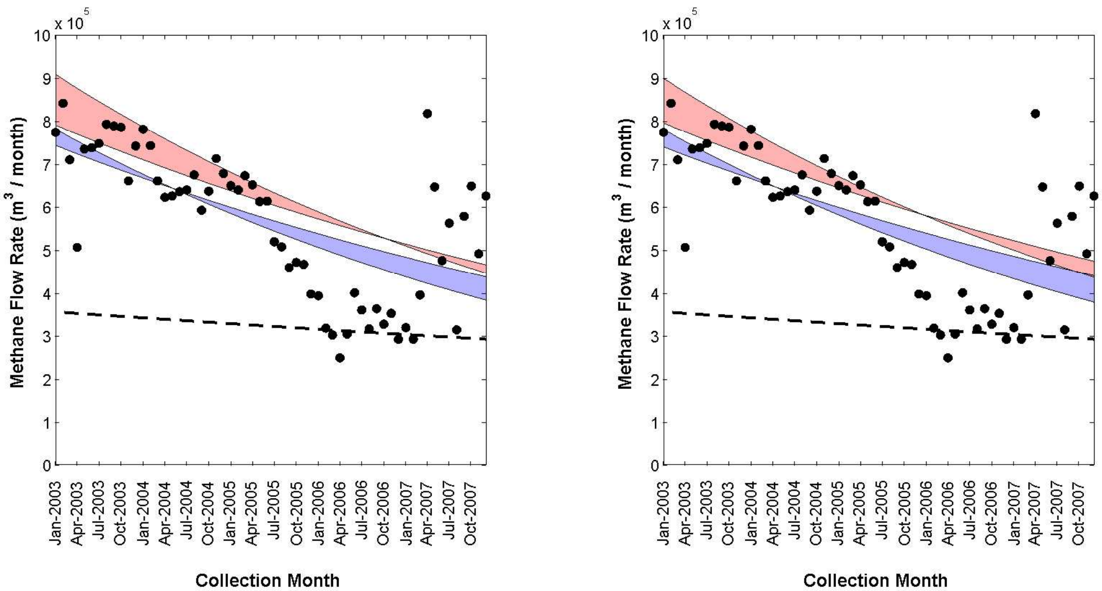


Figure S12 - Landfill S. Observed methane collection (dots), estimated methane generation (pink band), and estimated methane collection (blue band). The left panel only includes uncertainty in landfill gas collection efficiency, while the right panel includes uncertainty in both collection efficiency and the fraction of waste considered as MSW.

