Long-term biosolids planning with an operational mega reservoir for combined sewer overflow-impacted stormwater capture

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Abstract

The Metropolitan Water Reclamation District of Greater Chicago adopted the Tunnel and Reservoir Plan (TARP) to reduce combined sewer overflow (CSO) events in the Chicago region. The Thornton Composite Reservoir (TCR) became operational in 2015 providing an additional 30 million m^3 of CSO-impacted stormwater capacity. In the United States, no other mega reservoirs are in operation to provide as a reference to study the long-term impacts of biosolids operations in water resource recovery facilities. The mean daily volume pumped from the Calumet TARP system to the Calumet Plant increased 144–238 m^3 from 2012–2014 to 273–360 m^3 from 2016–2018. Overall annual digester feed solids for the 2016–2018 post-TCR period were 28,182 Mg, which was 11 percent less than the mean for the 2012–2014 period of 31,745 Mg. Annual digester draw solids for the 2016–2018 post-TCR period were 19,422 Mg, which were 4 percent less than the 2012–2014 pre-TCR period mean of 20,190 Mg. This paper demonstrated a decrease in digester feed loading to the Calumet Plant and, ultimately, a decrease in digester draw solids with an overall increase in plant and TARP flow in the years following operation of the TCR for the capture and treatment of CSO-impacted stormwater.

Practitioner points

- Reservoirs capturing combined sewer overflow-impacted stormwater improve water quality of local waterways.
- Mega reservoirs may impact solids loading to water resource recovery facilities.
- Hydraulic loading to water resource recovery facilities may be substantial with mega reservoirs.

Key words

biosolids; planning; reservoir; stormwater

Introduction

The U.S. Environmental Protection Agency adopted its Combined Sewer Overflow (CSO) Control Policy in 1994, which requires communities to develop a long-term control plan to reduce or eliminate CSOs (USEPA, 1994). Capturing CSO-impacted stormwater prior to discharge to local waterways has been well established as an effective stormwater management practice (NRC, 2009). Although newly constructed and smaller communities have built separate storm sewers, many older cities have combined sewer systems in which sanitary sewage drains into the same sewer infrastructure as stormwater during heavy rainfall. Most of these combined sewers were built before wastewater treatment existed so they drained directly into local waterways.

This system becomes overwhelmed during heavy rainfall events when local sewers and water resource recovery facilities (WRRFs) can reach capacity resulting in combined sewer overflows (CSOs) to local waterways. The introduction of CSO-impacted water into local waterways can have adverse effects on water quality by increasing turbidity and conductivity, decreasing dissolved oxygen concentrations, and increasing the concentration of pollutants, including pathogens, in receiving streams (Irvine, McCorkhill, & Caruso, 2005; Piro, Carbone, & Sansalone, 2012; Salmore, Hollis, & McLellan, 2006; Vogel, Frankforter, Rus, Hobza, & Moser, 2009).

For the past 40 years, the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) has been constructing the Tunnel and Reservoir Plan (TARP) to reduce the number and severity of CSO events in the Chicago metropolitan region. The TARP system is comprised of deep, large diameter tunnels, and reservoirs that were designed to capture 85 percent or more of the CSO-impacted stormwater in its service area as required by the 1994 EPA CSO Control Policy. The TARP system captures and stores combined stormwater and sewage until it can be pumped from the TARP system to one of the MWRDGC's plants for treatment and release to local waterways.

The Calumet tunnel system is one of the four tunnel systems that make up MWRDGC's TARP system (Figure 1). Although the Calumet tunnel system, comprised of 60 km (37 miles) of tunnel and 2.38 million m^3 (630 million gallons) of storage capacity, has been operational since the 1980s, the Thornton Composite Reservoir (TCR) only became operational in 2015. Once operational, the TCR provided an additional 30 million m^3 (7.9 billion gallons) of storage capacity to

