DEMONSTRATING THE POLLUTANT LOADING FROM STORMWATER DISCHARGE TO AN URBAN RIVER IN THE INTERMOUNTAIN WEST USING HIGH-FREQUENCY DATA

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INTRODUCTION

The Jordan River

The Jordan River is a 51-mile-long river running south to north from Utah Lake to the Great Salt Lake through the Salt Lake Valley in northern Utah. It is a highly urbanized river, fed by urbanized streams, running through four of the six largest cities in Utah (Epstein et al. 2016): Salt Lake City, West Valley City, West Jordan, and Sandy (Figure 1). The Salt Lake Valley is a semi-arid environment receiving an average yearly precipitation of 47.2 cm (18.6 in), most of which falls in the form of snow. The Jordan River is generally considered to be comprised of two parts, the Upper and Lower Jordan, the division of which occurs at a major diversion called the Surplus Canal at the southern Salt Lake City boundary. This canal diverts as much as 90% of the water directly to the Great Salt Lake to prevent flooding of neighborhoods and developed areas in the Lower Jordan.

In its prime condition, the Jordan River is designated to support the following beneficial use classifications: domestic use (with treatment), secondary contact such as boating and fishing, cold water fishery, agricultural irrigation, and habitat for wildlife dependent on the river and its associated food chains. A total maximum daily load (TMDL) study performed by the Utah Department of Environmental Quality in 2012 determined that all sections of the river are non-supporting for at least one of the beneficial uses, and the river is therefore considered impaired. The Lower Jordan is impaired due to insufficient dissolved oxygen (DO) levels driven by high organic matter loading to the Lower Jordan from a variety of sources (Cirrus Ecological Solutions 2017). The purpose of this study was to evaluate the contribution to this organic matter loading from large urban stormwater discharges to the Lower Jordan River to support future TMDL decision making.

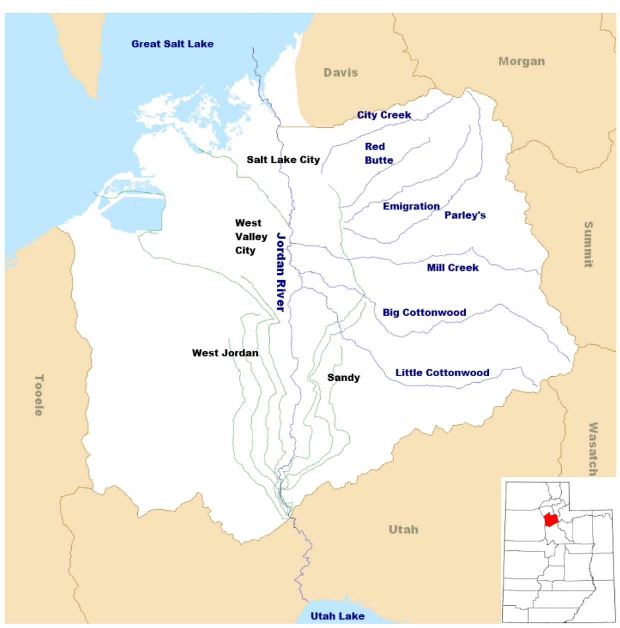

Figure 1. Jordan River tributaries and canals (Wikimedia Commons 2018).

Previous Stormwater Loading Studies on the Jordan River

Organic loading and its impact on oxygen levels in the Lower Jordan River, have been an ongoing concern. A large summer rainfall event in the Salt Lake Valley on July 4th, 2013, resulted in complete oxygen depletion in the 300 North section of the Lower Jordan River (Figure 2) some 10 blocks downstream of two major storm drains in the Salt Lake City area. This event prompted a study by Richardson (2014) to explore the chemical and biological characteristics of organic matter transported via stormwater and to evaluate the potential contribution of this storm derived organic matter to the oxygen imbalance in the Lower Jordan River. Richardson collected a range of particulate organic matter sources (wood, grass, leaves) from throughout the urban drainage area of the two major storm drains in Salt Lake City (Figure 3), chemically analyzed the material and subjected it to a series of leaching studies simulating its transport and residence within a stormwater conveyance system. Analysis of sequential leaching solution at 1, 3, 6, 10, and 24 hours indicated a rapid and exponential leaching of dissolved organic carbon (DOC) reaching more than 90% complete for all types of organic matter within 6 hours of leaching. In addition, the relative biodegradability of the leached DOC, as indicated by ultimate carbonaceous BOD (cBODu) and the BOD decay rate, was highest in the initial leaching solution (up to 100 mg cBOD/g solid/hr) and both decreased exponentially over time. Richardson's study confirmed the July 4th Jordan River observation, that organic solids carried into the Salt Lake City storm drain system rapidly dissolves, contributing highly biodegradable DOC to the Lower Jordan River and severely impacting DO levels there. The current study was designed to build on Richardson's work to document long-term contributions of stormwater carbon loading and oxygen impairment.

