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Effect of long-term successive storm flows on water reclamation plant resilience

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ABSTRACT

A water reclamation plant (WRP) needs to be resilient to successfully operate through different kinds of perturbations. Perturbations such as storm events, especially long-term successive storm flows, can adversely affect operations. A better understanding of these effects can provide benefits for plant operation, in terms of effluent quality and energy efficiency. However, the concept of resilience for a WRP has not been widely studied, and we are not aware of any studies specifically related to storm flows. In this work we applied measures of resistance and recovery time to quantify resilience, and used a WRP simulation model to investigate how different storm flow characteristics (flowrate and duration) and the amount of aeration influence resilience. Not surprisingly, increasing storm flowrate leads to decreasing resilience. Although the aeration rate plays an important role in determining resilience, there is an aeration threshold (6 m^3/s for our WRP model); higher aeration rates do not increase resilience. Results suggest that aeration costs could be reduced by as much as 50% while still maintaining the resilience needed to meet effluent quality permit requirements through the perturbations examined in this study.

1. Introduction

This paper describes how monitoring and control information can promote more efficient operation at the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) Calumet water reclamation plant (WRP). The work is part of a collaborative project involving the MWRDGC and the Illinois Institute of Technology (IIT), to reduce energy demands and to improve control of nutrient loading in the Chicago Area Waterway System (CAWS) (CPS, 2010). To provide more efficient operations at the Calumet WRP, it is important to understand how influent conditions, effluent quality, and the energy requirements for aeration are related. To assess these relationships, we simulated process response to long-term successive storm flows using a WRP process model, and used resistance and recovery time to quantify process resilience. A brief introduction of the motivation of this study is provided below, followed by a review of related, relevant studies, which helped us to define and develop a method to quantify WRP process resilience.

The concept of resilience was initially developed in the ecological sciences to describe the capacity of an ecosystem to tolerate disturbances that significantly influence the function and structure of that ecosystem (Holling, 1973; Westman, 1978; Lopez et al., 2013). Grimm and Wissel (1997) suggested that resilience has been confused with "stability" in ecological studies; the confusion stems from the fact that resilience is a quantitative index, whereas stability is a qualitative property. Holling (1996) suggested that the concept of resilience could also be applied to engineered processes, but there was a difference between ecological resilience and engineering resilience:

- Ecological resilience is the amount of disturbance a system can withstand before its function changes.
- Engineering resilience has two components; one is the resistance to the disturbance and one is the time to return to an acceptable steady-state.

Holling (1996) concluded that ecological resilience involved maintaining system function, but engineering resilience focused on the efficiency of that function (such as, to achieve a single operating objective). Whereas ecological resilience can apply to several different states, engineering resilience focuses on the designed state (Peterson et al., 1998; Botton et al., 2006). Because a WRP is an engineered microbial ecosystem, it is helpful to review how these perspectives have been applied in previous studies, and how those

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studies interpreted and measured resilience.

In previous studies that applied the concept of engineering resilience it was common to treat the resistance as an independent parameter, and define resilience as a function of the return time. For example, Wertz et al. (2007) investigated the effect of decreasing soil microbial diversity on resistance and resilience in response to a disturbance (heat). They measured resistance and resilience based on function and diversity of denitrifiers and nitrite oxidizers. Cabrol et al. (2012) assessed resistance and resilience for a gas biofilter, based on changes in the removal efficiency (RE) with respect to several constituents, when the biofilter was exposed to shock loading. They defined the resistance as the percentage of time-integrated RE during the shock loading relative to a reference RE without shock loading. They also calculated resilience based on the time required after the shock loading to return to 95% of the original stable RE. A few researchers have focused specifically on microbial ecosystems in wastewater treatment. For example, Saikaly and Oerther (2011) measured the resistance of an activated sludge microbial community to a toxic shock loading. They quantified the resistance as the concentration of toxicant that can result in 50% reduction (relative to a reference control experiment without toxicant) of oxygen uptake rate during a 30 min exposure to that toxic loading. More recently, Marsolek et al. (2014) used resistance and resilience to measure bioreactor performance with respect to microbial diversity and perturbations (based on exposure to 2,4,5-trichlorophenol) in wastewater treatment. They quantified the response based on the ratio of system performance following a perturbation (on day 1), to performance under steady-state conditions. Resistance was defined as the value of that ratio on days 2, 4, and 6, and resilience was defined as that ratio on days 10 and 11.