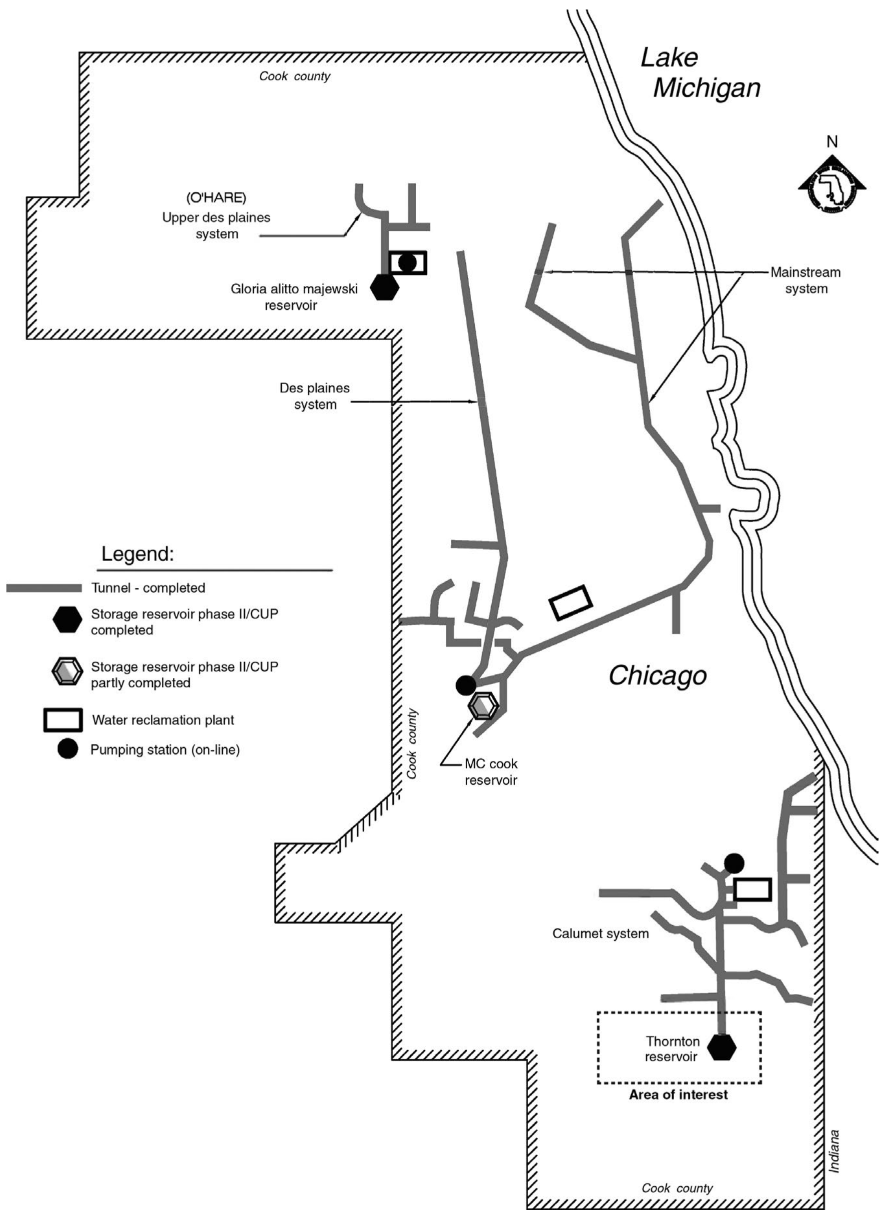

Figure 1. The MWRDGC's Calumet tunnel system and Thornton Composite Rservoir of the Tunnel and Reservoir Plan.

the Calumet Plant's service area. Prior to the TCR being operational, CSO-impacted stormwater and any associated solids were pumped from the Calumet tunnel system directly to the Calumet Plant for treatment. Although municipalities such as Boston and Atlanta have also constructed direct stormwater capture and treatment using tunnels and/or reservoirs, there were no reservoirs in the United States at the scale of the TCR to provide a basis for establishing estimates of what the long-term impacts to biosolids operations would be from the operation of the TCR. This study examined meteorological and plant operation data prior to and after the TCR was operational to understand any impacts the reservoir has had on solids processes at the Calumet Plant in order to inform long-term biosolids planning.