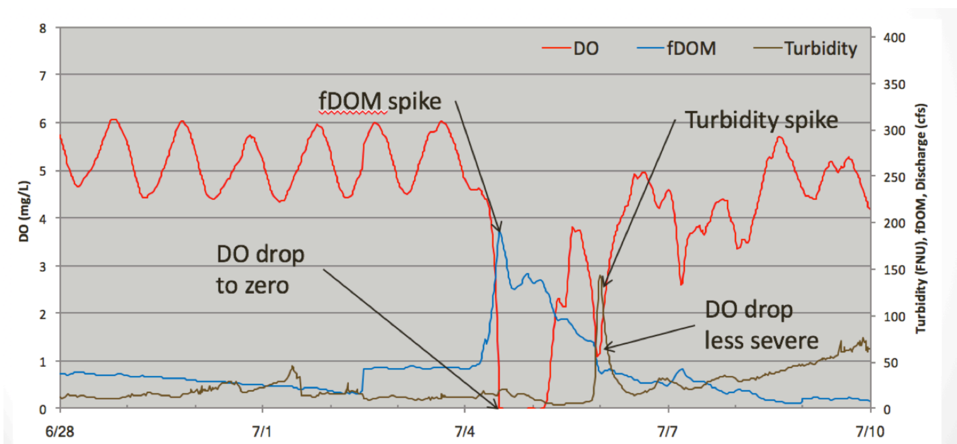

Figure 2. Continuous monitoring data for the Jordan River at the 300 S sampling location, June 28 to July 10, 2013.

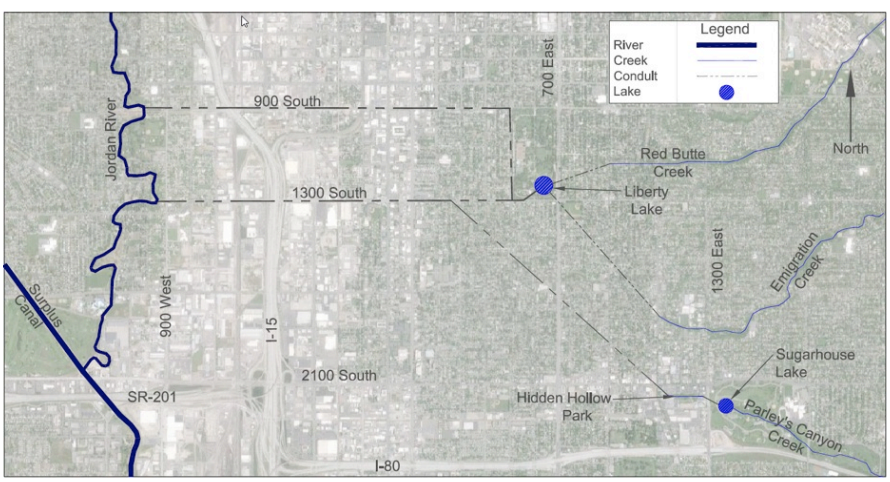

Figure 3. Tributaries and Salt Lake City urban stormwater discharges to the Lower Jordan River.

MATERIALS AND METHODS

iUTAH and GAMUT

iUTAH (Innovative Urban Transitions and Arid region Hydro-sustainability) was a National Science Foundation-funded EPSCoR hydrologic science capacity building program focused along the Wasatch Front in northern Utah to assess current and future water needs under population and climate pressures. As part of the project a water quality and terrestrial monitoring sensor network, the Gradients Along Mountain to Urban Transitions (GAMUT) network, was constructed in the three primary watersheds in the Wasatch Front region: Logan River, Red Butte Creek/Jordan River, and the Provo River. Real-time, continuous data from these monitoring sites for a variety of water quality (flow, pH, water temperature, conductivity, turbidity, etc.) and climate data (solar radiation, air temperature, wind speed, relative humidity, ET, etc.) are collected every 15 minutes and reported online via the iUTAH Modeling and Data Federation (http://data.iutahepscor.org/mdf/Data/Gamut_Network/) for public use and accessibility. The continuous monitoring data available through the GAMUT network for one of two primary urban stormwater discharges from Salt Lake City into the Lower Jordan River at 900 W and 1300 S (http://data.iutahepscor.org/mdf/river_info/iUTAH_RedButte_OD/ RB_900W_BA/) for the period from May 2015 to May 2016 were used to develop estimates for stormwater discharge contributions of organic loading to the Lower Jordan during this monitoring period.