Because a WRP is an engineered ecosystem that uses controls to manage a microbial ecosystem, we were most interested in describing resilience in the context of engineered controls. The existing literature contains little information about WRP resilience, especially related to wet-weather perturbations. For example, Mabrouk et al. (2010) defined the return time as the time required until the excess pollution concentration returned to the permit limit value following a perturbation, and examined how return time could be used to quantify resilience. Weld and Singh (2011) compared the resilience of each component in a hybrid anaerobic digester/microbial fuel cell system based on a perturbation in the acetic acid concentration. They used the time for the pH to recover to its original value as an indicator for resilience. Weirich et al. (2015) used part of the U.S. Environmental Protection Agency's Integrated Compliance Information System WRP data to develop time series generalized linear models for BOD, TSS, ammonia, and fecal coliform concentrations. They used the models to simulate ten years of results to evaluate resilience and stability, which were defined as the recovery time after a violation and the frequency of violation, respectively.

Methods from the studies summarized above suggest that recovery time or/and resistance can be used to better understand process resilience at a WRP, and that parameters such as RE, pollutant concentration, pH, or effluent quality can be used to monitor system response to perturbations. In our study we used resistance and recovery time as indicators of resilience; these indicators were evaluated based on a critical constituent, which we defined as the constituent with the longest recovery time.

Our study focused on the MWRDGC Calumet WRP, which began operations in 1922 and now serves more than one million people. The plant treats about 11.4 m^3/s (260 mgd) of wastewater and uses an activated sludge process (including nitrification) in all five batteries (A, B, C, E1, and E2). We investigated battery E2 in this study.

To evaluate process resilience, we simulated process response to relatively challenging influent perturbations. Two types of storm flows were considered:

- A single storm event, and
- Multiple storm events with a long total duration

Zhu (2015) simulated operations through representative single daily storm events and concluded that the Calumet WRP typically operates with excess aeration. The current aeration rate of about 13.9 m^3/s (42.3 mcfd) could be decreased by as much as 50% without adversely affecting operations. However, historical data indicate that long-term successive storm flows frequently occur. (These storms are described in more details in the methodology section and the Supporting Information, Fig. S1). Influent to the Calumet WRP includes storm flow from the tunnel and reservoir plan (TARP), which is part of the local stormwater management system. Although TARP provides a buffer that reduces the magnitude of major storm events, in doing so it also increases the duration of storm flows, which means there can be above average flow even during dry-weather days. As a result, a rapid succession of storm events can lead to especially challenging conditions, and it is important to understand the impact of these storm flows on process resilience. To evaluate these kinds of long-term perturbations, we tested the following hypothesis: Process resilience will not significantly change even after a 50% decrease in aeration and the process can still successfully manage long-term storm flows. The next section describes how representative long-term storm events were synthesized and simulated using a WRP model to evaluate process response.

2. Methods

The three major tasks that comprised this study were the historical data inventory, WRP model simulation, and resilience quantification. Data inventory and model simulation are only briefly described here, more detailed information is provided by Zhu (2015).

2.1. Historical data inventory

For this study we did not have access to high frequency (more detailed than daily resolution) dynamic data for the Calumet WRP. Therefore, to synthesize storm flows we used daily and dynamic (hourly samples) flow data from the Stickney WRP (MWRDGC, 2012a; 2012b) and daily data from the Calumet WRP (MWRDGC, 2013). Based on a cross-correlation test (cross-correlation coefficient of about 0.6; at the 95% confidence level the critical value is 0.1), these two MWRDGC facilities share a similar flow pattern (Fig. S2). In previous work Zhu (2015) simulated single storm events (including changes in flow and influent concentrations) at flowrates of 2.6 (60 mgd), 3.5 (80), 4.4 (100), and 5.3 (120) m^3/s, to represent the range of relatively high flowrate (2.3–5.7 m^3/s) into the Calumet WRP. Based on dynamic data from the Stickney WRP, individual storms can be characterized by their *event duration* (duration time for a single storm flow), *peak duration* (elapsed time during peak flow), and *amplitude* (ratio of peak flow to initial minimum flow) (Fig. S3). Although a single, challenging storm flow will have relatively longer event duration and peak duration, it is unlikely that maximum values of event duration and peak duration occur simultaneously. Therefore, we defined a challenging single