Methods

The Calumet Plant services an area of approximately 844 km^2 (326 mi^2) and just over one million residents. It is a conventional activated sludge plant with 12 mesophilic, anaerobic digesters. The TCR's service area is approximately 233 km^2 (90 mi^2) of the Calumet's service area. Calumet Plant operations data were downloaded from the MWRDGC's Monthly Plant Operating Report database, including TARP flow, total plant flow, and digester solids feed and draw for 2012–2014, the three years prior to the TCR being operational, and 2016–2018, the 3 years after the TCR was operational (MWRD, 2018). TARP and total plant flow data were summarized only for days that TARP system pumping to the Calumet Plant was reported. Meteorological data, including rainfall and snowfall data, were downloaded from the National Oceanic and Atmospheric Administration's Climate Data Online database for the Lansing Municipal Airport weather station (ID: USC00114890) in Lansing, IL, which is located within the Calumet Plant's service area and 11 km (7 mi) to the southeast of the TCR (NOAA, 2018). Maximum ambient air temperature was not available from the Lansing weather station and was downloaded for the Chicago Midway International Airport weather station in Chicago, IL (ID: USC00111577) 18 km (11 mi) to the northwest of the Calumet Plant.

To account for the contribution of snowmelt in the Calumet Plant's service area, the snowfall (assumed snow depth) for a given day was converted to snow water equivalent (SWE). Snow water equivalent is the liquid water equivalent that would theoretically result if the snow depth on that day melted instantaneously. It was calculated using snow depth (h_s) and the relationship between snow density (ρ_b) to the density of water (ρ_w):

$$\mathrm{SWE} = h_s \frac{\rho_b}{\rho_w} \tag{1}$$

Judson and Doesken (2000) found that daily new snow densities ranged from 160 to 20 kg/m^3 and decreased with decreasing temperatures; however, snow density did not decrease appreciably until below −10°C (14°F). Only three snow days occurred in the current data set at or below −10°C (14°F), so the snow density was conservatively taken to be 100 kg/m^3, resulting in a conversion factor of 0.10. To illustrate, the single greatest day of snowfall in the six-year record was 23 cm (9.0 in) reported on March 6, 2013 with a maximum temperature reported of 2.2°C (36°F), which resulted in a SWE of 2.3 cm (0.90 in).

Data were non-normally distributed as determined by the Shapiro–Wilk test of normality with unequal variances as determined by Bartlett's test for homogeneity of variances. Statistically significant differences among data were determined using the Kruskal–Wallis rank sum test, which ranks the data and tests for differences in the locations of the distributions between groups. The Kruskal–Wallis rank sum test is a non-parametric test and does not assume a distribution for the data, such as a normal distribution. When the Kruskal–Wallis rank sum test was found to be significant ($p < .05$), the Dunn post hoc test for multiple comparisons was performed

Table 1. Rainfall, snowfall, snow water equivalent, and total precipitation reported for the lansing municipal airport, Lansing, IL for 2012–2014 and 2016–2018

	RAINFALL	SNOWFALL	SNOW WATER EQUIVALENT[a]	TOTAL PRECIPITATION[b]
YEAR	CM (IN)			
2012	76 (31)	38 (15)	3.8 (1.5)	80 (32)
2013	89 (36)	55 (22)	5.5 (2.5)	95 (38)
2014	102 (41)	152 (61)	15 (6.1)	117 (47)
Mean ± *SD*	89 ± 13 (36 ± 5.0)	82 ± 62 (33 ± 25)	8.1 ± 6.0 (3.4 ± 2.4)	97 ± 19 (39 ± 7.5)
2016	96 (39)	70 (28)	7.0 (2.8)	103 (41)
2017	108 (43)	39 (15)	3.9 (1.5)	112 (45)
2018	105 (42)	85 (34)	8.3 (3.4)	114 (45)
Mean ± *SD*	103 ± 6.2 (41 ± 2.1)	64 ± 23 (26 ± 9.7)	6.5 ± 2.3 (2.6 ± 0.97)	110 ± 5.9 (44 ± 2.3)
Difference from 2012–2014 Mean	+14 (+5.0)	−18 (−7.0)	−1.6 (−0.8)	+13 (+5.0)

[a]Snow water equivalent was calculated by multiplying snow depth by a conversion factor of 0.1, which is the ratio of the density of snow to the density of water.

[b]Total precipitation = rainfall plus snow water equivalent.

