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The Application of Monitoring and Modeling in Watershed Management

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Cover photo courtesy of DuPage River Salt Creek Workgroup
showing City of Elmhurst employees recovering a dissolved oxygen probe from Salt Creek in Illinois as part of a stream dissolved oxygen feasibility study.

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Stream Dissolved Oxygen Improvement Feasibility Study—Salt Creek and East Branch DuPage River

*Stephen McCracken[a] * and James Huff[b]*

Abstract

In 2004, the Illinois Environmental Protection Agency (IEPA) developed dissolved oxygen (DO) total maximum daily loads (TMDLs) for several mainstem reaches of Salt Creek and the East Branch DuPage River in Illinois. The TMDLs recommended steep reductions in effluent concentrations of five-day carbonaceous biochemical oxygen demand and ammonia-nitrogen at the 17 wastewater treatment plants (WWTPs) that discharge into the two basins. Members of the local regulated community objected to the TMDLs, partially because of costs, but also on the grounds that the TMDLs' modeling lacked empirical data and overemphasized wastewater input contributions to the impairments. Local environmental groups also voiced skepticism about the ability of the TMDLs to improve the local aquatic environment. IEPA and the local regulated community reached an agreement that allowed local partners time to examine a number of scenarios by which to achieve compliance with the DO water quality standards. A group of local stakeholders rebuilt the models used in the original TMDLs and populated them with data from a newly implemented network of stream monitoring stations and actual WWTP loading information. The result was two calibrated and validated models that were accepted by the regulated community, local environmental groups, and IEPA. Stakeholders then used the models to project the impacts of a number of possible alternatives, including effluent loading reductions, instream aeration, and dam removal. The first wave of project implementation based on the model output is currently underway.

Introduction

In 2004, the Illinois Environmental Protection Agency (IEPA) completed dissolved oxygen (DO) total maximum daily load (TMDL) studies for several mainstem reaches of Salt Creek and East Branch DuPage River (CH2M HILL 2004a,b). To achieve the Illinois DO standards (Table 1), the TMDLs recommended further reductions in five-day carbonaceous biochemical oxygen demand ($CBOD_5$) and ammonia-nitrogen concentrations in the effluents of area wastewater treatment plants (WWTPs), based on outputs from QUAL2E models developed for each waterway. The TMDL studies noted that dam removal might abate the need for waste load reductions for oxygen-demanding pollutants, and indicated that this option could be further evaluated (CH2M HILL 2004 a,b). Dams have been observed to lower DO in their impoundments by creating conditions for excessive algae growth, decreasing re-aeration rates and increasing detention times and sediment oxygen demand (SOD) (Butts and Evans 1978).

Reactions to the TMDLs were uniformly unfavorable. WWTP operators pointed to the large costs associated with reducing wastewater loadings; the Illinois Association of Wastewater Agencies (2003) estimated compliance costs at $48 million for Salt Creek alone. They also had reservations about model accuracy. Among other things, they noted that the models used design average flow, as opposed to actual flows; the loadings were the National Pollutant Discharge Elimination System permit limits, rather than the actual discharge loadings; the data were more than seven years old; and neither model had been validated. The regulated community was skeptical that the reductions would improve aquatic biology. Environmental advocacy groups noted that the TMDL reports themselves placed low confidence in the models. According to the implementation plan of the Salt Creek report (CH2M HILL 2004b, 13), "[discharge monitoring report] data for WWTPs ... show that average summer values for $CBOD_5$ and ammonia are below the proposed limits.... Thus it may be possible that these [waste load allocations] can be met with little or no additional treatment." As such, the environmental advocacy groups were also skeptical that the reductions would improve conditions for aquatic life. The WWTP community argued that this language ignored the elimination of the margin of safety needed to consistently meet recommended limits.

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Table 1. Illinois Pollution Control Board DO standards.