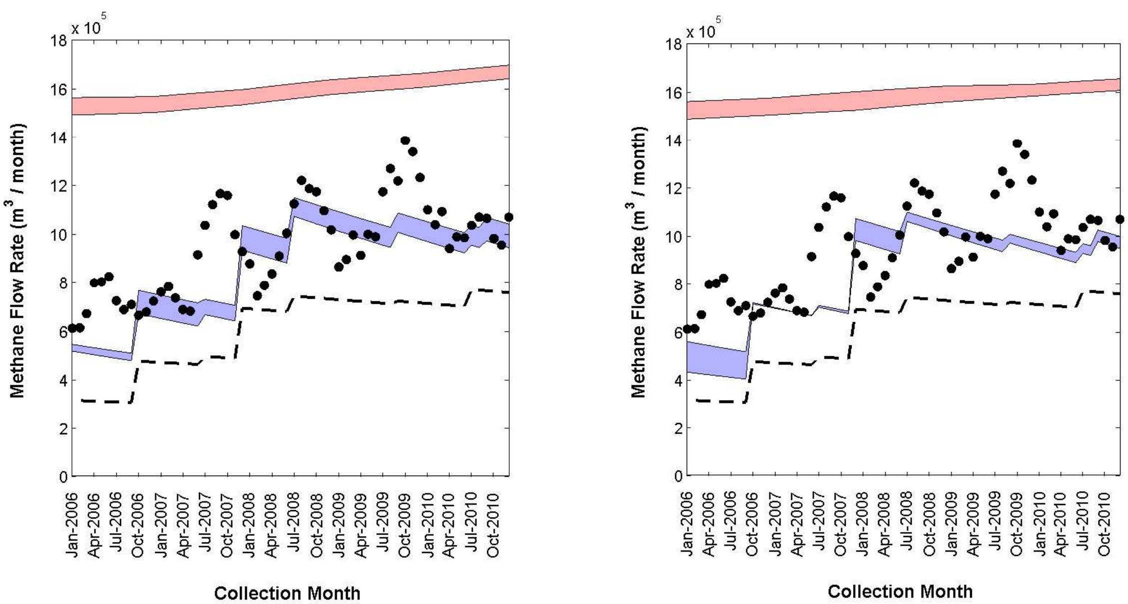


Figure S13 - Landfill G

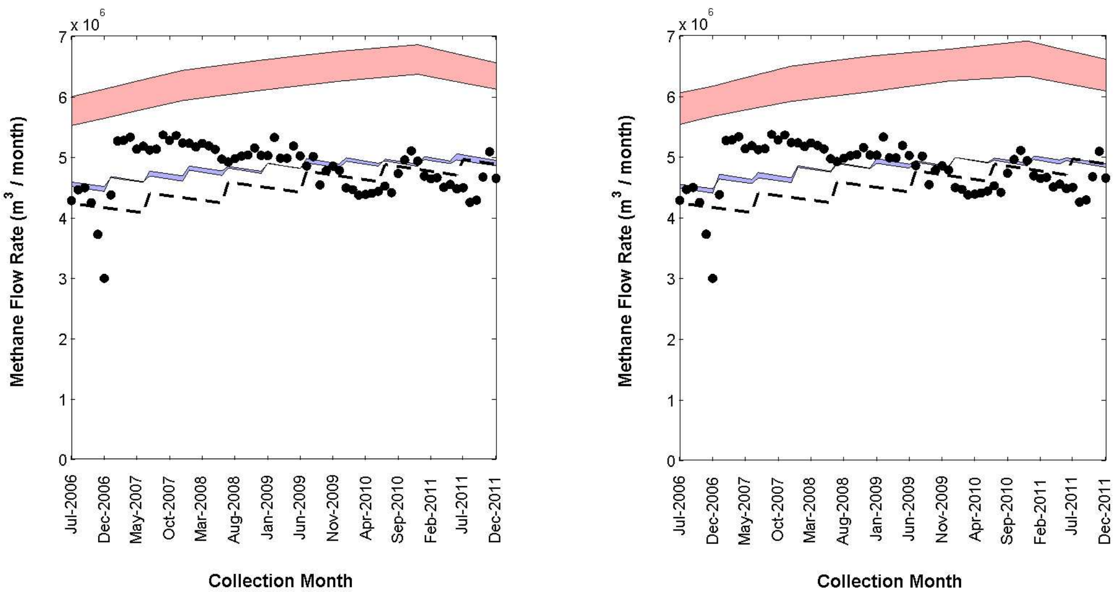


Figure S14 - Landfill T

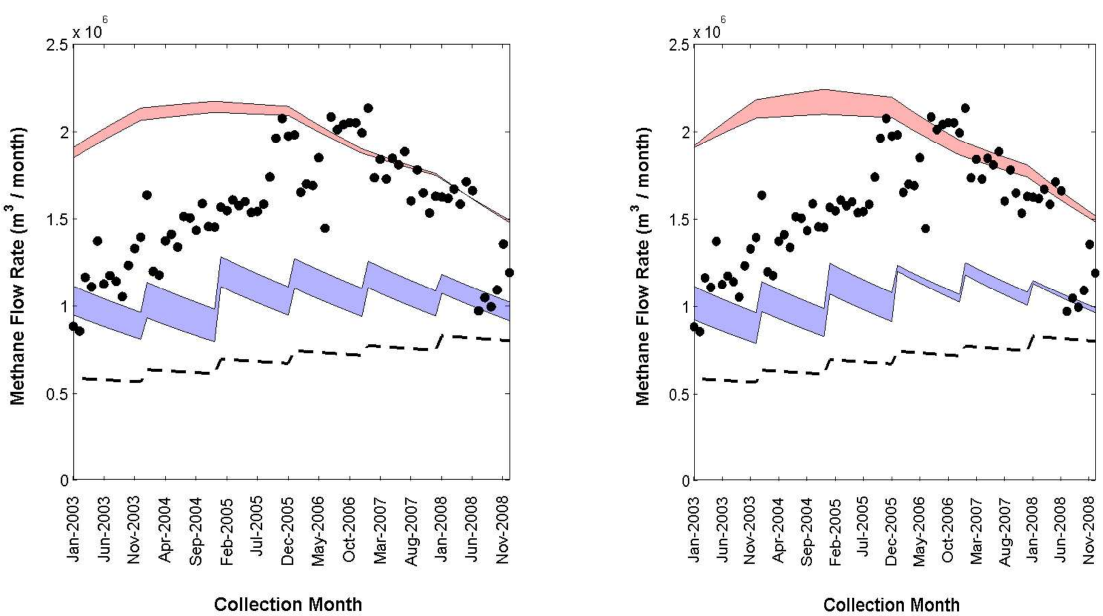


Figure S15 - Landfill C1

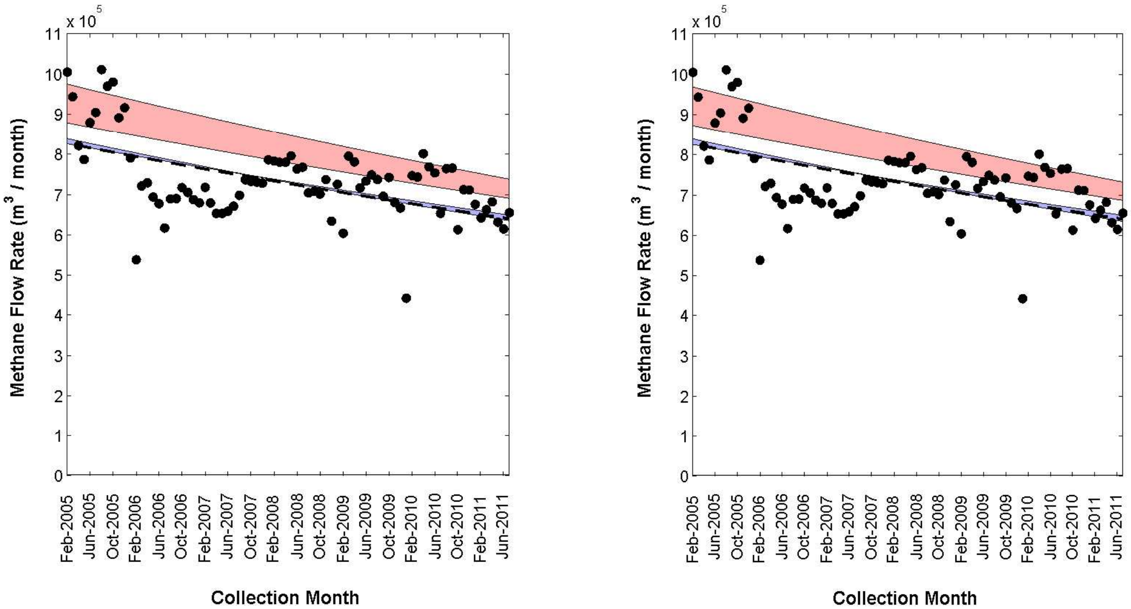


Figure S16 - Landfill P1