Table 2. Metropolitan Water Reclamation District of Greater Chicago Calumet Plant flow, total tunnel and reservoir flow, and Tunnel and Reservoir Plan flow percentage of total flow for 2012–2014 and 2016–2018

YEAR	TOTAL PRECIPITATION CM (IN)	DAILY PLANT FLOW (MEAN ± *SD*)	DAILY TARP FLOW (MEAN + *SD*)	TOTAL ANNUAL PLANT FLOW	TARP FLOW PERCENTAGE OF DAILY PLANT FLOW (MEAN + *SD*)
		M^3 (MILLION GALLONS)			%
2012 (*n* = 337)	80 (32)	756 ± 247d[a] (200 ± 65)	144 ± 128e (38 ± 34)	254,625 (67,272)	17 ± 9.8f
2013 (*n* = 347)	95 (38)	903 ± 379c (238 ± 100)	215 ± 203d (57 ± 54)	313,619 (82,749)	21 ± 13e
2014 (*n* = 362)	117 (47)	969 ± 912b (256 ± 81)	238 ± 164c (63 ± 43)	351,125 (92,645)	23 ± 12d
2016 (*n* = 320)	103 (41)	1,009 ± 276b (267 ± 73)	274 ± 161b (72 ± 43)	323,272 (85,296)	26 ± 12c
2017 (*n* = 282)	112 (45)	1,094 ± 319a (289 ± 84)	359 ± 184a (95 ± 49)	308,972 (81,523)	31 ± 13a
2018 (*n* = 309)	114 (45)	1,007 ± 379b (266 ± 100)	319 ± 248b (84 ± 65)	311,682 (82,238)	29 ± 14b

Note. Abbreviation: TARP, Tunnel and Reservoir Plan.

[a]Different letters between years indicate significant differences at $p < .05$ using the Kruskal–Wallis rank sum test with a Dunn post hoc test for multiple comparisons.

to determine significant differences between years ($p < .05$). All statistical analyses were conducted in the R software package v.3.4.1.

Results and Discussion

The Calumet service area received 76- to 102-cm (31–41 in) total rainfall and 3.8–15 cm SWE (1.5–6.1 in) which equals to a total of 80- to 117-cm (32–47 in) total precipitation (rainfall plus SWE) from 2012–2014 before the TCR was operational (Table 1). From 2016–2018, the service area received 96- to 108-cm (39–43 in) rainfall and 3.9- to 8.5-cm (1.5–3.4 in) SWE which equals to a total of 103- to 114 cm (41–45 in) total precipitation after the TCR was operational (Table 1). Total precipitation was greatest in 2014 at 117 cm (47 in); however, the three years after the TCR was operational received, on average, 13 cm (5.0 in) more total precipitation than the 2012–2014 average (Table 1). The Illinois Department of Natural Resources (2015) reports an average annual rainfall for northern Illinois of 91 cm (36 in); furthermore, they state Illinois precipitation has increased by 10 percent over the last century largely due to more intense storms of over 2.5 cm (an inch). This trend is expected to continue in the future (IDNR, 2015).

During these heavy rainfall events, CSO-impacted stormwater fills the Calumet tunnel system until approximately two-thirds full at which point it triggers plant personnel to open a gate to the TCR to accommodate additional stormwater capture. The CSO-impacted stormwater stored in the Calumet tunnel system and TCR is gravity-drained back to the Calumet Plant via the 8-km (five-mile)-long Calumet tunnel and pumped up nearly 107 m (350 ft) for treatment from a pump station at the plant; therefore, total TARP flow reported for a given day can be only tunnel flow or a combination of tunnel and TCR flow. The mean daily volume of water pumped from the Calumet tunnel and reservoir system to the Calumet Plant on days that pumping was reported significantly increased from 144 m^3 (38 million gallons) to 237 m^3 (63 million gallons) from 2012–2014 to 274 m^3 (72 million gallons) to 359 m^3 (95 million gallons) from 2016–2018 ($p < .05$) with the TCR operational (Table 2).

The mean percentage of total daily plant flow comprised of TARP flow also significantly increased from 17–23 percent in the pre-TCR period to 26–31 percent post-TCR (Table 2). Although total precipitation was greatest in 2014, the post-TCR period resulted in a significant increase in TARP flow and a significant increase in the percentage of total plant flow that was comprised of TARP flow. Total plant flow was greatest in 2017 at 1,094 m^3 (289 million gallons), which was also the year with the greatest TARP flow of 359 m^3 (95 million gallons and 31 percent of total plant flow).