Field Site Location - 900W 1300S, Salt Lake City, UT

The sampling site for this study is located at the 900 W 1300 S storm drain within the Red Butte Creek watershed and is referred to as 1300 S (Figure 3). This storm drain is fed by the Red Butte Creek and Emigration Creek which originate in the mountains to the east of Salt Lake City and are channeled to the lower Jordan River via pipes and box culverts. Stormwater throughout the watershed east of the Jordan River is channeled and drained into these streams and box culverts as well, serving as a potential source of urban stormwater pollutants to the Lower Jordan. GAMUT stations in the Red Butte Creek watershed record electrical conductivity, pH, turbidity, dissolved oxygen, water temperature, water depth, and flow rate. A select few sites, including the one monitoring discharge into the Lower Jordan at 1300 S, also record fluorescent dissolved organic matter (fDOM) and nitrate-N.

Figure 4 indicates a typical instrumentation package installation at GAMUT water quality sites and includes the following sensor packages: YSI EXO2 multi-parameter water quality sonde (pH, DO, conductivity, temperature), FTS DTS-12 turbidity sensor, Campbell Scientific SC451 pressure transducer, Teledyne ISCO 2150 area velocity flow module, and at the 1300 South site a SUNA V2 UV nitrate sensor, and an EXO fDOM Smart Sensor. Continuous flow and EXO fDOM Smart Sensor monitoring data in the Lower Jordan River from the Jordan River Farmington Bay Water Quality Council (JRFBWQC) monitoring location at 1700 South were also used for comparison with the 1300 South stormwater channel discharge data during the study period.

Grab samples were collected from the stormwater channel at the 1300S site, during six storm events and four dry periods, to develop correlations between laboratory DOC and BOD results and continuous monitored surrogate measurements from the GAMUT network. Storm channel grab samples for laboratory analysis were collected using an ISCO Model 6712C Compact Portable Sampler (Figure 5) either actuated based on elevated turbidity readings during storm events, or manually actuated for sampling during dry periods. Corresponding manual grab samples for laboratory DOC and BOD analyses were also collected directly from the Jordan River upstream of the 1300 South stormwater discharge at five sampling times during the study period.

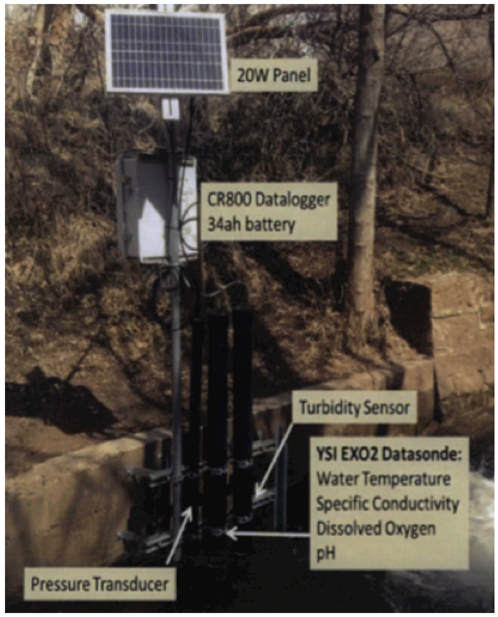

Figure 4. Typical GAMUT water quality sensor bundle installation.

Figure 5. ISCO Model 6712C compact portable sampler and sample bottle carrousel installation at the 1300 South stormwater channel site.

Laboratory Methods

Two specific analytes were used for organic loading analysis in this study, DOC and 5-day and ultimate soluble cBOD. A 250 mL subsample of the stormwater drain or Jordan River samples were filtered through a 0.45μm Whatman Glass Fiber filter (Cat No. 1827 047) for analysis of both DOC and soluble BOD testing. Approximately 40 mL of the subsample were filtered and placed in three amber vials for DOC analysis and were preserved with phosphoric acid and stored at 4°C until analyzed using a Teledyne Tekmar Apollo 9000 Combustion TOC Analyzer according to Standard Method 5310B (APHA, AWWA, WEF 2012).