Measurement Interval	DO Water Quality Standard	
	August–February	March–July
At any time	3.5 mg/L	5.0 mg/L
7-day average	4.0 mg/L daily min average	6.0 mg/L daily mean
30-day average	5.5 mg/L daily mean	N/A

Source: 35 Illinois Administrative Code 302.206 (January 24, 2008).

Given the opposition, the stage was set for years of contentious implementation efforts. In 2005, IEPA came to an agreement with local stakeholders, now incorporated as the DuPage River Salt Creek Workgroup (DRSCW or Workgroup), to delay implementation of the TMDL recommendations while the DRSCW developed a plan to address DO and other impairments. Stakeholders immediately set about rebuilding the DO models. The first DRSCW project, summarized in this paper, assessed the feasibility of stream DO improvement for the East Branch DuPage River and Salt Creek. DRSCW set the following objectives for the Stream DO Improvement Feasibility Study:

- identify the principle low-flow DO sags in both waterways
- evaluate the impacts of decreasing oxygen-demanding loadings from WWTPs on the low-flow ambient DO concentrations
- evaluate the impacts of five existing dams on DO and, where significant, identify alternatives for specific dam sites (e.g., complete removal, "bridging," or some other modification that meets project goals while addressing applicable concerns)
- identify criteria and sites where stream aeration could be used to improve DO levels during low-flow conditions
- determine financial impacts, including project capital costs (e.g., for sediment removal and disposal), operation and maintenance needs, and costs associated with stream improvement projects (life cycle costs)

At all steps of this process, a diverse group of DRSCW stakeholders—representing WWTPs, municipalities, Forest Preserve Districts, and environmental groups—worked collaboratively to plan, manage, and collect data for the project. By early 2006, DRSCW had contracted with a team consisting of HDR Inc (water quality modeling), Huff & Huff Inc (water quality analysis), and Inter-Fluve Inc (stream restoration and dam evaluation) to work on the project.

Model Selection

To model DO impairments, the DRSCW chose the QUAL2K model. The fundamental utility of QUAL2E and QUAL2K is essentially the same: they are one-dimensional, steady-state models for the prediction of DO and associated water quality constituents in rivers and streams. Steady-state modeling assumes that stream conditions, such as flow, point-source discharge, and loadings, are constant in time. However, QUAL2K is capable of diurnally varying headwater and meteorological input data and includes a full sediment diagnosis model to compute SOD and nutrient fluxes between the bottom sediment and the water column. In addition, the QUAL2K model offers more options for decay functions of water quality constituents, re-aeration rate equations, heat exchange, and photosynthetically available solar radiation calculations (Chapra et al. 2005).

Given the similarities between the two models, the first step in preparing the QUAL2K model was to input data previously used in QUAL2E to produce QUAL2K outputs that could be compared to the results in the TMDL reports. The QUAL2K initial model set-up closely followed the input files from the QUAL2E model. DRSCW did not initially use the more refined features in QUAL2K, described above. DRSCW compared the QUAL2K model outputs for DO, $CBOD_5$, and ammonia-nitrogen to the QUAL2E outputs reported in CH2M HILL (2004a,b). After some manipulation of internal coefficients, QUAL2K satisfactorily reproduced the general trend of DO profiles previously generated with QUAL2E.

DRSCW modified river reach lengths in QUAL2K based on updated geographic information system (GIS) data developed as part of this project. In contrast, the QUAL2E model used US Geological Survey (USGS) river mile information. The reach lengths used in the two models differed by as much as 2.4 miles (3.9 km) in the upstream reaches of Salt Creek. DRSCW collected detailed bathymetric data from major impoundments on both rivers and adjusted the geometric files accordingly. DRSCW revised main channel slopes using the digital elevation model (DEM) developed by USGS for Salt Creek, which is publicly available in a GIS format. DRSCW extracted elevation information for the end points of each reach segment from the overlay of the DEM and reach end points set up in QUAL2K. The model proved sensitive to both geometry and SOD inputs.