There were significant differences in solids loading to the Calumet Plant between pre- and post-TCR operational periods. Mean daily digester feed total solids in 2013 and 2014 were 92 and 96 megagrams (Mg) (102 and 106 dry tons), respectively. These pre-TCR means were significantly greater than any of the digester feed total solids means for the 2016–2018 period, which ranged from 69 to 84 Mg (76–93 dry tons) (Table 3). The difference in daily mean digester feed total solids between 2014 and 2018, which had 3 cm more total precipitation, was 18 Mg (20 dry tons). This corresponded to an annual digester feed total solids difference of 6,630 Mg (7,304 dry tons) (Table

Table 3. Annual and mean daily digester feed and draw total solids for the MWRDGC's Calumet Plant pre- and post-Thornton Reservoir

RESERVOIR OPERATIONAL	YEAR	TOTAL PRECIPITATION CM (IN)	ANNUAL DIGESTER FEED TOTAL SOLIDS MG (DRY TONS)	ANNUAL DIGESTER DRAW TOTAL SOLIDS	DAILY DIGESTER FEED TOTAL SOLIDS[a] (MEAN ± *SD*)	DAILY DIGESTER DRAW TOTAL SOLIDS (MEAN ± *SD*)
No	2012	80 (32)	26,407 (29,115)	18,108 (19,965)	72 ± 25d (79 ± 28)	49 ± 16d (55 ± 18)
No	2013	95 (38)	33,736 (37,195)	20,173 (22,241)	92 ± 38b (102 ± 42)	55 ± 19c (61 ± 21)
No	2014	117 (47)	35,092 (38,690)	22,289 (24,574)	96 ± 38a (106 ± 42)	61 ± 17a (67 ± 19)
Mean ± *SD*		97 ± 19 (39 ± 7.5)	31,745 ± 4,672 (35,000 ± 5,151)	20,190 ± 2,091 (22,260 ± 2,305)		
Yes	2016	103 (41)	30,864 (34,029)	19,468 (21,464)	84 ± 38c (93 ± 42)	53 ± 19c (59 ± 21)
Yes	2017	112 (45)	25,215 (27,800)	17,872 (19,705)	69 ± 24d (76 ± 27)	49 ± 17d (54 ± 19)
Yes	2018	114 (45)	28,462 (31,386)	20,925 (23,071)	78 ± 22c (86 ± 24)	57 ± 17b (63 ± 19)
Mean ± *SD*		110 ± 5.9 (44 ± 2.3)	28,182 ± 2,835 (31,072 ± 3,126)	19,422 ± 1,527 (21,413 ± 1,683)		

Abbreviation: Mg, megagram.

[a]Different letters between years indicate significant differences at $p < .05$ using the Kruskal–Wallis rank sum test with a Dunn post hoc test for multiple comparisons.

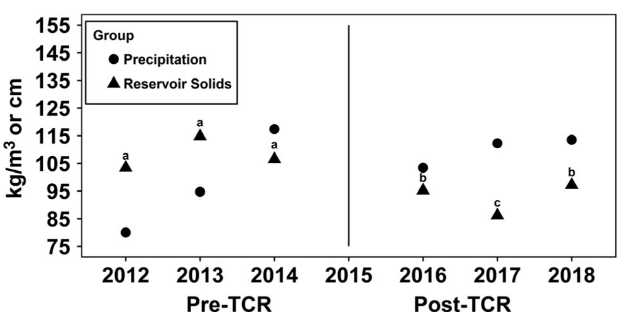

Figure 2. Annual precipitation and the MWRDGC's Calumet Plant's digester feed total solids loading per unit total flow pre- and post-operation of the Thornton Composite Reservoir from 2012–2018. Different letters above reservoir solids values indicate significant differences between years at $p < .05$ using the Kruskal-Wallis rank sum test with Dunn post-hoc test for multiple comparisons.

3). The overall annual digester feed total solids mean for the 2016–2018 post-TCR period was 28,182 Mg (31,072 dry tons), which was 3,563 Mg (3,928 dry tons) or 11 percent less than the mean for the 2012–2014 pre-TCR period of 31,745 Mg (35,000 dry tons).