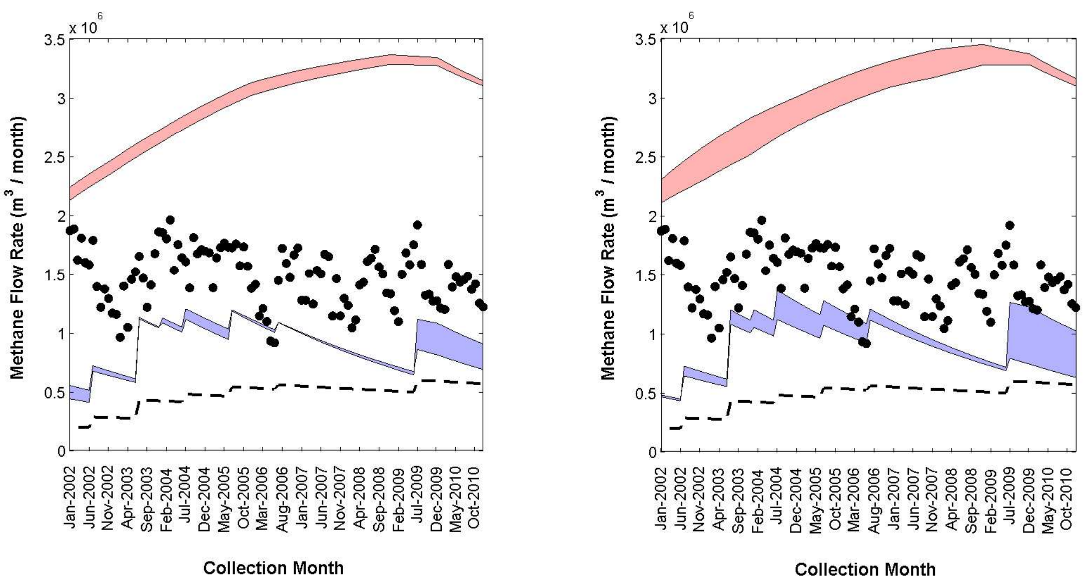


Figure S17 - Landfill M

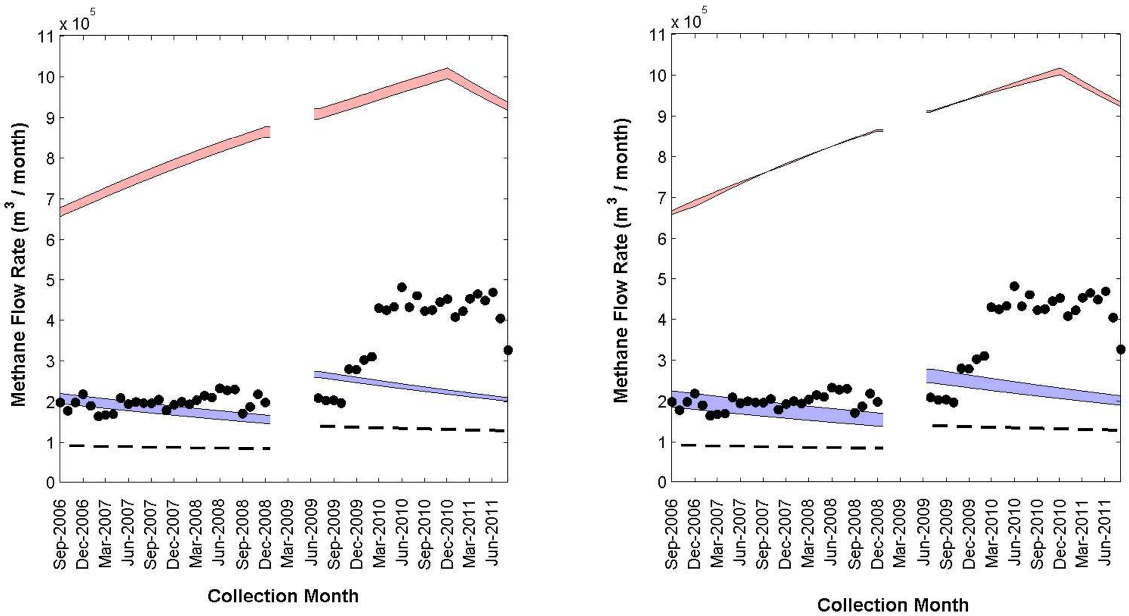


Figure S18 - Landfill Q

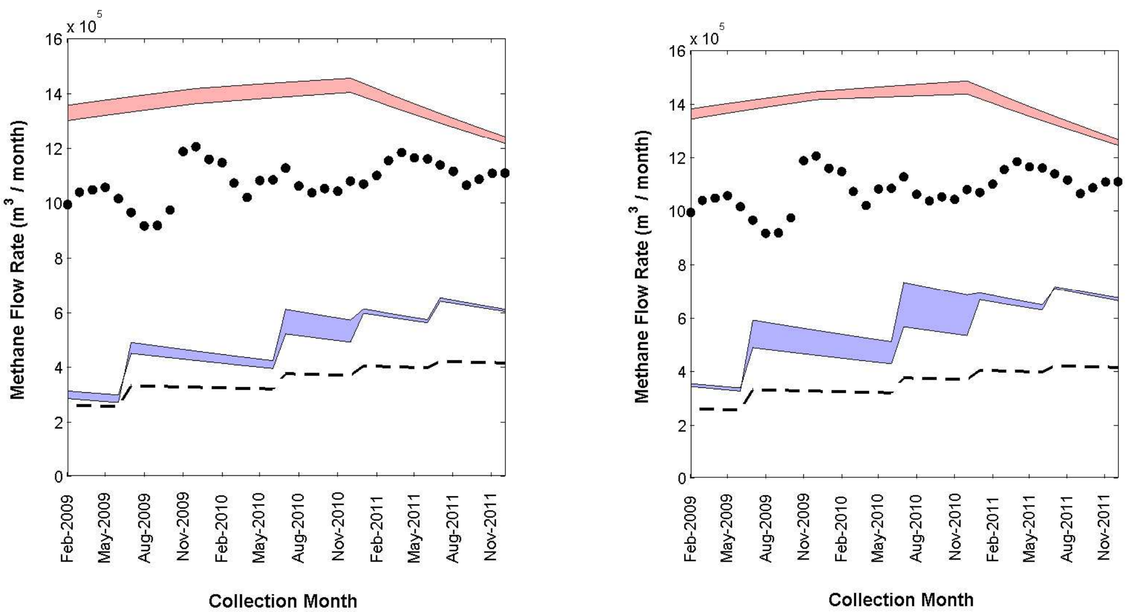


Figure S19 - Landfill C2

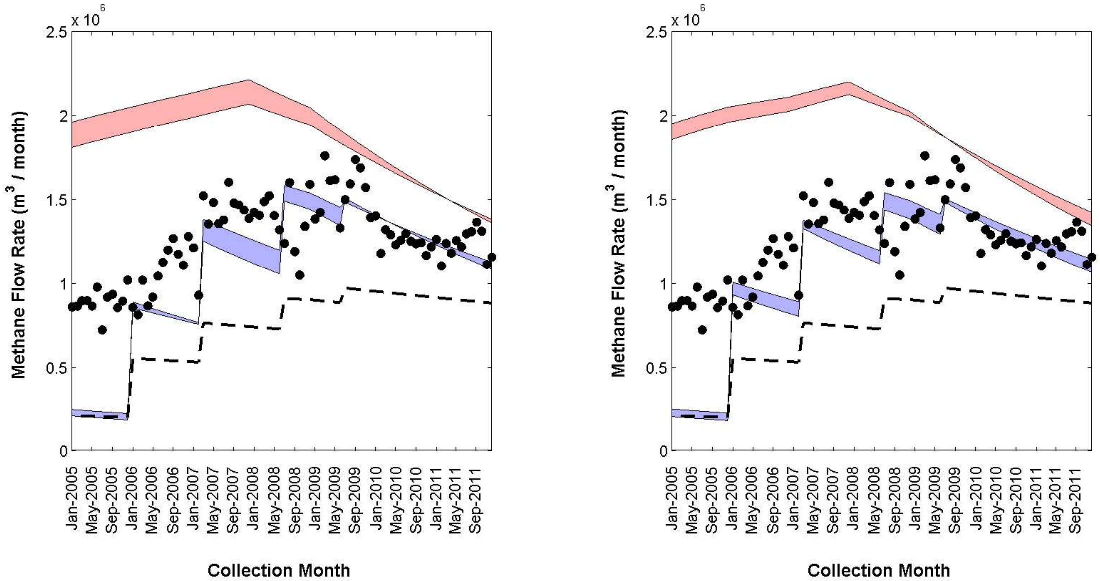


Figure S20 - Landfill N

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(3) Wang, X.; Padgett, J. M.; De la Cruz, F. B.; Barlaz, M. A. Wood biodegradation in laboratory-scale landfills. *Environ. Sci. Technol.* **2011**, *45*, 6864–6871.

(4) De la Cruz, F. B.; Barlaz, M. A. Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data. *Environ. Sci. Technol.* **2010**, *44*, 4722–4728.

(5) Staley, B. F.; Barlaz, M. A. Composition of Municipal Solid Waste in the United States and Implications for Carbon Sequestration and Methane Yield. *J. Environ. Eng.* **2009**, *135*, 901–909.