DRSCW also completed sensitivity analysis for cloud cover variation. QUAL2K calculated stream velocity and depth except for impounded reaches, for which survey data were used. Changes to the stream geometry meant that reaction rate coefficients would also change. DRSCW modified CBOD, nitrification, and the settling rates of various water quality constituents using stream characteristics reported by Chapra (1997), Thomann and Mueller (1987), and the US Environmental Protection Agency (1987). Because the QUAL2K model did not simulate suspended solids in the stream or the light extinction caused by elevated suspended solids, DRSCW used a higher background light extinction rate compared to that used for QUAL2E inputs, effectively reducing the diurnal DO flux in the model.

Data Collection

A major criticism of the original DO model was its lack of quantitative data. Although data were available on streamflow, wastewater flow, and effluent quality, very limited data existed on stream quality. Gathering such information became an immediate priority. In spring 2006, DRSCW set up a system of "continuous" DO monitoring stations, which collected hourly DO, water temperature, conductivity, and pH data. The short sample interval was selected to account for the expected variability of ambient DO concentrations. The stations recorded data from May through September (warm-weather months) at six sites on Salt Creek and five on the East Branch DuPage River. The density of the sites proved critical when calibrating the model because, at various times, DO probes were inoperable or recorded data outside of quality assurance guidelines. Additionally, because QUAL2K is a steady-state model, calibration and validation required that multiple monitoring stations capture some period of steady-state ambient conditions. The continuous DO monitoring stations also supplied data with the necessary resolution to gauge compliance with the Illinois DO water quality 7-day and 30-day standards (Table 1).

Sites were selected based on stream reconnaissance carried out in early spring. DRSCW consultants identified stretches of stream where warm-weather DO sags seemed likely, including areas upstream of dams and wide, sluggish areas of river without canopy cover. The DRSCW placed the DO probes at identified monitoring stations, using casings affixed to bridges and instream mobile casings for sites where no spanning structure was available (Figure 1). Although the instream casings were more flexible in terms of placement, they also required more staff time for deployment, data retrieval, and probe maintenance. DRSCW collected all DO data according to the quality assurance project plan (QAPP) approved by IEPA. For other parameters, the probes were calibrated according to the manufacturer's recommendations and the QAPP. Continuous DO data collected on the East Branch DuPage River from 2006 and 2007 indicated that DO concentrations upstream of the Churchill Woods dam, dropped to below 2.0 mg/L and exhibited a diurnal swing of greater than 12 mg/L. This was an expected result because of the longer retention time, lack of canopy cover, higher SOD, and higher water temperatures associated with the impoundment.

Figure 1. A technician from the City of Elmhurst, an agency member of the DuPage River Salt Creek Workgroup, retrieves a data logger from an instream casing on Salt Creek.

DRSCW consultants also collected SOD data at 16 sites using the in situ method described by Murphy and Hicks (1986) concurrently with the continuous DO monitoring. The SOD survey was completed in mid-summer to minimize temperature adjustments. SOD had been entered into the QUAL2E models as a uniform assumed value. The SOD survey found that the value was in fact highly variable. Individual SOD measurements at ambient temperatures in the East Branch DuPage River ranged from a minimum of 67 g/m^2/day [1] to a maximum of 9.53 g/m^2/day. Multiple samples from each location were collected to allow for averaging across each stretch of the river. The temperature in the model runs used station-averaged 20°C SOD values, which ranged from 1.13 to 3.61 g/m^2/day.

[1] SI units are industry standard for SOD measurements.

All WWTPs in the basins cooperated in the re-modeling exercise and supplied discharge monitoring report (DMR) data to the modeling team. These data included daily values for flow, $CBOD_5$, ammonia-nitrogen, total suspended solids, and pH. DRSCW collected field coordinates for all WWTP outfalls in the two basins to ensure accurate spatial placement of the data. USGS records provided additional data on river flow.