This trend of lower solids loading in the post-TCR period becomes further evident when digester feed total solids loading per unit total plant flow are examined (Figure 2). There were no statistical differences among mean digester feed loading per unit flow values from 2012 to 2014; however, all values from 2016 to 2018 were significantly lower than 2012–2014 means Figure 2). Although total precipitation was higher in 2016–2018 than in 2012 and 2014 (Table 1), the 2016–2018 mean digester feed loading per unit flow values of 86–95 kg/m^3 was significantly lower than the means for 2012–2013 of 103–115 kg/m^3 (Figure 2). These results strongly suggest the Calumet tunnel system was capturing nearly all of the solids in the Calumet tunnel system, as seen in the mean loading from 2012 to 2014 (Figure 2). The net dilution effect observed from 2016 to 2018 is likely indicating that after a certain point of hydraulic loading, the stormwater captured by the TCR in the 2016–2018 period is largely non-CSO-impacted stormwater.

The 2014 mean daily digester draw total solids of 61 Mg (67 dry tons) was greater than any mean from the 2016–2018 post-TCR period, which ranged from 49 to 57 Mg (54–63 dry tons) (Table 3). Overall, although total precipitation in the 2016–2018 post-TCR period was greater than the 2012–2014 pre-TCR period, the mean annual digester draw total solids for the post-TCR period of 19,422 Mg (21,413 dry tons) were 768 Mg (847 dry tons) or 4 percent less than the 2012–2014 pre-TCR period mean of 20,190 Mg (22,260 dry tons).

Digester draw total solids at the Calumet Plant are pumped to lagoons and stored for up to 18 months to age-stabilize the biosolids. From lagoons, biosolids are pumped and hauled to concrete-lined drying cells for distribution to farmland outside the Chicago metropolitan region. The biosolids are also air-dried further and distributed within the greater Chicago metropolitan region as Class A Exceptional

Quality biosolids as defined by the U.S. Environmental Protection Agency. Although the lagoon-aging and air-drying process is a cost-effective approach, the associated costs with the transport and distribution of biosolids still necessitated understanding the TCR's long-term impact on solids loading and thus, biosolids processing at the Calumet Plant. This study demonstrated a corresponding decrease in digester feed total solids loading at the Calumet Plant and, ultimately, a decrease in digester draw total solids while also demonstrating an overall increase in total plant and TARP flow in the three years following the operation of the TCR for the capture and treatment of CSO-impacted stormwater. This decrease in solids loading indicates no additional biosolids processing will be needed or associated costs incurred in the post-TCR period.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Illinois Department of Natural Resources (2015). *Report for the urban awareness flooding act*. Springfield, IL: Office of Water Resources

Irvine, K. N., McCorkhill, G., & Caruso, J. (2005). Continuous monitoring of conventional parameters to assess receiving water quality in support of combined sewer overflow abatement plans. *Water Environment Research*, *77*(5), 543–552. https://doi.org/10.2175/106143005X67467

Judson, A., & Doesken, N. (2000). Density of freshly fallen snow in the central Rocky Mountains. *Bulletin of the American Meteorological Society*, *81*(7), 1577–1588. https://doi.org/10.1175/1520-0477(2000)081<1577:DOFFSI>2.3.CO;2

Metropolitan Water Reclamation District of Greater Chicago (2018). Monthly plant operating data, Chicago, IL. Retrieved from https://www.mwrd.org.

National Oceanic and Atmospheric Administration (2018). Climate data online, Washington, DC. Retrieved from https://www.ncdc.noaa.gov/cdo-web/.

National Research Council (2009). *Urban stormwater management*. Washington, DC: National Academies Press.

Piro, P., Carbone, M., & Sansalone, J. (2012). Delivery and frequency distributions of combined wastewater collection system wet and dry weather loads. *Water Environment Research*, *84*(1), 65–75. https://doi.org/10.2175/106143011X13188633467111

Salmore, A. K., Hollis, E. J., & McLellan, S. L. (2006). Delineation of a chemical and biological signature for stormwater pollution in an urban river. *Journal of Water and Health*, *4*(2), 247–262. https://doi.org/10.2166/wh.2006.0021

U.S. Environmental Protection Agency (USEPA), (1994). Combined Sewer Overflow (CSO) Control Policy. *Federal Register*, *59*, 18688–18691.

Vogel, J. R., Frankforter, J. D., Rus, D. L., Hobza, C. M., & Moser, M. T. (2009) Water quality of combined sewer overflows, stormwater, and streams, Omaha, Nebraska, 2006–07, U.S. Geological Survey, Scientific Investigations Report 2009–5175.