The BOD analyses were conducted in general accordance with Standard Method 5210 Biological Oxygen Demand (BOD) #1 (APHA, AWWA, WEF 2012), The Amplified Long-Term BOD Test published by the Georgia Environmental Protection Division (1989), and the respirometric BOD procedure as described by Hach (2013) for its BODTrakII™ instrumentation. The GEPD method (BODLT) provides laboratory procedures and test specifications for analyzing samples for longer than the standard 5-day period, and the BODTrak2™ instrument provides a self-contained respirometer with programmed incubation periods up to 10 days with a BOD measurement every 40 minutes. These continuous BOD data were used in non-linear, least squares regressions to generate BOD related oxygen consumption rates for the various flow streams of interest in this study and to generate relative degradability data and correlations with continuous monitoring data, specifically the fDOM measurement, generated for both the stormwater channel and the Jordan River discharge.

RESULTS AND DISCUSSION

Hydraulic Loading from Stormwater Channel

The initial evaluation of the impact of stormwater discharge into the Lower Jordan River was focused on quantifying the relative flow contribution of the stormwater channel to the Jordan River at the 1300 South discharge. Continuous flow data from the GAMUT stormwater discharge site at 1300 South was aligned with continuous flow data from the JRFBWQC monitoring site on the Lower Jordan River at 1700 South. Each data set was quality control checked to eliminate periods of sensor malfunction (typically -9999 flow readings) and documented periods of sensor calibration. Further, manual calibration readings for discharges from the stormwater channel at 15 time periods and over channel discharges from 0.02 to 0.55 m^3/s (0.38 to 10.45 MGD) were carried out to ensure accurate and comparable flow measurements for all flow conditions observed during the study period.

When final quality-controlled flow data were aligned, a total of 35,003 paired data sets were available over a 13-month period from which to make comparisons. A large period of data was missing from the stormwater channel discharge due to equipment malfunction between mid-December 2015 and the end of January 2016, but essentially continuous data were available for the balance of the study period from June 1, 2015 through June 30, 2016. Over this period, Channel flow averaged 0.29 m^3/s (6.6 MGD) and peaked at 6.39 m^3/s (145.8 MGD), while the upstream Lower Jordan River flow averaged 4.86 m^3/s (110.9 MGD) with peak flow of 9.45 m^3/s (215.6 MGD). Figure 6 presents the ratio of Channel flow to Jordan River flow over the study period and indicates that although the Channel represents on average approximately 6% of the Lower Jordan River flow at its confluence, summer discharges routinely spike to 20% of the Jordan River flow and extreme storm events resulted in stormwater discharge of more than 150% of the Lower Jordan River flow.

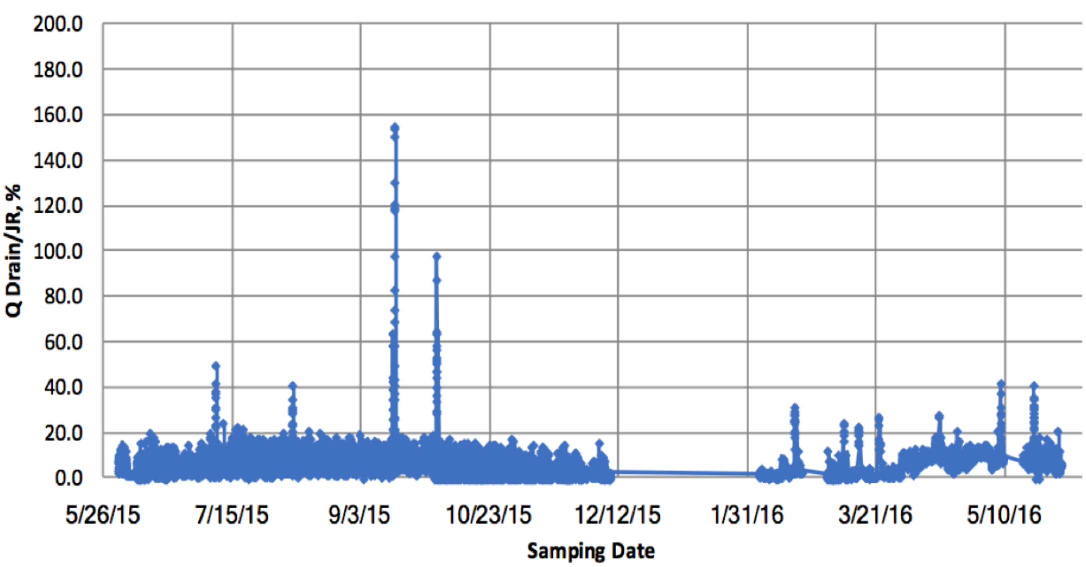

Figure 6. Ratio of stormwater channel flow to Lower Jordan River flow as a percent during the study period.