Calibrating the Model

Unless otherwise stated, the model referred to here is the East Branch DuPage River model. DRSCW calibrated and validated the model for Salt Creek using the same methodology, except that the modeling team completed a set of additional runs when initial results proved unsatisfactory. DRSCW changed model input to simulate the period of DO data collection in August 2006. In particular, the modeling team modified the characteristics of the Churchill Woods dam impoundment based on the bathymetric survey performed in 2006. The model also used more recent streamflow, stream geometry, and actual wastewater effluent water quality and flow data as inputs. The modeling team plotted a calibration run of the model, completed for August 20, 2006, against the continuous DO measurements taken during field sampling for the same date. This comparison demonstrated excellent agreement, with the exception of the diurnal pattern at Hidden Lake (River Kilometer 23, QUAL2K output is in kilometers), which was greater than the model predicted. The modeling team repeated the calibration exercise for August 13–17, 2006, and again compared the results with observed data for that period from the continuous DO stations. These results were also satisfactory. Based on the comparison between the computed and observed results, DRSCW revised the model and completed a third model run for validation. That validation run (for the period June 19–21, 2006; Figure 2), shows the computed DO against the ambient DO concentrations observed for that period. The relative size of each green triangle shown along the top of Figure 2, representing the locations of WWTPs discharging to the East Branch DuPage River, is representative of the quantity of discharge supplied by the plant during the modeling period. (In other figures, the WWTPs are shown only as locations.)

To help identify low-flow DO sags, the modeling team had to use the calibrated and validated model to predict ambient conditions under seven-day, ten-year, low-flow (7Q10) warm-weather conditions. Historical data sets compiled by the Metropolitan Water Reclamation District

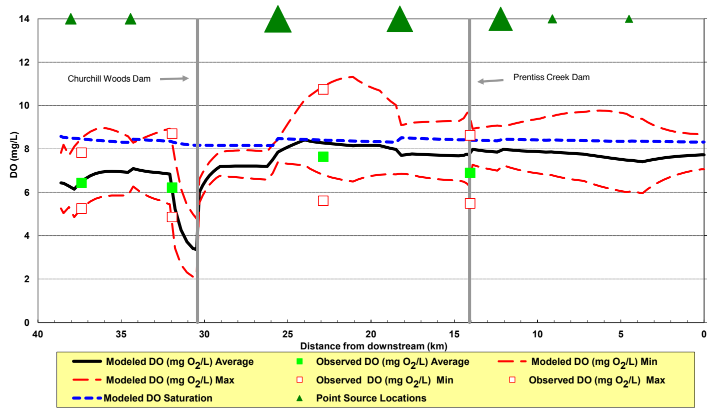

Figure 2. Observed and computed DO in the East Branch DuPage River from the QUAL2K validation run for the period June 19–21, 2006. (1 km is equivalent to ~ 0.62 miles.)

of Greater Chicago showed that, over the last 30 years, the highest recorded stream temperature was 3°C higher than the highest temperatures recorded during the validation and calibration periods.

The baseline model used the highest recorded historical temperature, the average $CBOD_5$ and ammonia-nitrogen levels discharged during summer months from WWTPs (based on DMR data from summer 2005, a period that approached the 7Q10 condition), and 7Q10 flow for the East Branch DuPage River (Singh and Ramanurthy 1993). This model run was intended to reflect worst-case conditions. The baseline output (shown graphically as Figure 3) showed that, upstream of the Churchill Woods dam, the minimum and daily mean DO levels were predicted to drop to 0 mg/L and 1.5 mg/L,

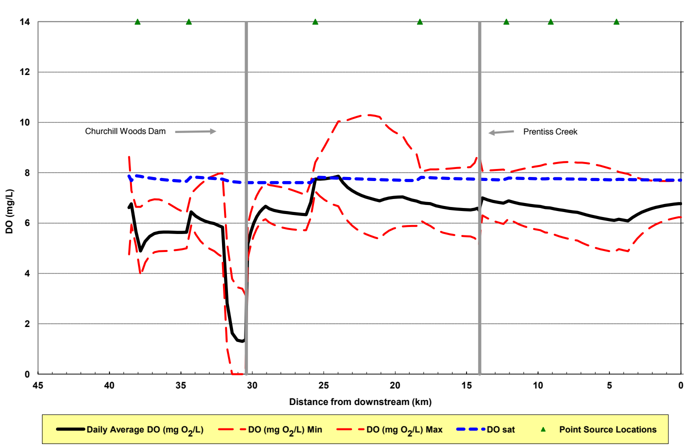

Figure 3. Computed DO for East Branch DuPage River mainstem. QUAL2K baseline model calculated using monthly average of June 2005 DMR conditions but with 3°C increased plant discharge and air temperature to simulate worst-case scenario. (1 km is equivalent to ~ 0.62 miles.)

respectively. The computed values suggested that other DO sags along the East Branch DuPage River were minor compared to the DO impact from the Churchill Woods dam.

Modeling Alternatives

The DRSCW worked with project consultants to develop, evaluate, and rank a number of aeration alternatives and to assess area dams. The group evaluated five dams according to their importance in flood control and the pros and cons of removal (ownership, sediment management, gradient at site). DRSCW removed one through-flow dam (Prentiss Creek dam) on the East Branch DuPage River from the study because modeling had not identified it as a cause of impairment and it was part of a local flood control system.

At this point, the DRSCW was ready to use the baseline model run to project the impacts of various remediation efforts on ambient DO concentrations. Initially, DRSCW evaluated riffles and various forms of instream aeration, including air and high-purity oxygen. However, the oxygen deficit above the Churchill Woods dam was so severe and the SOD so high, that only high-purity oxygen had the potential to achieve the DO water quality standard. In addition, the biological studies clearly showed a loss of aquatic biological integrity above the dam, something aeration would not ameliorate. In short, the Churchill Woods dam was clearly shown to be such a significant ecological problem that removal became the primary focus. The group selected the following alternatives for modeling on the East Branch DuPage River:

- lower WWTP loadings to zero while maintaining flow (strictly a theoretical exercise deemed necessary to demonstrate the effectiveness of such an approach)
- full removal of the Churchill Woods dam

The zero-loading model run for the East Branch DuPage River showed that, absent any pollutant loading from the WWTPs, the DO impairment would still exist at the site. The dam removal alternative model (shown in Figure 4) projected that daily average DO concentrations at the site would be in compliance following full removal, and that the higher DO levels would continue downstream. Given that the zero-loading model was projected to cost up to \$67 million[2] for just the two WWTPs above the Churchill

[2] Cost estimates were based on plant design average flow, the addition of a membrane bioreactor, and the use of granular activated carbon to treat that volume of flow. Maintenance and operation costs were not included.

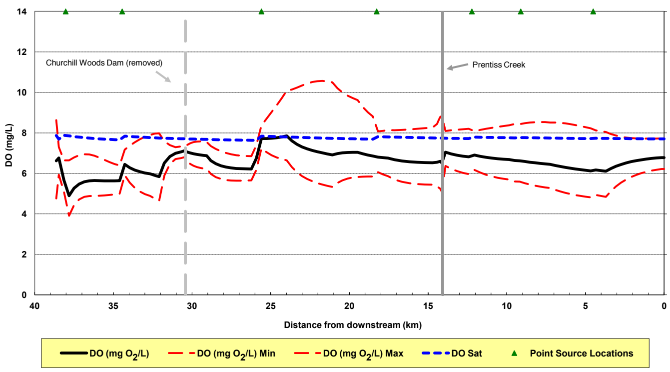

Figure 4. Modeled DO in the East Branch DuPage River. Baseline model showing removal of the Churchill Woods dam. (1 km is equivalent to ~ 0.62 miles.)