Organic Loading from Stormwater Channel
The next assessment of impact to the Lower Jordan from stormwater discharge was focused on evaluating the relative loading of the apparent cause of oxygen impairment to the Jordan, dissolved Organic Matter, from the stormwater channel to the Lower Jordan. Continuous flow data were combined with continuous readings of fDOM from the 1700 South sampling location on the Jordan River and the GAMUT station on the Stormwater Channel to determine loading rates for each flow stream. Both locations used identical fDOM instrumentation, and all fDOM readings from both locations were quality controlled to eliminate erroneous readings (general sensor readings of -999) and known periods of sensor maintenance and calibration. When final quality controlled fDOM data were aligned, a total of 19,008 paired data sets were available over a 13-month period from which to determine fDOM loading rates (fDOM concentration x Q) and make comparisons between flow streams. The ratio of Stormwater Channel fDOM loading to Lower Jordan River fDOM loading during the study period on a percent basis is shown in Figure 7 assuming that the fDOM measured in the Lower Jordan River has the same biodegradability and oxygen consumption characteristics as fDOM measured in the Stormwater Channel. Assuming equal reactivity, Figure 7 indicates that the average fDOM loading ratio, 3.2%, is lower than the average flow ratio, but that again, fDOM loading from the Stormwater Channel frequently peaks during rainfall events above 30% and was shown to exceed 180% during one storm in September 2015.

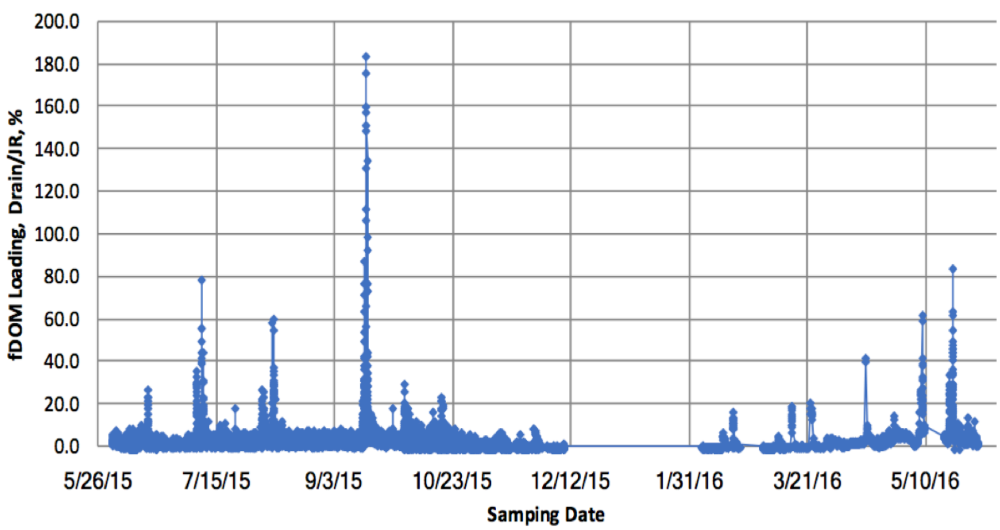

Figure 7. Ratio of stormwater channel fDOM loading to Lower Jordan River fDOM loading as a percent during the study period assuming equal fDOM degradability.

Relative Degradability of Organics in Stormwater and River Channels
Because of the finding by Richardson (2014) that DOC generated from organic matter located within the Stormwater Channel drainage area was rapidly produced and was highly biodegradable, an assessment of the relative biodegradability of DOC within the Lower Jordan River versus that found in the Stormwater Channel was carried out in this study. To assess relative biodegradability of the DOC found in each of these flow streams, samples were collected as described in the Methods Section above, either via ISCO autosampling initiated based on peak fDOM readings in the Stormwater Channel, or via grab sampling from the Lower Jordan River upstream of the Stormwater Channel for determination of BOD endpoints (BOD_5, BOD_{10}, BODu) and oxygen consumption rates based on BIOTrakII respiration measurements. Resulting BOD_5 and BOD_{10} values were generated directly as output from the BODTrakII instrument, while BODu values were estimated from the non-linear least squares regression of BODTrakII data fitted to the BOD curve, Equation 1.

$$Y = L_0(1 - e^{-k_1 t}) \quad (1)$$

where Y = BOD at time t, mg/L; L_0= ultimate BOD, mg/L; and k_1 = BOD rate constant, 1/d. Six storm events and four dry periods were used to collect samples for the BOD and fDOM relationship for the Stormwater Channel, while five sampling events were used to develop the BOD/fDOM relationships for the Lower Jordan River. Interestingly, BOD rate constants generated for the 1300 South Stormwater Channel samples (0.75 ± 0.14/d, n=43) were not statistically different from the Lower Jordan River samples (1.13 ± 0.4/d, n=9). The relative degradability of the fDOM measured in the two flow streams was found to be significantly different, however.