Woods dam, the DRSCW was confident that it could make a compelling case for full dam removal at that location (at a cost of $1.7 million, inclusive of engineering and permitting costs).

For the Salt Creek alternatives, modeling was more complex. The principle DO sag identified lay immediately upstream of the Fullersburg Woods dam, a local landmark. Given the nature of that site, the DRSCW devoted more resources to modeling alternatives in this waterway than on the East Branch DuPage River. The Workgroup selected the following alternatives:

- lower WWTP loadings to zero while maintaining flow (strictly a theoretical exercise)
- full removal of the Fullersburg Woods dam
- partial breach of the dam
- incremental lowering of the crest of the dam
- instream aeration with air or high-purity oxygen in the dam impoundment

As with the East Branch DuPage River, biological assessments on Salt Creek found a significant drop in aquatic biological integrity upstream of the dam. Again, modification of the dam, which served multiple purposes, became the preferred option. Cost also pointed clearly to dam removal, with estimates for upgrading the ten upstream WWTPs estimated at greater than $388 million, while dam modification costs lay in the region of $1.1 to $2.5 million.

Project Implementation

In the second half of 2008, a team consisting of the Forest Preserve District of DuPage County (the property owner), DuPage County Division of Stormwater Management, the regional stormwater authority, and the DRSCW began investigating funding options to remove the Churchill Woods dam on the East Branch DuPage River. The team hired V3 Consultants and Huff & Huff Inc in early 2009 following a number of public meetings. Engineering plans and permits for the dam removal were completed in late 2010, and the dam was removed in March 2011 (Figure 5). The project was complicated by the presence of culverts immediately downstream of the dam, which set the post-project stream floor elevation higher than that used in the QUAL2K model, eroding some of the potential DO improvements. However, the elevation of the culvert inverts also prevented the mobilization of sediments during drawdown of the impoundment, a common issue in dam removal projects. Continued monitoring at the site will confirm whether project DO goals are achieved.

The Salt Creek recommendations have not yet been implemented. The DRSCW hosted and participated in several community stakeholder meetings prior to the release of the modeling report. Many of the dam impoundment's neighbors were resistant to any modification of

Figure 5. Removal of the Churchill Woods dam gets underway.

the structure. Given the enormous cost disparity between options and the high probability of biological improvement under a dam modification scenario, partial breech and full removal remain the DRSCW's preferred options. Several dams, including Churchill Woods, have been removed in the watersheds during the last two years. The DRSCW is optimistic that data and post-project conditions at these sites will help convince community stakeholders to work for a compromise on modifying the Fullersburg Woods dam.

Conclusions

The Stream DO Improvement Feasibility Study has proven to be a very successful project. It allowed local stakeholders to organize around a joint project and build an objective decision-making process using empirical data that all parties accepted. The graphical outputs from the models made the analysis accessible to lay audiences—notably, the dam owners and those with abutting properties. All discussions emphasized the amount of empirical data involved in calibrating and validating the model. The modeling alternatives to predict the effects of reducing WWTP pollutant loading to zero clearly demonstrated that such actions were unlikely to eliminate DO violations under low-flow conditions. For both sites, modeling predicted that, compared to a WWTP loadings reduction strategy, dam removal would more effectively improve DO and would do so at lower cost. Dam removal holds the extra value of directly and beneficially impacting aquatic biology and riparian and instream habitat: pre- and post-project fish surveys of the Churchill Woods site have shown that, post-project, five species not previously found in the area have moved into the location of the former impoundment.

Acknowledgments

The DRSCW would like to thank the consultants who worked on the Stream DO Improvement Feasibility Study: HDR Inc, Huff & Huff Inc, and Inter-Fluve Inc. The DRSCW would also like to thank IEPA for its support through the 319 program and the Metropolitan Water Reclamation District of Greater Chicago for supplying data to the study.

More information on the project and on the DRSCW can be found at http://www.drscw.org/dissolvedoxygen.html.

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