Figure 8 shows the relationship between fDOM and BODu measured in the Stormwater Channel samples during the study period. A wide range of fDOM, up to 228 Quinine Sulfate Units, were observed that yielded measured BOUu values of over 100 mg/L in these samples. The relationship found between BODu and fDOM for the Stormwater Channel and Lower Jordan River Samples were as follows:

Stormwater Channel: BODu = 0.19 fDOM ± 0.07, n = 36 (2)
Lower Jordan River: BODu = 0.033 fDOM ± 0.016, n = 5 (3)

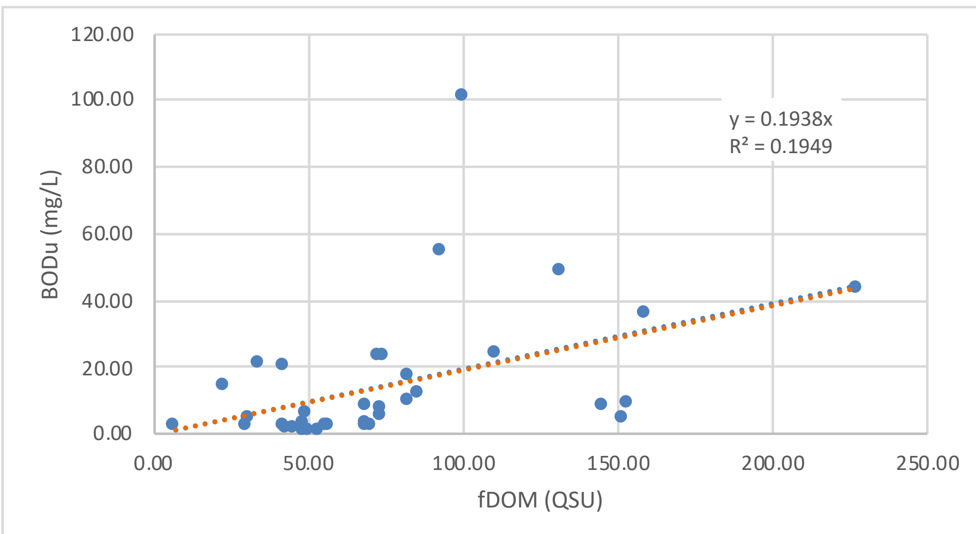

Figure 8. fDOM and BODu relationship for samples of stormwater channel discharge during the study period.

These relationships between BODu and fDOM were then used to estimate the impact of the Stormwater Channel discharge, accounting for the difference in fDOM degradability, during both dry and wet periods based on continuous fDOM data available from both sites.

Overall Stormwater Oxygen Depletion Contributions to Jordan River

BODu values for the Stormwater Channel and Lower Jordan River were estimated by applying Equations 2 and 3 to the continuous fDOM data available from each sampling location during the study period. A total of 19,008 paired data sets were available to calculate the % BODu loading of the 1300 South Stormwater Channel normalized to the upstream BODu loading of the Jordan River. This ratio of BODu loading is shown in Figure 9, and indicates that BODu loading from urban storm drainage can reach over 1200% of background Jordan River base load when the relative degradability of DOC (as indicated by fDOM) is accounted for.

The impact of Stormwater Channel discharge, even during relatively low flow, dry periods, can be seen in Figure 10, that expands the y-axis of Figure 9 to highlight the BODu loading ratio from 0 to 100%. Despite the average Stormwater Channel/Lower Jordan River fDOM ratio being approximately 3.2%, because of the high biodegradability of the fDOM generated from the Stormwater Channel, the average Stormwater Channel/Lower Jordan River ratio is over 26%, with routine excursions during even small storm events of over 100%.

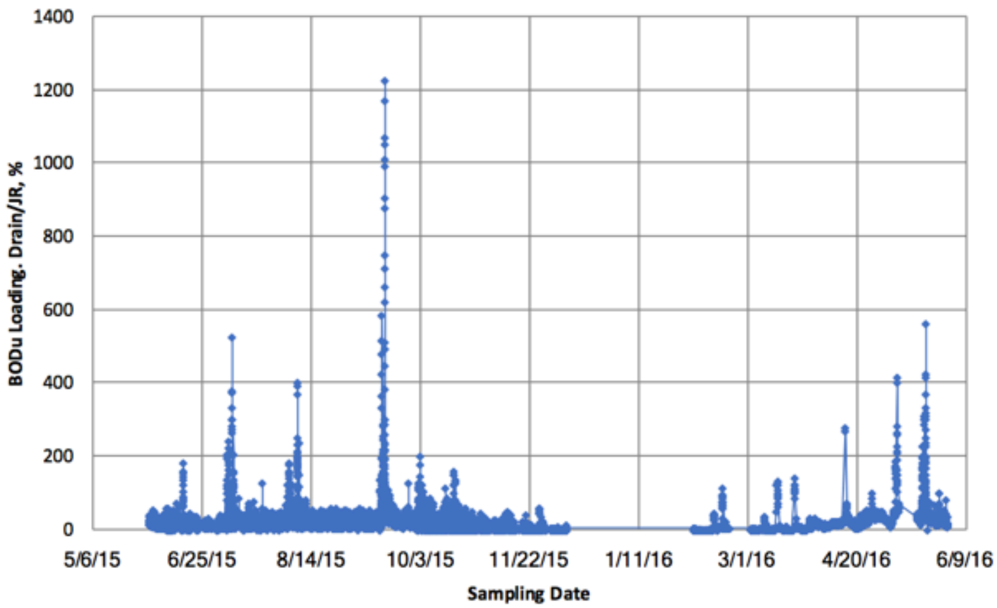

Figure 9. Ratio of stormwater channel BODu loading to Lower Jordan River BODu loading as a percent during the study period**.**

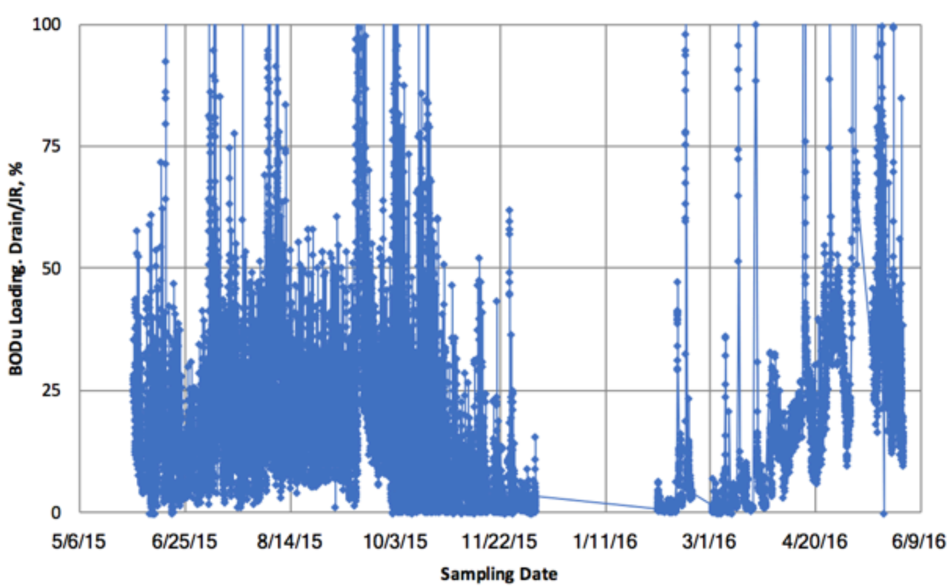

Figure 10. Ratio of stormwater channel BODu loading to Lower Jordan River BODu loading as a percent during the study period, showing an expanded y-axis from 0 to 100%.

Implication of Findings to Stormwater Loading Reductions

Based on the projection of BODu loading to the Lower Jordan River from the 1300 South Stormwater Channel discharge a significantly higher contribution of oxygen demand was observed than was projected in the Jordan River TMDL, and than was expected from a direct comparison of fDOM levels in the two flow streams. The high biodegradation rate found in the earlier study by Richardson (2014) was verified for both the organic matter in the Stormwater Channel and in the Lower Jordan River samples. The significant finding here is that the organic matter (as measured by fDOM) being discharged during both dry and wet weather conditions from the 1300 South Stormwater Channel contributes nearly six times more oxygen demand than an equivalent amount of fDOM being transported in the Lower Jordan River. To manage oxygen impairment in the Lower Jordan River, the source of the highly biodegradable, soluble organic material in the Stormwater Channel must be eliminated. The use of standard stormwater vaults designed to retain coarse suspended solids and floating debris is insufficient to reduce the soluble BODu loading observed during this study. Elimination of the source of the dissolved organic material is required before it enters the stormwater conveyance system if this high base load and peak loading of BODu during storm events is to be controlled.

SUMMARY AND CONCLUSIONS

This study was designed to investigate the impact of urban stormwater discharge to an urban river that is currently oxygen impaired. Original assumptions of stormwater impact in early TMDL work (Cirrus Ecological Solutions 2017) implicated the transfer of particulate organic matter and its decomposition within the Lower Jordan River as the cause of oxygen impairment. Initial studies conducted at the UWRL by Richardson (2014) indicated that coarse organic matter from the urban drainage area would be expected to very quickly solubilize and rapidly generate highly degradable dissolved organic matter that would represent the true source of oxygen impairment to the lower sections of the Jordan River. Continuous flow and dissolved organic matter measurement, in the form of fDOM, were available from the main Stormwater Channel and upstream in the Lower Jordan River to allow an assessment of flow and organic matter contributions from the stormwater discharge during both dry weather and wet weather conditions over the course of a 12-month period. Through grab sampling during dry and wet weather events, relationships were developed between BODu and continuous fDOM readings to allow a prediction of BODu contribution from the stormwater discharge over time using fDOM as a continuously monitored surrogate parameter. Based on the field and laboratory data collected in this study, the following conclusions can be reached.

1. Evidence of fDOM rather the turbidity spike driven oxygen depletion events in the Lower Jordan River that was evident from continuous monitoring data in the river from as early as 2013 provided the impetus for this study and proved correct in predicting the main cause of oxygen impairment in the Lower Jordan.
2. Continuous monitoring data available from both the NSF-funded GAMUT network that included the stormwater drain at 1300 South in Salt Lake City, and from the JRFBWC monitoring site at 1700 South on the Jordan River, provided quality controlled, paired data (19,002 to 35,003 data sets), to allow high frequency analysis of flow and organic loading dynamics in the Lower Jordan River.
3. These data (35,003 paired data sets) showed that average flow from the 1300 South Stormwater Channel represented 6% of the average Jordan River flow at the confluence of these two flow streams. Summer discharges were also shown to routinely spike to 20% of the Jordan River flow while extreme storm events can result in stormwater discharge of more than 150% of the Lower Jordan River flow.
4. Available continuous flow and fDOM readings at the two study sites were combined to determine the relative contribution of fDOM loading from the stormwater channel to the Lower Jordan River assuming equal fDOM degradability in the two flow streams. A total of 19,002 data sets were available for the combined data and indicated that average fDOM loading from the stormwater channel, 3.2%, was lower than the average flow contribution. The fDOM loading from the

Stormwater Channel was shown to frequently peak during rainfall events above 30% and was shown to exceed 180% during one storm in September 2015.

5. Relative degradability of fDOM in the two flow streams was evaluated by measuring BOD and determining the BOD decay rate for a total of 43 Stormwater Channel samples and nine Lower Jordan River Samples. BOD decay rates for the Stormwater Channel samples (0.75 ± 0.14/d) were high and not statistically different from the Lower Jordan River samples (1.13 ± 0.4/d). It was found, however, that the relative biodegradability of the two streams was significantly different.
6. The Stormwater Channel fDOM was found to be much less degraded than the Lower Jordan River fDOM, with the Stormwater Channel fDOM generating approximately six times more BODu than an equivalent quantity of Lower Jordan River fDOM.
7. The BODu loading contribution of the 1300 South Stormwater Channel to the Lower Jordan River was found to be significantly higher than the fDOM contribution alone, showing that the average BODu contribution from stormwater discharge is over 26% at the 1300 South location, with routine excursions during even small storm events exceeding 100% of the upstream Lower Jordan River loading.
8. An extreme BODu loading from the Stormwater Channel in the Fall 0f 2015 exceeded 1200% of the corresponding Lower Jordan River BODu loading, and clearly indicates a significant and on-going source of oxygen impairment to the river for urban stormwater discharges.
9. Results of this study have confirmed that the major source of water quality impairment to the Lower Jordan River is from highly biodegradable, soluble organic matter being conveyed to the river via stormwater drains. Knowledge of the rapid rate of DOC generated from the solids in the drainage area suggests that to reduce the impact of stormwater on the Lower Jordan, improved stormwater management up in the drainage area to prevent solids or its solubilized DOC from entering the conveyance system is necessary. Green Infrastructure/Low Impact Development approaches to capture, infiltrate, and treat the stormwater throughout the drainage area rather than collect and convey it to the Lower Jordan River should positively impact the Lower Jordan River water quality and mitigate the oxygen impairment that persists there.

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